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RAPID INTEGRATION TEST ENVIRONMENT: AN INTEGRATED PROCESS FOR AIRCRAFT DESIGN

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ABSTRACT

An integrated process has been developed at NASA-Ames Research Center to facilitate the design of aerospace vehicles by integrating flight simulation facilities into the design process from the beginning. This process, known as the Rapid Integration Test Environment (RITE), allows the multi-disciplinary vehicle design team to obtain information from simulator facilities in a timely fashion, and to make improvements before the design is frozen. The process has been used in the design of a re-entry vehicle, and the design has been tested in piloted simulation.

BACKGROUND

The traditional process for aircraft design is sequential, where each step is completed before the next one begins. This facilitates scheduling each of the facilities (such as wind tunnels and simulators). However, it also guarantees that the knowledge gained during the simulation tests will not be used to refine the aerodynamic configuration – at least not until a subsequent design cycle, or a later model is designed. This is because there is no room in the process for lessons learned in the flight simulation phase to be fed back to the vehicle designers in time to make a difference. Some iteration may be done on the flight control system design during the flight simulation, but usually not on the aerodynamic shape of the vehicle.

In order to solve this problem, the simulation phase of the process must be introduced earlier in the design cycle. It is this goal that has driven the RITE project team to develop a new, integrated process, in which pilots (in this case, astronaut-pilots) have an input early in the cycle by evaluating a flight simulation of the design before the design has been finalized.

Recent advances in computer speed, computational fluid dynamics technology, and modern control techniques, have made it possible to rapidly make changes to the design, calculate new math model parameters, re-optimize control gains, and integrate the new data into a flight simulator. This allows the simulator test results to be fed back to the vehicle designer, and a modified design to be created and re-tested during the simulation test period.

THE RITE PROCESS

The RITE process is an extension of the traditional design and analysis process in that it adds the dimension of piloted flight simulation to the decision making process. In this environment, design cycle times are shortened by using a number of modern techniques, including codes that facilitate rapid development of parametric geometries and the resulting surface and volume grids of vehicle designs; an integrated information system to allow rapid distribution of data; and control design tools to allow rapid re-optimization of the control system parameters when the vehicle design is changed. These capabilities allow design modifications to be accomplished rapidly during piloted flight simulation testing.

The RITE process, like traditional development, begins with a conceptual design of the aircraft. The design is

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drawn using a graphic design tool, then lofted in CAD software, and the aerodynamic characteristics of the design are determined using a combination of computational methods and wind tunnel tests. The aerodynamic model is then developed in a form usable in a real-time flight simulator. If the aircraft were powered, a simplified engine model would be developed. Since the particular aircraft studied in this project does not have an engine, this step was bypassed. Next, a flight control system must be developed, and the gains optimized for desired performance. Then the various parts of the model are integrated into the flight simulator, and a simulation experiment is conducted to evaluate the total vehicle performance. Several iterations may be needed to refine the flight controls, after which tests may be performed to determine the handling qualities of the vehicle. The results of these tests are then fed back to the designers, who now have an opportunity to improve the design. CFD simulations are once again used to calculate the aerodynamics of the modified design, the control gains are re-optimized, and the modified vehicle is tested again in the flight simulator. This process is shown in Figure 1.

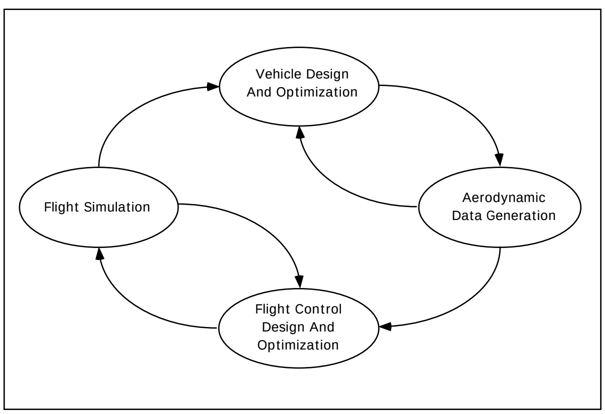

Figure 1. The RITE Process

VEHICLE DESIGN AND OPTIMIZATION

In order to develop this process, a conceptual aircraft design of interest to NASA-Ames researchers was chosen as a test case. This aircraft was a Crew Transfer Vehicle (CTV).[1,2] A CTV is a re-entry vehicle that could be used to return astronauts to earth following a space station mission – or in the case of a mission abort, possibly due to a launch vehicle failure. This particular vehicle incorporated sharp leading edges, made of high-temperature ceramics, in order to improve the hypersonic lift-to-drag (L/D) ratio.[3] The improved L/D would give the vehicle the capability to land within a larger footprint on the earth, thus giving the crew more options.[4]

