MISSILE SIMULATION WITH ACTUAL HARDWARE USING AD-10'S

The Flight Control Simulation Program (FCSP) is an integrated set of user-oriented software that supports the development and verification of the Missile Flight Program. The features which make this simulation unique are:

1) Real-time execution
2) On-board missile computer in-the-loop
3) Six degrees of freedom
4) Monte Carlo capability.

The missile has intercontinental range and follows a ballistic trajectory after launch from a canister. The three boost stages are fueled by solid propellants and controlled using a single axial nozzle, which is vectored by pitch and yaw turbo-hydraulic actuators. The fourth stage, fueled by a hypergolic liquid propellant, contains a single axial nozzle controlled by electro-mechanical actuators, eight Attitude Control Engines (ACE), and a bus for carrying multiple independent targetable Reentry Vehicles (RV's).

Included in the guidance and control hardware is an Advanced Inertial Reference Sphere gyro-stabilized platform which utilizes a floated ball to provide the missile attitude with respect to an inertial reference. It contains three orthogonally positioned gyroscopes and three orthogonal Specific Force Integrating Receiver accelerometers (SFIR's).

The simulator is divided into two parts: the Modified Flight Simulator Program (MFSP), which performs the discrete simulation, and the Dynamic System Simulator (DSS), which performs continuous simulation.

Three Gould 32/7780's, each containing dual processors, host the discrete portion of the simulator. Dual processors allow two software programs to execute simultaneously. The discrete simulation is driven by the missile computer; thus the simulator responds only when commands are issued by the missile computer. The current iteration cycle time is ten milliseconds.

Five functions in five Gould processors are simultaneously executed to perform real-time simulation. Inter-task communications between the Gould processors are performed through shared memory. Each Gould computer contains two types of memory: shared memory, which allows access to common data by all five processors, and private memory, in which the actual program code is contained. Tasks running simultaneously in the different processors are kept synchronized and pass data to each other through flags and buffers in shared memory.

The five real-time functions executed in the discrete portion of the simulator include: Inertial Measurement Unit (IMU); Launch Regional Gravity Model (LGRM); Attitude Control System (ACS) engine model; Reentry Systems Communications and Ordnance Discretes; and the Execution Monitoring Function.

The Dynamic System Simulator (DSS) resides in two AD-10 computers built by Applied Dynamics International (ADI). The DSS performs a continuous simulation, meaning it is not interrupt-driven. Once the DSS is commanded to go it will continually execute without any further external commands. The two AD-10 computers, called ADO and AD1, each contain six special purpose, extremely fast processors which allow the DSS to execute at very high speeds. Currently the iteration cycle time is 1.94 milliseconds.

The four models simulated in the DSS are: the Missile Dynamics and Bending Models in AD1 and the SFIR Dynamics and Thrust Vector Actuator Model in ADO. ADO also contains all necessary interfaces between the DSS and the MFSP, the post-processing equipment, and the missile computer. The interface between the two AD-10's is also handled in ADO.

The Thrust Vector Actuator (TVA) Model simulates the rocket engine nozzle movement and associated electronics. The Input/Output Processor (IOP) of the Missile Computer transmits a nozzle command to the TVA model, which responds with a nozzle position feedback. The nozzle command is a Pulse Width Modulation (PWM) signal which is proportional to the rate at which the nozzle is to move. A fifty percent duty cycle is zero degrees per second. The PWM is decoded and sent to the AD-10 via a Sense Board as an equivalent digital value, one value for pitch and one value for yaw. These signals reflect the nozzle commands issued from the Missile Flight Program. The TVA model provides pitch and yaw actuator feedbacks to the IOP. The feedback is sent via the control board and is encoded in Phase and Amplitude Modulation (PAM) format. The IOP samples the position feedback every two milliseconds. The execution of the DSS must be less than the sample rate of the IOP or fidelity is lost.

If the Flight Program commands indicate no nozzle movement is necessary, then the PWM and the PAM will reflect no movement. However, if for example the Flight Program commands a six-degree movement, then adjustments must be made. The IOP issues the error signal indicating the six-degree command. The TVA model responds to the signal but must regulate the nozzle movement to reflect the missile's physical constraints. The model then sends the feedbacks to the IOP, telling it how far the nozzle moved and the current nozzle position. The IOP subtracts this response from its initial command, thus calculating a new error. If the error is not zero, the TVA model will again respond to the command. The process is continued until a zero error is achieved.

The TVA model equations are implemented for pitch and yaw with the two loops cross coupled through the pump pressure. The execution of the TVA model must take place in less than one-half millisecond in order to achieve the DSS execution time of less than two milliseconds.

The TVA model must select different parameters and equations for each stage. To accomplish this, staging discretes are issued by the missile Flight Program to the MFSP and transferred to the DSS over sense lines. Along with these staging discretes and the IOP commands, the missile axial thrust is a necessary input to the TVA model. In addition to the feedbacks sent to the IOP, nozzle accelerations and the thrust vector deflection angle for pitch and yaw are calculated by the TVA model as inputs for the Missile Dynamics and Bending Models.

The IMU model calculates the position of the missile during flight. The axial accelerations are used in the calculation of the missile position. The lateral motion of the missile can corrupt the axial acceleration. The current simulated missile weighs approximately 200,000 lbs and is eighty feet long, with a diameter of more than eight feet. A missile this size cannot be considered a rigid body; it must bend and flex. The lateral motion of the missile will be affected by the resistance to the nozzle brought about by the bending of the nozzle. By modeling the bending of the missile in real-time, the effects on the lateral motion can be determined and accounted for in the acceleration calculations, which are inputs to the IMU model via the SFIR Dynamics model.

