AIAA Modeling and Simulation Technologies Conference and Exhibit
11-14 August 2003, Austin, Texas

AIAA 2003-5457

SIMULATING A TAIL-LESS RE-ENTRY VEHICLE

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ABSTRACT

Virtual Flight – RITE (Rapid Integration Test Environment) is a NASA program devoted to the development of rapid prototyping technology for the design of aerospace vehicles. In the fourth simulation entry in this series of projects, a Crew Transfer Vehicle concept design developed at NASA-Ames Research Center was simulated. This concept vehicle, known as CTV8, is a delta-wing design with sharp leading edges to improve the hypersonic lift-to-drag ratio (L/D). Control surfaces included ailerons and elevators on the trailing edge of the wing, a rudder on the trailing edge of the vertical tail, and upper and lower body flaps (on the aft upper and lower edges of the fuselage) for speed control.

During the experiment, one of the astronaut pilots who flew the simulation, Scott "Doc" Horowitz, commented that it would be interesting to simulate a similar vehicle, but without the vertical tail and rudder assembly. If such a vehicle could be designed to have reasonable flying qualities, there might be a significant weight saving, as well as reduced vulnerability to damage from high temperatures and dynamic pressures during re-entry.

In order to develop an aerodynamic database representing a tail-less vehicle, the CFD (computational fluid dynamics) team re-calculated the data using the same geometry but with the tail removed. Arbitrary, undefined control devices (which could be split-ailerons or other asymmetric drag devices) were assumed to replace the yawing moment of the rudder. These surfaces were not modeled in the CFD analysis; rather, the yawing moment coefficient due to the yaw control devices was arbitrarily set to a value that would yield approximately the same yaw control power that the rudder had produced. The flight control system was then modified to augment the directional stability of the tail-less aircraft, and the gains were re-optimized. The aircraft math model was then tested in the Vertical Motion Simulator (VMS) facility at NASA-Ames. This not only showed the quick turnaround possible with the RITE process, but also demonstrated the feasibility of the tail-less re-entry vehicle concept, and provided insight into the required control effectiveness of the yaw control devices.

RAPID INTEGRATION TEST ENVIRONMENT

The RITE (Rapid Integration Test Environment) process was developed at Ames Research Center to promote rapid turnaround in the aircraft design cycle.[1] In this process, a multi-disciplinary integrated team developed the design using design optimization tools, calculated the aerodynamic data using CFD techniques, designed a flight control system architecture, and optimized the control gains using an off-the-shelf control design software tool. Then the vehicle was simulated in the VMS facility.

A SHARP RE-ENTRY VEHICLE

The CTV8 vehicle was a modification of the final geometry developed in the RITE-3 project.[2] It is a crew transfer concept vehicle, smaller than the Space Shuttle and intended only for transport of personnel to and from the International Space Station, not for cargo delivery. The CTV8, like its predecessors, incorporates SHARP (Slender Hypersonic Aerothermodynamic Research Probes) technology.[3,4,5] By using ultra high temperature ceramics (UHTC) for the leading edges, the leading edges can be made sharper than is the case in current re-entry vehicle design, which yields a higher

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hypersonic lift-to-drag ratio, thus allowing a larger potential landing footprint. The CTV8 design is shown in Figure 1.

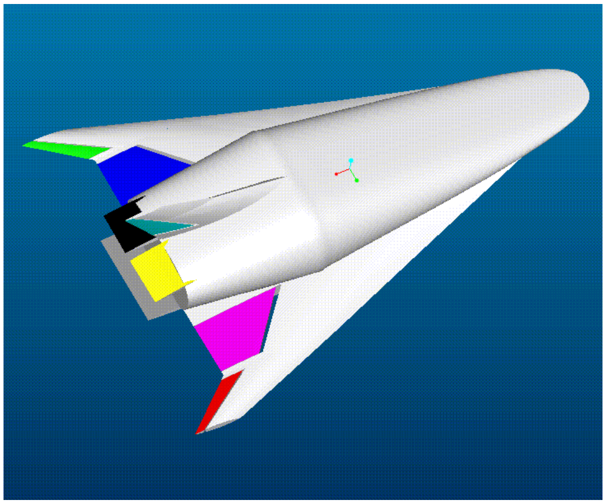

Figure 1 The CTV8 Design

A modification was made to the control surface configuration of the vehicles tested in RITE-3. In those simulations, it was found that the split-rudder used as a speed brake caused excessive pitch-up moment, which made it difficult to control when the speed brakes were opening. To mitigate this problem, upper and lower body flaps were added for use as speedbrakes. Each of the flaps produced a smaller pitching moment due to their proximity to the plane of the center-of-gravity of the vehicle, and simultaneous deflection of the upper and lower flaps causes their pitching moments to partially cancel each other.

