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Developing a Workstation-Based, Real-Time Simulation for Rapid Handling Qualities Evaluations During Design

by

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ABSTRACT

This Paper describes the Rapid Aircraft DynamIcs AssessmeNt (RADIAN) project--an integration of the AirCraft SyYNThesis (ACSYNT) design code with the USAF DATCOM code that estimates stability derivatives. Both of these codes are available to universities. These programs are then linked to flight simulation and flight controller synthesis tools and the resulting design is evaluated on a graphics workstation. The entire process reduces the preliminary design time by an order of magnitude and provides an initial handling qualities evaluation of the design coupled to a control law. The integrated design process is applicable to both conventional aircraft taken from current textbooks and to unconventional designs emphasizing agility and propulsive control of attitude. The interactive and concurrent nature of the design process has been well received by industry and by design engineers at NASA. The process is being implemented into the design curriculum and is being used by students who view it as a significant advance over prior methods.

INTRODUCTION

The integration of strong, lightweight composite structures, high thrust-to-weight engines, and modern fly-by-wire control systems has opened a new era in the aerospace industry. The conventional design-by-discipline progress is rapidly becoming obsolete. Although only small percentages of life-cycle costs are spent in preliminary design stages, mistakes and oversights in the early phases of a project have enormous financial leverages that can cripple an aircraft design process. Using advanced modeling on interactive computer graphics workstations, conceptual design in aeronautical engineering can now relate performance, aerodynamics, structures, weights, propulsion, and vehicle stability. Concurrent engineering (CE) and integrated product development (IPD), now widely accepted by the aerospace industry, are requiring that universities re-think their education methods to provide integrated knowledge of many disciplines.[1]

In the Aeronautical Engineering Department at Cal Poly State University, aeronautical research is expanding conceptual design and synthesis capability to

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incorporate agility and handling quality metrics. This expanded capability will allow designs to be developed and evaluated in an early stage that include thrust vectoring, vortical flow modification, and advanced control techniques. This new capability resides primarily in aircraft computer design codes, many of which are available to all universities. The goal is to develop an effective tool for the rapid evaluation of aircraft stability, control, maneuverability, and handling qualities very early in the design process.

The systems analysis and aircraft design engineers at NASA Ames have successfully developed a computer-aided design package called ACSYNT (AirCraft SYNThesis) which is the focus of a government/industry institute administered by Virginia Polytechnic University.[2] This package is widely used throughout the aerospace industry and in the design program at Cal Poly, San Luis Obispo. It gives engineers and students the capability to rapidly investigate the synergistic effects of various geometries, some highly unconventional, on the performance capabilities of an aircraft. ACSYNT is highly interactive and ideally suited to the modern workstation environment. It allows the user to design an aircraft while optimizing it for a number of possible parameters. The parameters range from economic figures, such as aircraft cost, to mission figures, such as payload. This package, however, does not provide the stability and control derivatives that are needed to simulate and to analyze the flying qualities of an aircraft.

These derivatives are especially important for agile aircraft, not only to determine the piloting characteristics and thus suggest flight management schemes, but also to analyze control power requirements for agile flight at the edge of the flight envelope. For example, longitudinally an agile aircraft needs extra control power to both initiate and stop a pushover from very high angles of attack and to rapidly dump induced drag to gain energy. Laterally, the agile aircraft must be able to make maneuver plane changes at high angles of attack. In order to fully realize the potential for dynamic analysis, it is required to have a rapid, reliable, and fully automated system of obtaining and analyzing the aircraft's stability and control derivatives throughout the flight envelope.

Stability and control derivatives in the academic environment are often computed from published tables, curves, and equations. Many of them, however, can be estimated using a batch computer program called Digital DATCOM.[3] It was developed by the U.S. Air Force in the 1970's. Unfortunately, the program is not interactive, may not apply to a highly unconventional configurations, and does not contain provisions for developing control architectures and feedback control laws. The RADIAN project at Cal Poly links digital DATCOM to ACSYNT, providing a semi-automated system of determining aircraft stability and control derivatives and using these derivatives in a non-linear aircraft simulation implemented with a generic control law to provide a preliminary assessment of aircraft handling qualities.

