Integrated navigation, guidance and control system and validation

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The navigation, guidance and control (NGC) system of Reusable Launch Vehicle – Technology Demonstrator (RLV-TD) is the most complex system ever flown in ISRO's launches. It includes a navigation system employing traditional inertial navigation system along with global positioning system aiding and radar altimeter, ceramic servo accelerometer package, angle of attack-based control, different control systems, including secondary injection thrust vector control, reaction control system and aero control surfaces. Closed loop simulations of integrated NGC system of RLV-TD are of utmost importance to ensure mission success by assessment of system performance in nominal and off-nominal flight conditions. Validation is achieved through progressive evaluations in different levels of integrated simulation, namely autonomous simulations, software in loop simulation, on-board processor in loop simulation, hardware in loop simulation and actuator in loop simulation using Iron Bird test facility. This article discusses the overall NGC system, challenges faced during the realization of the simulation test bed, including system design to validate the new on-board elements, commissioning of Iron Bird facility and validation through various phases of simulation. The outcome of these simulations played a crucial role in bringing about improvements and helping in the evolution of the on-board system to the final configuration, ensuring the success of the mission.

Keywords: Control, guidance, integrated simulation, navigation, Reusable Launch Vehicles, validation.

Introduction

IN the Reusable Launch Vehicle – Technology Demonstrator (RLV-TD) mission, technology demonstrator vehicle (TDV) is propelled by a slow burn rate solid booster. The TDV gets separated at hypersonic speed from the booster and coasts achieving a peak altitude. It re-enters and descends in a controlled manner and finally lands on a defined point in the sea. The mission profile consists of an ascent phase, hypersonic re-entry phase, descent phase and landing phase.

NGC system

The navigation, guidance and control (NGC) system, the brain of the launch vehicle system, directs the vehicle energy in order to achieve the mission objectives precisely under normal as well as dispersed environments. This involves proper functioning of all elements of the system, including hardware and software. The success of the mission depends on flawless functioning of the NGC system and hence the system has to be thoroughly validated in a closed-loop environment. Figure 1 shows a functional diagram of the NGC system.

Navigation system

The configuration of the navigation system is decided by the accuracy requirement during the landing phase. Position accuracy of 50 m along runway and 5 m across runway is required for carrying out an autonomous landing. During landing the altitude accuracy requirement is 1 m and velocity accuracy requirement is 0.5 m/s. These requirements cannot be met by stand-alone inertial navigation system (INS). Hence global positioning system (GPS) aided navigation system (GAINS), which provides position and altitude accuracy of 50 m and velocity accuracy of 0.5 m/s is used. In addition, radar altimeter (RA) enhances the altitude accuracy to 1 m during landing.

Inertial navigation system: This system consists of the following:

- Three gyros mounted in the ortho-skewed configuration (each gyro mounted in pitch/yaw/roll orthogonal axis, senses rate outputs in the direct axis and also skewed rate of the other two axes) which give fail-operational redundancy for rate measurement.

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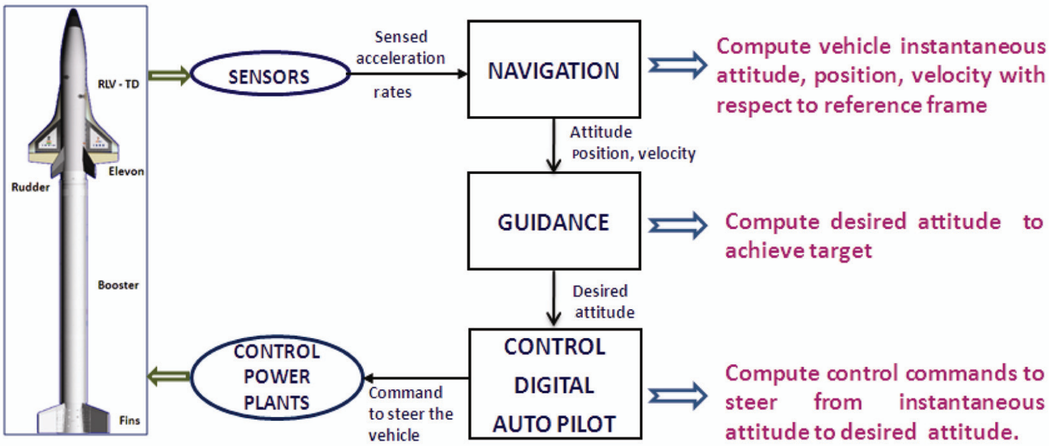

Figure 1. Functional diagram of navigation, guidance and control system.