AERODYNAMIC MATH MODEL

A simplified aerodynamic math model of the vehicle was developed using computational fluid dynamics simulations[6]. The methods used included both the Navier-Stokes (viscous) and Euler (inviscid) formulations of the flow equations.[7,8] A vortex lattice method was used to calculate the dynamic stability derivatives.[9] The resulting file was then uploaded to an Internet-based data management system, to allow easy access by all interested parties to the project.

The aerodynamic data tables were converted to the format required by the Function Table Processor (FTP) used in the NASA-Ames Vertical Motion Simulator facility. The data tables were then downloaded to the simulation host computer, and processed by the FTP. The FTP compiles the aerodynamic data into code that provides efficient table lookup with linear interpolation for real-time simulation.

FLIGHT CONTROLS

As in the previous CTV simulations, the flight control system was developed using SimuLink and the CONDUIT® control optimization tools.[10]

Unlike most other control optimization tools, CONDUIT® accepts flying qualities specifications defined by the user, and attempts to optimize the control gains to meet those specifications. This provides a user-friendly environment, and allows vehicles having different aerodynamic characteristics and/or different control system architectures to be optimized to meet a common set of specifications.

The pitch control system used the same Nz-Q architecture as the CTV simulations in the previous year's RITE experiment (see Figure 2). This blended feedback system, previously used in the HL-20 (a re-entry vehicle design concept investigated at NASA-Langley), provides an approximate glideslope angle rate command by scaling the normal acceleration by the inverse of the airspeed, and augments the pitch damping with pitch rate feedback.[11]

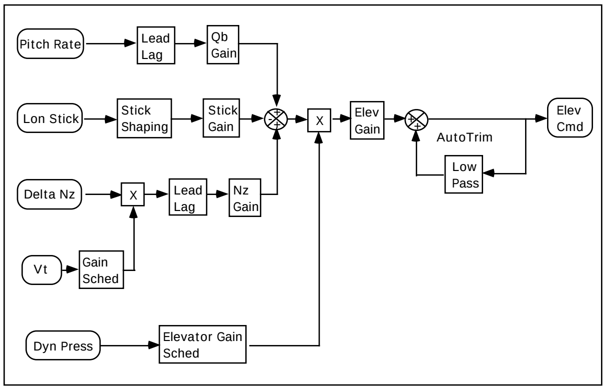

Figure 2 Pitch Command Generator

The roll control system provided augmented roll damping by feeding back roll rate to the ailerons (see Figure 3). The aileron command was scheduled inversely with dynamic pressure to maintain relatively constant performance throughout the approach.

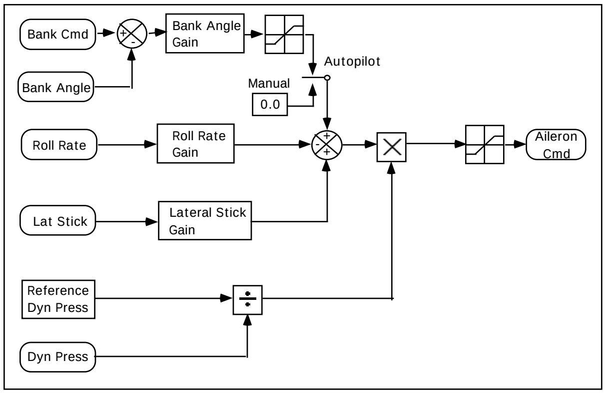

Figure 3 Roll Command Generator

An “aileron fail” mode was provided, as well, to demonstrate the capability of the RITE process to assist in the development of fault-tolerant flight controls. This mode used the elevators differentially for roll control, as well as symmetrically for pitch control. This capability was implemented in an aileron-elevon control mixer (see Figure 4).