In this way, the quality of the preliminary design is greatly improved with much of the iterative aspects of design development completed at this low-cost initial stage. Rapid dynamic assessment offers aircraft design students fast qualitative and quantitative feedback about how the design decisions they are making affect the way the airplane flies. Within moments, for example, a student could fly a simulation, modify wing aspect ratio, and fly again to get physical insight into the effect of this parameter change.

SYSTEM DESCRIPTION

The RADIAN package consists of three principle elements: software which links ACSYNT and digital DATCOM; a six-degree-of-freedom, non-linear simulation; and linear analysis software. The concept behind this system is simple. The aircraft is defined using ACSYNT's CAD interface. RADIAN uses the geometry and mission profile from the ACSYNT design file to create a DATCOM input file. DATCOM then runs, creating an output file which contains stability derivatives throughout the aircraft's flight envelope. RADIAN then parses this file into the table lookup format used by its flight simulator (files with a .SIM extension). At this point, the designer can choose to run the simulator or use the linear analysis features of RADIAN. The resulting aircraft dynamics assessment serves as feedback for design refinement. This design cycle is presented schematically in Figure 1.

Simulator features:

The RADIAN simulator is a six-degree-of-freedom simulator which uses full, non-linear equations of motion to determine aircraft dynamic response. Aircraft forces and moments are generated by stability derivatives which come from a lookup table as the aircraft transitions through its flight envelope. The simulator can either be run in an interactive, real-time mode or as a constant time-step, batch simulation. In both modes data logging is possible. When run in the real-time mode the pilot is presented with a simple, out-the-cockpit view, upon which a Head Up Display (HUD) has been superimposed (see Figure 2). Control inputs are received either by a flight control stick or by the workstation's mouse. These inputs are then filtered through the control module which allows the user to include a feedback control system in the simulation. Multiple control architectures can be selected as the simulator runs. In batch mode, control inputs are defined by the user prior to run-time and executed by the computer during the course of the run.

The heart (or engine!) of the flight simulator is its package to solve the six degree-of-freedom (DOF) equations of motion. Forces and moments are generated via stability and control derivatives. These forces and moments are then converted into aircraft body axes and used to calculate both linear and angular acceleration. Assuming constant mass, the vector equation of linear motion from Reference 4 is

$$\mathbf{F} = m\frac{d\mathbf{V}}{dt} + m\,\Omega \times \mathbf{V} \tag{1}$$

where **F** is the force vector, [F_X, F_y, F_Z], **V** is linear velocity in the body frame, [u, v, w], and Ω is angular velocity in the body frame, [p, q, r]. Since the force vector is known, this equation can be solved for d**V**/dt:

$$\frac{d\mathbf{V}}{dt} = \frac{\mathbf{F}}{m} - \Omega \times \mathbf{V} \tag{2}$$

The resultant vector d**V**/dt is then integrated to become the aircraft velocity in the body frame [u, v, w] which is transformed into flat-earth, inertial velocity [v_X, v_y, v_Z] and this velocity is integrated to yield position.

The equation of angular motion is expressed:

$$\mathbf{M} = \frac{d\mathbf{H}}{dt} + \Omega \times \mathbf{H} \tag{3}$$

where **M** is the moment vector [l, m, n], Ω is angular velocity in the body frame, [p, q, r], and H is angular momentum, **I** Ω. Assuming a constant moment of inertia, **I** (d Ω /dt) can be substituted for d**H**/dt. dΩ /dt is then given as:

$$\frac{d\Omega}{dt} = \mathbf{I}^{-1}\mathbf{M} - \Omega \times \mathbf{H} \tag{4}$$

The angular acceleration is integrated and transformed to Euler rates which are integrated into the inertial heading, pitch and roll angles Ψ, Θ, and Φ.

Evaluation features:

A variety of evaluation techniques have been developed in order for the designer/pilot to quantitatively assess the handling qualities of the aircraft. In the real-time simulation mode, either a landing task or an "up-and-away" flying task may be used. In the landing task, the simulation is begun with the aircraft displaced both horizontally and vertically from the glideslope to the runway. The pilot's task is to intercept the glideslope and fly a final approach, flare, and touchdown. A score for the approach is assessed based upon the mean square of the aircraft's linear deviation from the glidepath. The landing is scored based upon vertical speed at touchdown, distance from the runway's centerline, and distance from the touchdown point.

In order for the pilot to determine the proper glideslope, a series of "telephone poles" have been placed at the end of the runway. The height and placement of these poles is such that when the pilot is on glideslope, the tips of the poles appear even with the horizon. When viewed from above or below glideslope, the tips of the poles form a peak or valley, respectively (Figure 2).