- Three accelerometers along the three orthogonal axes of the vehicle and two accelerometers in roll–yaw plane of the vehicle, which give fail-operational redundancy for acceleration measurements in yaw and roll axes.

The navigation software residing in the on-board computer, processes the data from inertial sensors to generate functional parameters for closed-loop guidance (CLG) and control. It computes body rates and quaternions; position, velocity and altitude; inertial velocity and acceleration and air data parameters.

GPS-aided inertial navigation system: GAINS is used to improve the navigation accuracy. GAINS computer is interfaced to GPS receiver and Mission management computer (MMC). Kalman filter-based error estimation is carried out to estimate the velocity and position error. The navigation software in MMC uses the error estimates to correct the velocity and position data in a feed-forward manner.

Air data parameters from INS and wind data: Based on the stored wind profile, atmospheric properties and aided navigation data, air data parameters such as angle of attack, sideslip angle, bank angle, dynamic pressure, relative velocity and Mach number are estimated. The wind data closer to launch time are measured and stored on-board.

Altitude estimation using aided INS and RA data: During the landing phase, the RA data are used to estimate the error in navigation altitude. The estimated error is used to correct the navigation altitude to meet landing accuracy.

Ceramic servo accelerometer package: During the descent phase of the flight, where wind effects are prominent and estimation of air data parameters is less accurate, Ceramic Servo Accelerometer Package (CSAP) is used to generate acceleration data for control. It consists of six ceramic servo accelerometers mounted in skewed triad–hexad geometry (six accelerometers, 60° apart on the planar surface of a cone with half-cone angle 54.736°) along with processing electronics. The measurement range of the system is ±20 g in coarse range. To meet the resolution requirements of the mission, the measurement range is switched from coarse (±20 g) to fine range (±4 g) at booster burnout. The data from CSAP are processed in MMC to generate lateral acceleration (N_y, N_z). The resolution is 3.5 mg and 2.8 mg in yaw and pitch axis respectively. Figure 2 shows the overall elements of navigation system.

Guidance system

The guidance system steers the vehicle from liftoff to touchdown meeting the various constraints on aerodynamic load, dynamic pressure, load factor and heat flux. The CLG steers the vehicle to the desired landing point, meeting constraints such as horizontal and vertical velocity at touchdown.

The ascent phase of the mission is similar to conventional launch vehicles and hence open loop steering is used. In launch vehicles, CLG algorithms are designed for the exo-atmospheric phase of the flight. However, since RLV dwells most of the time in the atmosphere, a different guidance strategy is used. In re-entry vehicles, aerodynamic forces are used to control the translational dynamics, whereas in launch vehicles propulsive forces are used. Moreover, the launch vehicle system takes the payload from a low-energy state at liftoff to a high-energy state at orbital injection, using the energy provided by the boosters. In atmospheric entry mission, the vehicle starts with high energy and moves to a low energy state, dissipating the excess energy by