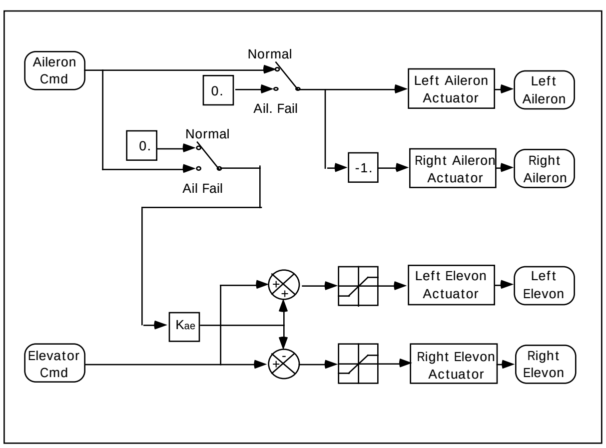

Figure 4 Aileron-Elevon Mixer

The yaw control system used in the previous RITE/CTV simulations had used sideslip rate (beta dot) feedback (see Figure 5). This was found to provide excellent tracking over the runway in the presence of gusty winds. However, in order to do that, the control system caused the aircraft to make rapid yaw corrections in response to the gusts. The astronaut pilots felt that this would be unacceptable, since it would be disorienting to a “de-conditioned” pilot returning from a long space mission. Therefore, alternatives were developed. One of these was to use a complimentary filtering technique to combine the low frequency components of the sideslip rate with the high frequency components of the yaw rate. This worked well; but, somewhat surprisingly, did not seem to have any real advantage over a classical yaw damper, consisting of a simple washed-out yaw rate feedback to the rudder. These different mechanizations were implemented by varying the feedback gains in the yaw control system. In each mechanization, the rudder command was scheduled inversely with dynamic pressure in order to maintain constant performance.

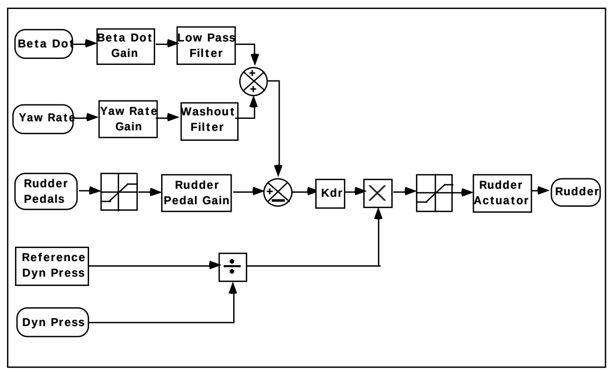

Figure 5 Yaw Control System

As with the previous simulations, a speed control system was included. This system modulated the speedbrake deflection in order to provide an airspeed hold capability (Figure 6). Because the vehicle configuration used upper and lower body flaps as speedbrakes, it was expected that the pitching moment changes produced by speedbrake deflection would be negligible. However, when the astronaut pilots began to fly the simulation, they discovered an objectionable tendency of the aircraft to overshoot the desired attitude in the pre-flare maneuver. It was determined that this was caused by the changing pitching moment produced by the speedbrakes, which were closing because of the increasing drag due to the change in attitude. This was mitigated by scheduling the lower body flap as a function of the average deflection of the upper body flaps in such a way as to minimize the net pitching moment. This was successful, and the tendency to overshoot in the pre-flare was barely detectable with the modified schedule.

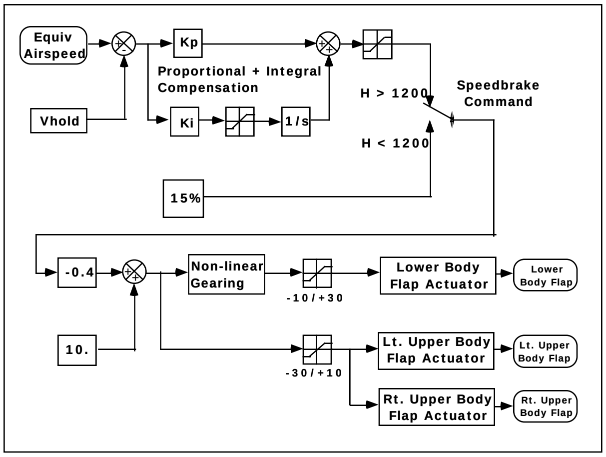

Figure 6 Speed Control System

THE TAIL-LESS CTV

During the simulation experiment, one of the astronaut pilots suggested that it would be interesting to try to simulate a similar vehicle, but without a vertical stabilizer. Such a design might have weight saving benefits and possible drag reduction, as well as one less protrusion that has to withstand the extreme temperatures and pressures of re-entry. Such a design concept may be new to the world of re-entry vehicles, but has been used successfully for the B-2 Spirit stealth bomber.