The baseline aircraft design for the project, designated V-7, was developed by the Systems Analysis Branch of the Aeronautical Projects and Programs Office at NASA-Ames Research Center. Five modifications were made to this baseline, and each was tested in the Vertical Motion Simulator (VMS) with a pilot-in-the-loop. Five of these configurations are shown in Figure 2, where the baseline is shown in the center as CTV0. In the figure, the models are color coded by pressure coefficient at Mach 0.3, at an angle-of-attack of 10 degrees.

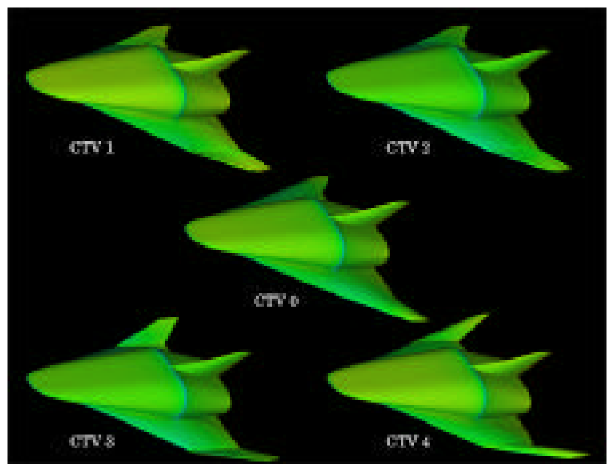

Figure 2. The Aircraft Configurations

There are subtle differences in the configurations shown in Figure 2. Wing twist and camber were modified to produce the CTV1 configuration. In CTV2, the concavity of the upper surface was eliminated. In an attempt to stabilize the Dutch roll mode, more dihedral was added to the configuration of CTV3.[5] CTV4 was developed using an optimization code to vary the wing twist, dihedral and sweep.[6] The CTV5 configuration (not shown) was developed during the simulation period, using feedback from the piloted tests. These models were designed at Mach 6 and Mach 0.3 using unsteady aerodynamic shape optimization.

AERODYNAMIC DATA GENERATION

Computational fluid dynamics (CFD) simulations and wind tunnel tests were used to develop mathematical models of the aerodynamics of several variations of the conceptual vehicle.

Computational Fluid Dynamics

Several forms of computational fluid dynamics codes were used in the RITE process. These included a vortex lattice method, as well as both the Euler (inviscid) and Navier-Stokes formulations of the flow equations.[7,8,9]

The vortex lattice method, simplest and fastest of the computational methods employed, was used to obtain preliminary estimates of the aerodynamics. This method was also used to develop approximations to the dynamic derivatives (such as roll moment due to roll rate), since computing them with the more sophisticated CFD techniques would have been very costly and time-consuming.

The Euler method is computationally faster, and therefore cheaper, than the Navier-Stokes method. However, the Navier-Stokes formulation is usually more accurate, especially when flow separation is a factor. Both methods were used: the Navier-Stokes formulation was used to compute the “clean” aerodynamics (without control surface deflections), and the Euler method was used to compute the control effectiveness and the ground effect model.

Wind Tunnel Testing

One problem with wind tunnel testing is the delay caused by the need to construct a physical model of the aircraft. This delay was minimized by using a stereo-lithography technique to create the model. This process uses two computer-aimed lasers, shining into a vat of resin, which cause the resin to harden where the lasers intersect. The hardened resin forms a model for use in the wind tunnel. Two such models were tested manufactured and tested in the Ames 32 inch by 48 inch atmospheric low speed wind tunnel.[10] This manufacturing technique is most useful for small-scale, low-speed tests where structural loads on the model are minimized. For tests demanding greater structural strength, other rapid-prototyping techniques are now available to hasten model fabrication.

DATA TRANSFER

An internet-based data management system was used to allow all members of the design/test team ready access to the aerodynamic data during the development of the mathematical model. The data were then converted to the Function Table Processor (FTP) format used in the VMS simulation facility. The Function Table Processor compiles function table data into a run-time database, with linear interpolation. This database system allows up to seven independent variables, can either use equally spaced or arbitrary breakpoints, and provides a number of features that enhance real-time computational efficiency.