The landing task effectively evaluates the handling qualities of the aircraft over a large operational frequency band. Maintaining the glideslope at long range is a relatively low bandwidth task, while doing so at close range requires greater intensity of control. Atmospheric turbulence can be added to prevent the pilot from learning to perform the task.

The "up-and-away" task requires the pilot to track a moving target. This X-shaped target traces a path across the horizon while four aiming points at the tips of the X alternate randomly (Figure 3). The speed of the target is determined by passing random noise through a digital low-pass filter with a pole at 0.1 rad/sec. The aiming points alternate randomly within a frequency band of 0.5 to 3.0 rad/sec. Scoring is based upon the mean square angular error in aiming.

Naturally, the scores assigned during these tasks are dependent upon the individual skill of the pilot and therefore highly subjective. Even if a trained test pilot is not available, however, the scores (pilot ratings) from one individual can help determine relative handling qualities differences between competing configurations during the design process.

More objective measures of aircraft handling qualities can be obtained by operating the simulator in the batch evaluation mode. In this mode, the aircraft self-trims at a user-determined flight condition and one of a variety of commands is executed by the computer. The user can select from a step input, a pulse, a doublet, or a sinusoid of a specified frequency. These commands can be applied to any of the aircraft's controls. The resulting time response is then analyzed for such figures of merit as rise time, settling time, time delay, percent overshoot and control anticipation parameter (CAP), and the bandwidth criterion.[5]

The batch mode of operation also allows includes an experimental method of determining the aircraft frequency response. Sinusoidal command inputs are automatically generated at frequencies ranging from 0.1 to 10.0 rad/sec. The resulting output phase and magnitude are saved to disk as a function of frequency. This data is then used either to fit a transfer function or to directly calculate frequency domain figures of merit such as phase margin, gain margin, and bandwidth. Fitting a transfer function to this data gives a low-order, linear approximation of the non-linear aircraft dynamics in the frequency range of interest.

Linear Analysis Features

RADIAN's linear analyzer uses stability derivatives at a user-specified point in the aircraft's flight envelope to create the matrices **A**, **B**, **C**, and **D** in a ninth-order state space representation of the aircraft dynamics given as:

$$
\begin{aligned}
\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\
\mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}
\end{aligned}
\tag{5}
$$

where **X** is the aircraft state vector, **U** is the control vector, and **Y** is the system output vector. This system is fully coupled in the lateral and longitudinal modes. The state-space system may then be converted to transfer functions. These transfer functions are then used to evaluate handling qualities metrics.

Work is currently in progress to incorporate the feature of automatic flight control system generation into the linear analysis software. This would allow the designer to fly a highly unstable design without first designing a control law for it.

CONCLUSIONS

The RADIAN project as described in this paper relates aircraft flying qualities to a given preliminary design rapidly and early in the design process. To accomplish this aircraft synthesis and stability derivative extraction computer-aided design tools are tied together with a non-linear simulation and heads-up display. The entire process is currently being implemented in the senior design class. The project also supports work being accomplished for the NASA multi-disciplinary design project.

ACKNOWLEDGEMENT

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REFERENCES

1. Simms, R., "CE: Engineering a Change in the Design Process," Aerospace America, Vol. 31, No. 4, April 1993, pp. 18-24.
2. Myklebust, A., and P. Gelhausen, "Putting the ACSYNT on Aircraft Design," Aerospace America, Vol. 32, No. 9, Sept. 1994, pp.26-30.
3. The USAF Stability and Control Digital DATCOM, Volume II, "Implementation of Datcom Methods," AFFDL-TR-79-3032, McDonnell Douglas Company, St. Louis, Missouri, April 1979.
4. McRuer, D., Ashkenas, I., and Grahan, D., Aircraft Dynamics and Automatic Control, Princeton University Press, Princeton, New Jersey, 1973.
5. MIL-STD-1797 (USAF), Flying Qualities of Piloted Vehicles, ASD/ENES, Wright-Patterson AFB, OH 45433-6503.