It should be noted that no design tradeoff was done in this study, so no conclusions have been reached regarding whether a tail-less design would really be better than the more conventional design with a vertical stabilizer and rudder. This study was just a first look at the tail-less option, to see if it would be potentially controllable, and if reasonable handling qualities were potentially achievable.

In order to provide an aerodynamic model of the modified vehicle, the CFD team developed a design in which the only difference was that the vertical tail (including both the vertical stabilizer and rudder) was removed (see Figure 7). Due to lack of time and funds, the vehicle geometry was not optimized as a tail-less design. Also, the new yaw control surfaces required to replace the rudder were not designed, nor were they included in the CFD analysis. New CFD simulation runs were made, using the baseline CTV8 configuration with the vertical tail removed, without yaw control devices, and the data were integrated into the piloted simulation.

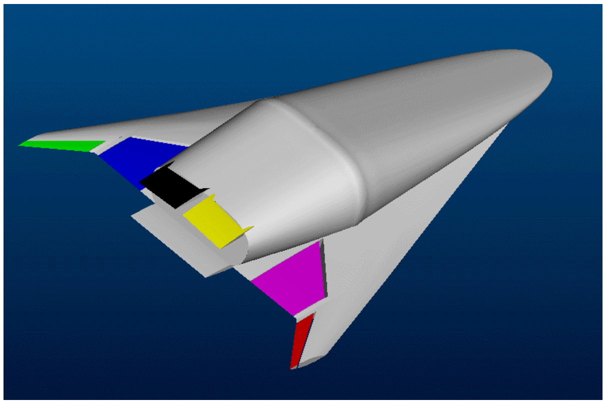

Figure 7 The Tail-Less CTV

Of course, such a design requires an active stability augmentation system (SAS) to provide adequate weathercock stability. This means that the yaw SAS must operate full-time, and must have adequate redundancy to mitigate the possibility of failure. For the purposes of this preliminary study, it was assumed that suitable yaw control devices (such as "split ailerons" or other differential drag devices) could be developed, having sufficient yaw control power to provide the needed stability and control. Then, if the vehicle could be made stable and controllable, a first cut approximation of the necessary yaw control power could be specified to the designers as a requirement.

In order to provide weathercock stability, a sideslip angle feedback path was added to the directional control system, using proportional plus integral compensation (see Figure 8). The architecture of the flight controls for the other axes was not changed; however, the gains for all axes were re-optimized, since the aerodynamic data had changed.

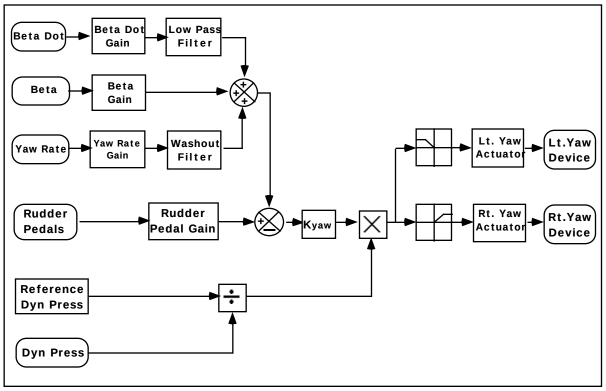

Figure 8 Modified Yaw Control System

Figure 9 Simulator Cab Interior

The resulting vehicle simulation turned out to have very good handling qualities. In addition, it was determined that the new vehicle also worked well with the "failed aileron" flight control system, using the elevators differentially for roll control, as well as symmetrically for pitch control, as was done with the nominal CTV8 configuration. This was good news, since it meant that the tail-less vehicle would not require ailerons for roll control. That meant that yaw control devices could be installed in place of the CTV8's ailerons. This would, however, remove some control redundancy from the design. Or, if "split ailerons" were used to provide both roll and yaw control, then the elevators could still provide control redundancy as on the CTV8.

THE SIMULATION EXPERIMENT

The tail-less CTV configuration was simulated in the Vertical Motion Simulator at NASA-Ames Research Center. The simulator cockpit was configured as it would be for the Space Shuttle simulation (Figure 9). The simulation was compared with simulations of the CTV8 and the Space Shuttle. Both CTV configurations were found to be much more maneuverable in roll than the Space Shuttle, and to have excellent handling qualities in all axes.