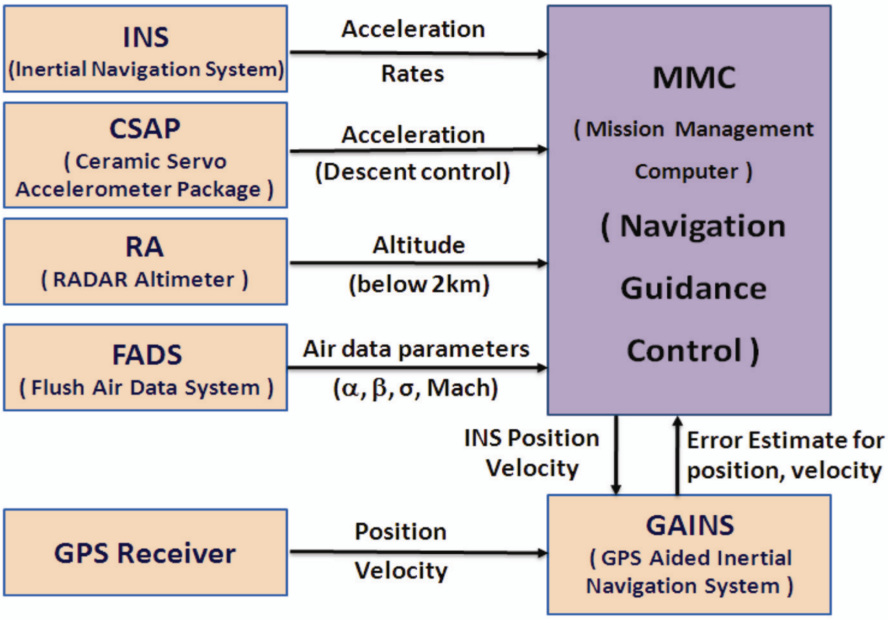

Figure 2. Block schematic of the navigation system.

aerodynamic deceleration. The different phases in the guidance include the following:

Ascent phase: It is similar to a conventional launch vehicle, where altitude-based open-loop steering (quaternions) with a pre-stored profile is used.

Orientation phase: The vehicle coasts for a fixed time after booster burnout to achieve the favourable dynamic pressure for separation. After booster separation, TDV continues the ascent flight and reaches a peak altitude. During this regime, guidance orients the vehicle's angle of attack from zero degree to a pre-defined value at a constant rate. Sideslip and bank angle are commanded to zero degree.

Entry phase: In this phase, the angle of attack is commanded using pre-defined Mach versus angle of attack profile stored on-board. This profile is generated meeting constraints such as dynamic pressure, heat flux, load factor and trim capability. Sideslip and the bank angle are commanded to zero degree. Below Mach number 2, the vehicle is commanded with normal acceleration commands from the table stored on-board. The manoeuvres in this phase are rate-limited to a pre-defined Mach number-based rate limit table, which contains the rate limits for angle of attack, sideslip angle, bank angle and normal acceleration commands.

Approach and landing phase: In this phase, the CLG commands (normal acceleration and bank angle) are provided to steer the vehicle to a desired landing point. This is selected on-line, based on the energy available. The approach and landing phase guidance includes an on-line trajectory design and a path controller to track the planned trajectory. The entire approach and landing phase trajectory is generated on-board at the start of this phase. The trajectory is divided into vertical and horizontal planes. The vertical dynamics is controlled by commanding normal acceleration (N_{ZC}) and the horizontal dynamics is controlled by bank angle (σ_C) command. The guidance problem is formulated by assuming that the vertical dynamics is decoupled from horizontal dynamics. The algorithm features include: (i) Retargetting: on-line selection of landing point based on the range to be covered. (ii) Safe mode guidance: for extreme performance variations. (iii) Dynamic normal acceleration command limit: to steer the vehicle to fly in the safe angle of attack envelop.

Control design

Ascent phase: Attitude control during liftoff phase in pitch, yaw is achieved using secondary injection thrust vector control (SITVC) systems and roll by reaction control system (RCS). Once the dynamic pressure builds up, the four aerodynamic surfaces (fins) attached to the booster become effective. Then pitch, yaw and roll control are achieved by deflecting the fins.