FLIGHT CONTROLS

In order to test an aircraft design in a real-time, piloted flight simulator, a flight control system model is required. SimuLink® and the CONDUIT® control design tools were used to facilitate the development of suitable control laws to complete the mathematical model of the vehicle. CONDUIT® provides a relatively user-friendly environment for optimizing control system gains to meet flying qualities specifications defined by the control engineers.[11] This was essential to the RITE process, as it allowed rapid re-optimization to account for changes to the aerodynamic design.

The flight control system design began using a slightly modified version of the HL-20 flight controls.[12] The pitch control system, shown in Figure 3, utilized an Nz-Q command, with a blend of pitch rate and normal acceleration feedback. This approximates a flight path command, since the airspeed is held nearly constant.

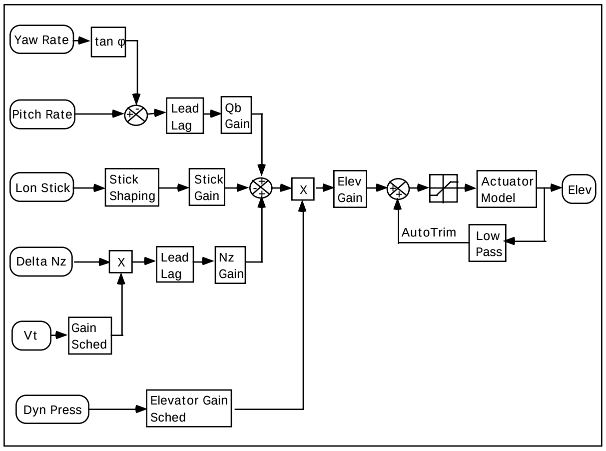

Figure 3. Pitch Control System

The roll command system, shown in Figure 4, used roll rate damping, together with bank angle command (from the guidance system) and bank angle feedback.

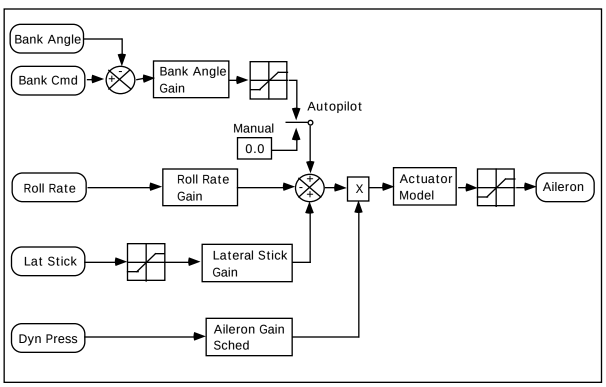

Figure 4. Roll Control System

The yaw control system, shown in Figure 5, originally used washed-out yaw rate feedback to augment the yaw damping. However, it was found that the Dutch roll mode was not sufficiently well damped, so an alternative system, consisting of inertial sideslip and sideslip rate feedback, was tried. This system worked very well, and it was found that the sideslip gain could be set to zero. The resulting system, using only inertial sideslip rate feedback, had the interesting property of automatically compensating for side gusts.

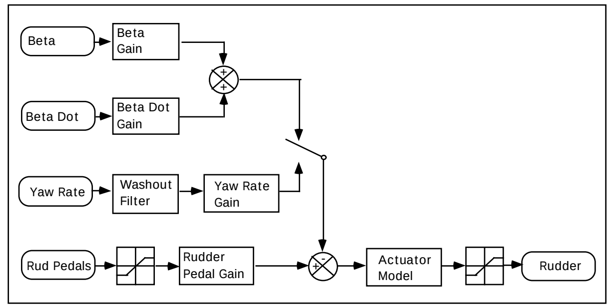

Figure 5. Yaw Control System

In order to provide an airspeed hold function, a split rudder was used as a speed brake. The speed control system, using equivalent airspeed feedback with proportional plus integral compensation, is shown in Figure 6. This system worked well to control airspeed, but introduced objectionable pitch transients in the flare maneuver.

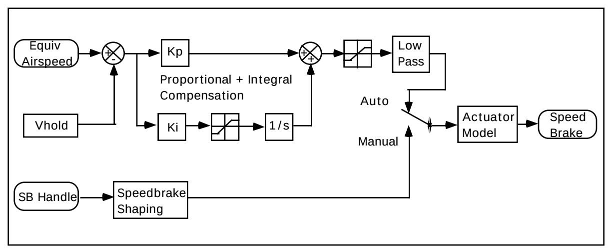

Figure 6. Speed Control System

FLIGHT SIMULATION

A real-time, piloted flight simulation was conducted in the VMS, using astronauts as the subject pilots to test the conceptual vehicle designs in approach and landing tasks on the Kennedy Space Center runway, and the results were fed back to the designers. The various CTV configurations were compared to both the Space Shuttle and the HL-20, a re-entry vehicle concept previously studied at NASA-Langley Research Center.[12] The simulator cab was configured exactly as it normally is when simulating the Space Shuttle for astronaut training (Figure 7).