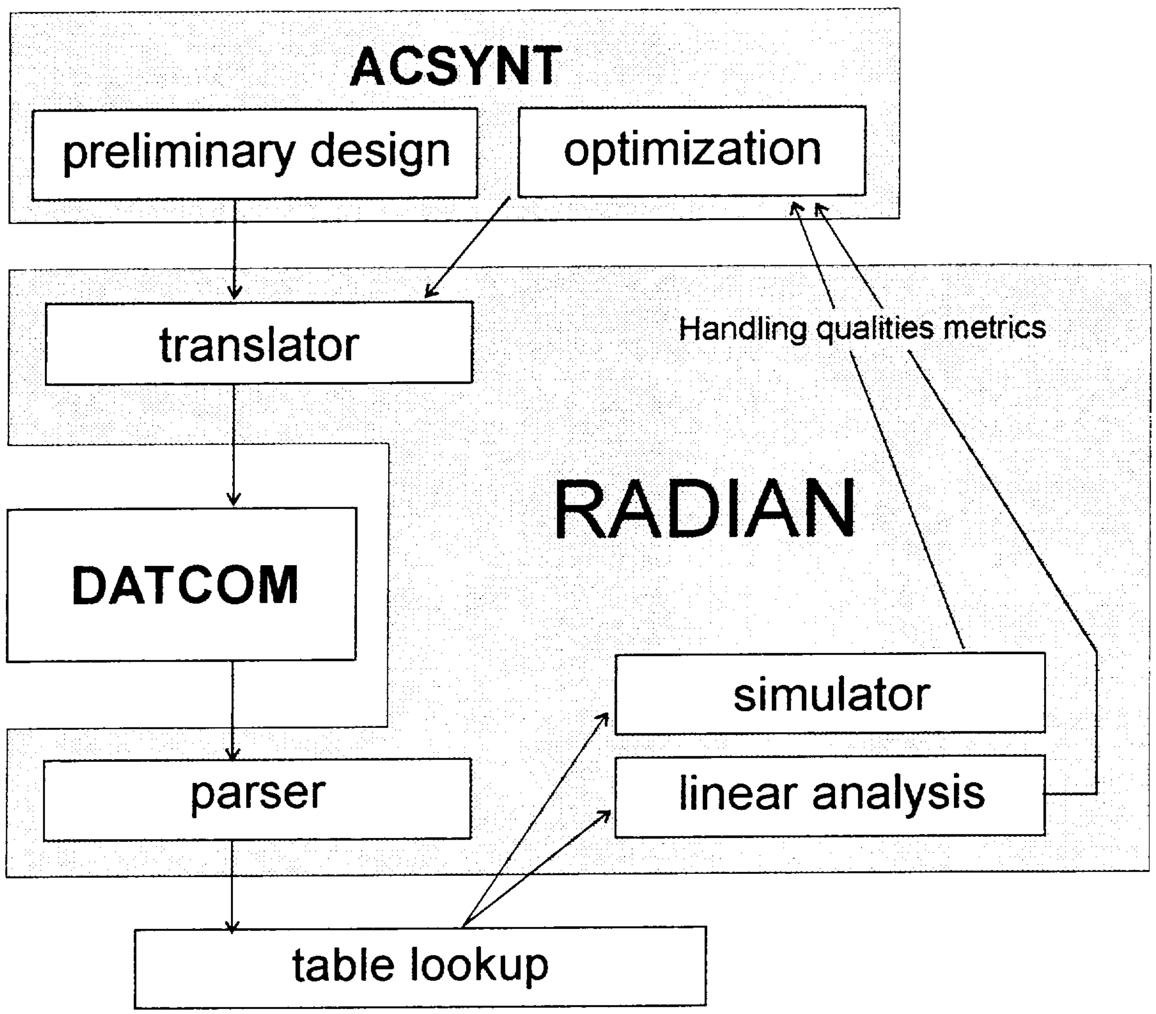
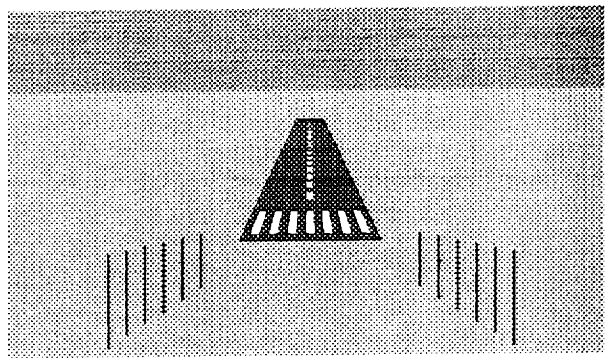
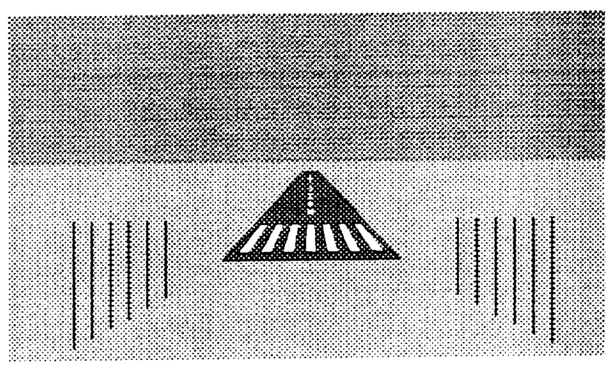