CONCLUSIONS

The Virtual Flight – RITE process resulted in a rapid design cycle. The tail-less CTV was developed and tested in piloted flight simulation in less than one week from the time that the decision was made to do it. The simulation experiment showed that a tail-less vehicle similar to the SHARP CTV conceptual designs developed at NASA-Ames would not be difficult to control, and could potentially be made to have excellent handling qualities. It was found that yaw control devices with approximately the same yaw moment control power as the rudder on the CTV8, driven by actuators with time constants of 0.025 seconds, would be adequate to stabilize the tail-less version. However, no analysis was performed to estimate the control power that could be achieved with physically realizable control surfaces. It was also demonstrated that adequate roll control performance could be achieved using the elevators as elevons, so that the ailerons could be replaced by differential drag yaw control devices.

RECOMMENDATIONS

Since the aerodynamics of the assumed yaw control devices were never calculated, any future work on such a vehicle should include the design of possible yaw control devices and calculation of their effect on the aerodynamics. Also, since the CTV8 was never optimized to be a tail-less configuration, optimization should be carried out. The mass distribution for the tail-less vehicle should also be determined, and new moments of inertia should be calculated. This would also allow determination of any potential weight savings. Finally, a design tradeoff study should be conducted to compare the costs and benefits of a tail-less configuration to the standard configuration with a tail.

ACKNOWLEDGEMENTS

The author would like to acknowledge the following people for their significant contributions to this work: Jorge Bardina, Kenny Cheung, Susan Cliff, Arsenio Dimanlig, Ron Gerdes, Veronica Hawke, Jeff Homan, Dave Kinney, Julie Mikula, Joe Ogwell, Chun Tang, Alex Te, Mark Tischler,and Dan Wilkins, as well as the astronaut pilots who participated in the flight simulation tests: Eric Boe, Ken Ham, Charlie Hobaugh, Scott "Doc" Horowitz, Greg "Ray Jay" Johnson, Steve Lindsey, Barry Wilmore, and George Zamka.

REFERENCES

1. Bunnell, J.W., and Mikula, J.A., "Rapid Integration Test Environment: An Integrated Process for Aircraft Design," AIAA-2002-4427, Monterey, CA August 2002.

2. Zuniga, F.A., Cliff, S.E., Kinney, D.J., Hawke, V.M., and Tang, C.Y., "Vehcile Design of a Sharp CTV Concept Using a Virtual Flight Rapid Integration Test Environment," AIAA-2002-4881, Monterey, CA, August 2002.

3. Reuther, J.J., Kinney, D.J., Smith, S.C., Kontinos, D.A., Saunders, D., and Gage, P., "A Reusable Space Vehicle Design Study Exploring Sharp Leading Edges," AIAA-2001-2884, June 2001.

4. Kinney, D.J., Bowles, J.V., Yank, L.H., and Roberts, C.D., "Conceptual Design of a 'SHARP' CTV," AIAA-2001-2887, June 2001.

5. Kontinos, D.A., Gee, K., Prabhu, D.K., "Temperature Constraints at the Sharp Leading Edge of a Crew Transfer Vehicle," AIAA-2001-2886, June 2001.

6. Rajkumar, T., and Bardina, J., “Prediction of Aerodynamic Coefficients Using Neural Network for Sparse Data,” Proceedings of FLAIRS 2002, Florida, 2002.

7. Meakin, R.L., and Wissink, A.M., "Unsteady Aerodynamic Simulation of Static and Moving Bodies Using Scalable Computers," AIAA-99-3302.

8. Aftmosis, M.J., Berger, M. J., and Melton, J.E., "Robust and Efficient Cartesian Mesh Generation for Component-Based Geometry," AIAA 97-0196, January 1977.

9. Miranda, L.R., Elliot, R.D., and Baker, W.M., "A Generalized Vortex Lattice Method for Subsonic and Supersonic Flow Applications," NASA CR-2866, Contract No. NAS1-12972, December 1977.

10. Tischler, M.B., et al, "A Multidisciplinary Flight Control Development Environment and Its Application to a Helicopter," IEEE Control Systems Magazine, Vol. 19, No. 4, pg.22-33, August 1999.

11. Jackson, E.B., Cruz, C.L., and Ragsdale, W.A., "Real-Time Simulation Model of the HL-20 Lifting Body," NASA TM-107580, Langley Research Center, Hampton, VA, July 1992.