The Bending model is hosted in AD1 and must execute in a frametime of less than half a millisecond. The equations are implemented for the pitch and yaw axes, with nine coupled bending modes in each plane. The model is only executed during the boost phase of the flight and the parameters to the equations are stage-dependent.

The Missile Dynamics, hosted in AD1, is used to calculate Sensed Acceleration at the IMU in Inertial Coordinates for input to the SFIR Dynamics model. It must execute in less than half a millisecond to support the SFIR model for all missile acceleration coordinates.

From the MFSP, the Bending Model and the TVA model, the Missile Dynamics Model receives all the forces and torques created by the missile's flight. From these inputs, the Dynamics model calculates all accelerations caused by the missile's motion, which are necessary to calculate sensed acceleration. They are the aerodynamic accelerations; attitude acceleration due to the ACS engines, angular accelerations, sensed accelerations at the IMU in body coordinates, bending accelerations and nozzle accelerations.

In addition, the Missile Dynamics model calculates the Missile Acceleration in Inertial Frame for use by the MFSP and the Sensed Euler Angles (Inertial to Control Coordinates). The Sensed Euler Angles, along with the Sensed Acceleration, give the simulator the required six degrees of freedom.

The acceleration of the missile is determined using three Specific Force Integrating Accelerometers, single degree-of-freedom specific-force receivers (SFIR's). The SFIR dynamics model in ADO simulates these gyro accelerometers by calculating the accelerations in all three axes and sending them to the MFSP for use in the IMU model.

The SFIR dynamics model receives the Sensed Acceleration in Inertial Coordinates calculated by the Missile Dynamics model. It implements the time domain equations for each of the three axes to calculate a SFIR angle output for each axis. These angles are sent to the MFSP for use in the IMU model to determine the number of actual rotations of the gyros. The rotation number is used by the Missile Computer to determine actual missile acceleration used to calculate missile position.

Although the MFSP feeds the number of rotations to the Missile Computer every ten milliseconds, to achieve real-time accuracy the SFIR dynamics model must execute at a less than two millisecond rate. The equations are not stage-dependent.

Interfaces between the missile computer and the Gould 32/7780's are handled via Direct Memory Access (DMA) controllers. They allow repetitive functions to be continuously performed without the computer's intervention. This capability increases the throughput, allowing the ten-millisecond cycle requirement to be met.

All read and write operations performed between the DSS and the MFSP utilize a Direct Digital Coupler (DDC) board in AD0. This interface allows the passing of data between the two simulators. The MFSP variables are floating point while the DSS variables are fixed point. The data are appropriately scaled in the MFSP prior to data transfer to the DSS.

Communication between AD0 and the post-processing equipment is necessary in order to record data at a real-time rate. The pitch, yaw and roll angles and rates, along with the thrust, pitch and yaw nozzle accelerations, feedbacks and error rates, are closely studied to verify the performance of the missile Flight Program. Currently, sixteen variables can be simultaneously recorded in real-time, using sixteen Digital-to-Analog Channels (DAC's). The input IOCC commands are sent to the I/O equipment through a data bus and the outputs are sent to two Gould stripchart recorders.

Communication between the two AD-10's is achieved via the Bus Interface Processor (BIP), which is a modular program in the MPS-10 programming system. The BIP's allow the transfer of data from AD0 to AD1 and vice versa. It also allows AD1 to receive inputs from the MFSP via AD0.

In order to qualify the missile Flight Program, all possible conditions that could be encountered in an actual flight should be simulated. However, to accomplish this feat would take three or four years and an almost infinite number of flights. Since schedules would not tolerate this approach, a random selection process is used. A nominal flight to test the pre-defined mission parameters is selected. Based on this nominal flight, the plus and minus worse cases are defined and tested. From the plus and minus worse case range, an additional sixty flights are randomly selected for testing. If any of these Monte Carlo flights reveals a problem, then additional flights with similar conditions are simulated to aid in the problem solving. Most of the Monte Carlo capability is achieved in the overall simulator via the DSS.

The AD-10 has a fixed-point limitation and all calculated values must be between negative one and positive one to prevent overflows. To achieve this result, the individual components of the model equations are scaled by multiplying them with a constant calculated in the Relate Files via the AD-10. The values of the constants are pre-determined; however, once the AD-10 is loaded and the Relate Files are executed, then the constants can be changed to alter the conditions of the flight. In addition, the values of the individual parameters used to calculate these constants can also be varied to again change the conditions.

For example, the wind velocities passed from the MFSP are scaled in the AD-10 to the highest wind velocity achievable. The corresponding constant or resulting output calculated from the scaling can be fixed to the highest wind velocity, no wind velocity or any value in between the two. This particular test determines if the control portion of the Flight Program can compensate accurately for the varying velocities and keep the missile under control.

In the MFSP, the Thrust tables can be randomly changed within pre-determined limits to again change the flight conditions.

Extensive testing on the simulator to insure the accurate performance of the Missile Flight Program is essential to the successful development of a missile weapon system. Only when the Flight Program has successfully performed in all possible conditions induced by the simulator will it reach a real missile. The simulator has been perfected to the point that telemetry taken from the simulator and from an actual missile flight are virtually indistinquishable.

The flight simulator allows the development of software in an environment that would otherwise be impossible to produce and still use actual hardware. The simulator is a reusable tool that can perform as many repetitive flights as necessary.

SIMULATOR ORGANIZATION