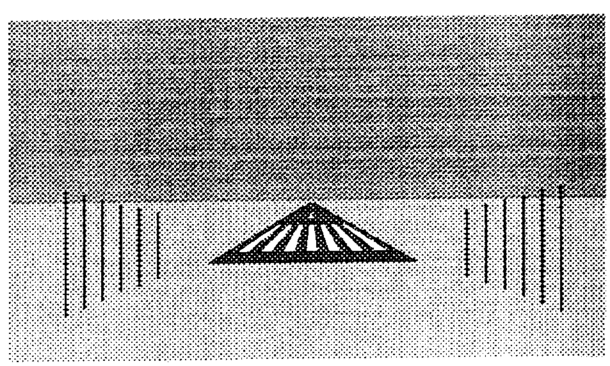
Figure 1: Schematic diagram of RADIAN system



above glideslope



on glideslope



below glideslope

Figure 2: "Telephone pole" glideslope indicators

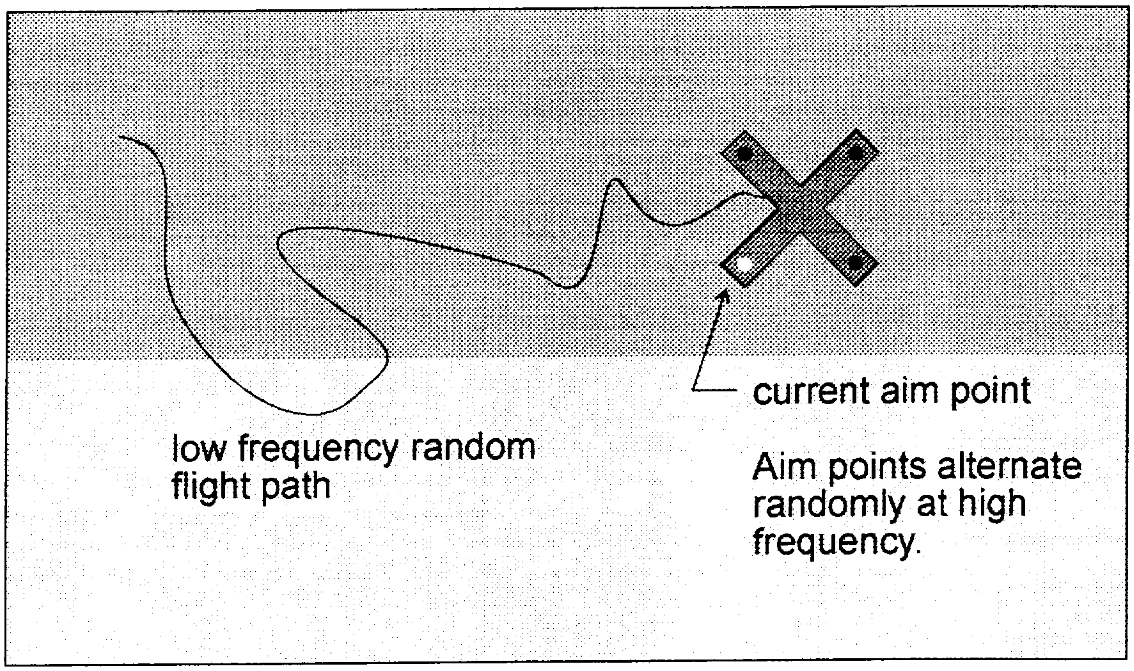


Figure 3: "Up-and-away" target.