Figure 7. Simulator Cab Interior

The Space Shuttle Orbiter simulation was used as a calibration point for the pilots. It was found that there was a significant difference between the handling qualities ratings given by astronauts who had piloted the Space Shuttle on an actual orbital mission, versus those who had been trained in the simulators but had not yet flown the real Space Shuttle. It was found useful to have every pilot fly and rate the Orbiter simulation, (which all had flown in their training) as this provided insight into their ratings of the CTV configurations.

A suite of tools known as the Virtual Laboratory (Figure 8) allowed members of the design/test team to participate in the simulation experiments in real time from a remote site.

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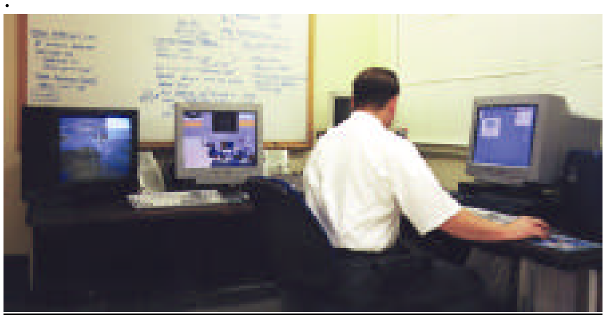

Figure 8. The Virtual Laboratory

The RITE process then allowed the designers to make changes based on the simulation results, and to perform evaluations with the integrated modifications. Significantly, within a few weeks the flying qualities were improved from barely controllable to excellent.

LESSONS LEARNED

There were several different categories of lessons learned during this experiment: information about the specific aircraft; information about the class of aircraft; information about the experiment; and information about the process.

About the Specific Configurations

Each of the configurations tested was determined to be acceptable, with Level I flying qualities, after proper optimization of the control system. However, some configurations required less control activity than others. This could indicate that those configurations might be able to use less powerful actuators, with consequent weight savings. More details on the results pertaining to each of the configurations have been published in another paper.[5]

About the Class of Aircraft

The CTV is a lifting-body re-entry vehicle, a class of aircraft that usually has a low L/D compared to winged aircraft. It also has no engine, so power cannot be used to control rate of descent at touchdown. This complicates the landing task, and there is no possibility for a go-around. Therefore, the L/D in ground effect is critical to pilot's ability to control the rate of descent at touchdown.

Since go-around is not possible, and the pilot is returning from the physical and mental stress of a space mission (possibly aborted), the flying qualities of the re-entry vehicle must be excellent. The pilot-astronauts who participated in this study are among the best pilots in the world, and they are well trained to fly the Space Shuttle. As expected, their performance with the Shuttle landing task was consistently excellent. Nevertheless, they consistently gave the Shuttle mediocre handling qualities ratings, and said that the next generation of re-entry vehicles must have better flying qualities.

It was also found that the guidance information on the Head-Up Display (HUD) was critical to the pilot's ability to meet the touchdown performance criteria. Since there is no engine in this vehicle, the trajectory must be accurately followed in order to control touchdown point, rate of descent, and landing airspeed.

About the Experiment

Since L/D is such an important factor in landing, in simulation it was found that the ground effect model is critical to the pilot's ability to control rate of descent at touchdown. It therefore had a large effect on pilot ratings for the landing task. Initially, there was no plan to develop a new set of ground effect data, but rather to use the ground effect model from the HL-20 simulation for all configurations (except the Space Shuttle).

When the astronauts discovered that they were having difficulty controlling the descent rate at touchdown, they suggested two experiments to determine the cause of the problem. First, the ground effect model was "turned off" in the simulation math model. The pilots found that the vehicle was equally difficult to land either way, implying that there was very little effect from the ground effect model. Next, they suggested a test in which the L/D was set to an arbitrarily high value of 6 for the entire run. This was done by setting the drag calculated by the simulation math model equal to the lift divided by 6, without regard for whether such a high value of L/D would be attainable with this type of vehicle. This test resulted in a simulated aircraft that was easy to land. Based on these tests, it was postulated that the difficulty in controlling rate of descent at touchdown was due to lack of a good ground effect model. Runs were made rapidly, using unstructured grid based Euler CFD methods, to generate a more realistic ground effect model. The new ground effect data were found to produce a greater L/D, which improved the touchdown performance significantly.

Another finding from the experiment was that the split rudder used for speedbrakes in the simulation produced too much nose-up pitching moment. This required it to be opened slowly and to remain at a fixed deflection when the aircraft was near the runway. Therefore, this speedbrake mechanization was not useful for manual control inputs.

Finally, the Rotational Hand Controller used to fly the simulated aircraft caused difficulty for the flight control optimization. This device is the same one that is used in the Space Shuttle. It was developed for maneuvering in space, but the astronauts don't like it for approach and landing. In addition, since there is no Military Specification for such a control inceptor, controller gains had to be determined by trial and error.

About the Process

The process worked well, but it could be improved by having a more systematic test procedure. The different configurations were tested in the simulator by having the pilot perform landings, either straight-in with no winds, offset laterally, or straight-in with gusty winds. The pilot then gave Cooper-Harper handling quality ratings.[13] This procedure showed how good each configuration was for the landing tasks, compared with the other configurations. But it did not provide any indication of how the configuration might be improved unless the pilot happened to make some observation (as they did in the case of ground effect) concerning the aerodynamic cause of deficiencies. So, a more systematic procedure should be developed that would have more probability of pointing out areas for possible improvements to the aerodynamic configuration.

FEEDBACK FROM SIMULATION

During the simulation, feedback was provided to the design and CFD teams regarding a number of issues. In one case, when the configuration was first flown, it exhibited excessive adverse yaw. When this characteristic was described to the CFD team, they were able to identify and correct an error that had been made in creating the data. The simulation then showed minimal yaw due to roll.

Another issue that was fed back to the CFD team was the ground effect problem. The team was able to rapidly generate ground effect data for the baseline CTV configuration, using the vortex lattice method, and this resulted in significantly better Cooper-Harper ratings. One astronaut commented, "With the new ground effect, my touchdown speeds are slower and my sink rate is slower. Overall, it would be easier."

During the experiment, a new configuration (CTV5), based on feedback from the piloted simulation, was implemented. New CFD data were calculated, function tables were generated, the control gains were re-optimized, and the simulation was flown again to evaluate the performance of the new configuration. The original plan was to try to do the re-design over a weekend, and test it in the simulator during the following week. Due to scheduling priorities, it was actually flown for the first time on Thursday, but the complete cycle required less than four days of work. This demonstrated the capability of fast turnaround.

The new configuration also incorporated body flaps that could be used as speedbrakes, in an attempt to reduce the pitching moment due to speedbrakes. This new feature was not tried, however, due to lack of time.

RECOMMENDATIONS

Since the RITE process is intended to provide a design team with guidance about how to improve its design, it would be advantageous to use a methodical test procedure that would show what could be improved. In this experiment, the test pilots were able to discover some potential improvements. However, there was no systematic procedure to look for areas of potential improvement to the aerodynamics of the vehicle. Some method should have been devised to systematically investigate what aerodynamic changes to the vehicle might improve its performance.

With hindsight, it is postulated that a procedure could be developed in which incremental changes to the various aerodynamic tables could be programmed into the simulation math model code. By evaluating the effect of each incremental change, data could be produced that would show the design team where improvements might be made. For example, an increment could be added to the roll damping in the rolling moment equation. If this hypothetical aerodynamic data set produced a better Cooper-Harper rating, that could suggest that the design might be improved by increasing the roll damping. In fact, such a procedure was used to some extent to investigate the ground effect problem in this experiment, by arbitrarily varying the L/D of the simulated vehicle, as described previously. The approach proved to be very useful, and will be incorporated into future RITE experiments.

CONCLUSIONS

This project has demonstrated the feasibility of the Rapid Integration Test Environment process for aircraft design. The strength of the RITE process is that it allows the vehicle designers to get feedback about the vehicle configuration before the design must be finalized. It also provides a way for pilots to be involved in the design process.

This approach has a number of benefits to the design process. First, it facilitates the rapid discovery of any errors that may have occurred in the calculation of the aerodynamic data. Second, it aids in the identification of any other math model deficiencies. Third, it provides insight into the handling qualities of the design, and allows the designers to make improvements and tradeoffs. For these reasons, the RITE process should become the standard for aircraft design.

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