The main challenge in the ascent phase control design is the higher aerodynamic instability compared to launch vehicles. The aerodynamic moment coefficient, which is an index of this instability, is very high and hence time-to-double is lower. Thus, the control moment should act very fast with a powerful actuator in lesser time. These challenges are handled in the control design by high rigid

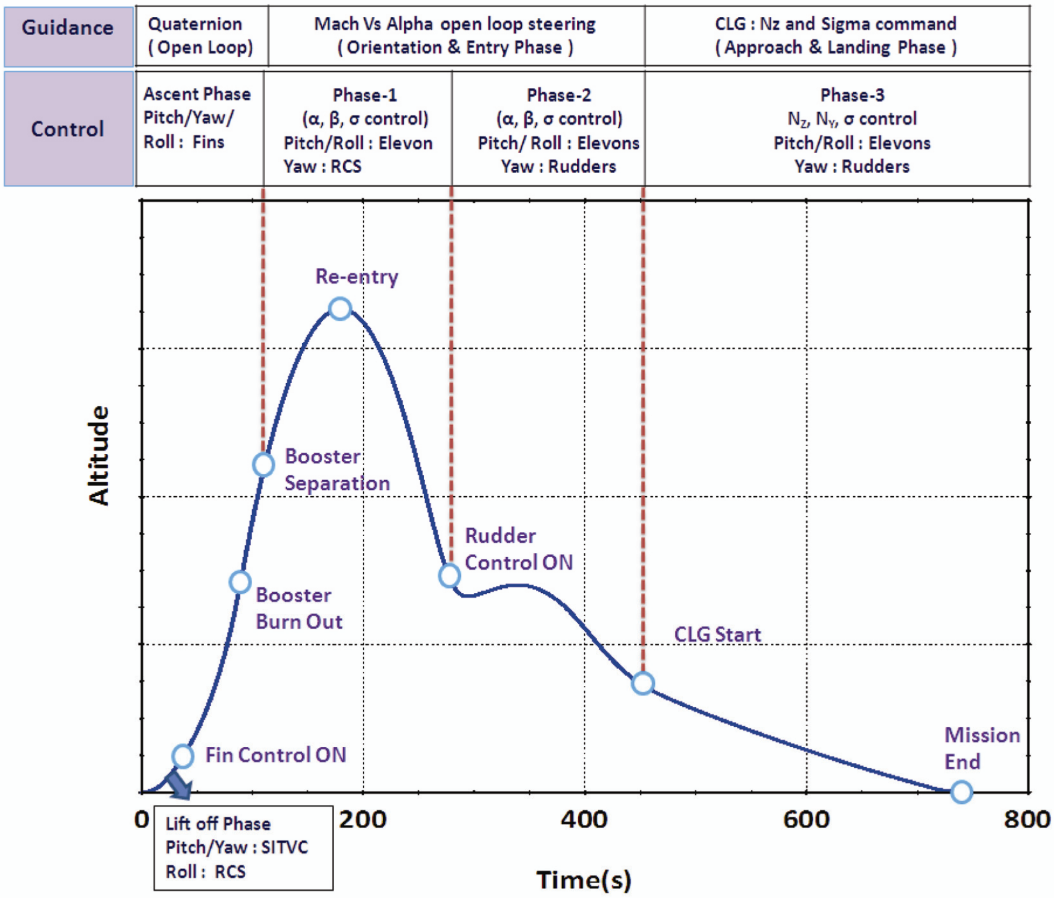

Figure 3. Guidance and control strategies in different phases of the flight.

body control bandwidth, actuator bandwidth and faster sampling time (10 ms, whereas in launch vehicles 20 ms is used). To take care of the dynamic pressure variations, velocity-based gain scheduling is adopted rather than the time-based approach used in conventional launch vehicles.

Descent phase: In the descent phase, pitch and roll control is achieved by two elevons and yaw by two rudders. During the high angle of attack regime, rudder is not effective and yaw control is achieved by RCS mounted on TDV. Once angle of attack reduces, a rudder become effective and thereafter is used for yaw control. RCS is provided as back-up for pitch, yaw and roll control. The aerodynamic angles (α, β, σ) are controlled till Mach number 2. Lateral acceleration (N_z, N_y) and bank angle (σ) are also controlled below Mach number 2. In conventional launch vehicles, pitch, yaw and roll plane dynamics is decoupled, whereas in RLV it is highly coupled and hence multi input multi output (MIMO) design is used. To take care of trajectory variations in control design, 2D gain scheduling based on Mach number–dynamic pressure is used.

Aerodynamic control starts after booster separation. Descent phase is divided into three sub-phases as follows:

Phase 1: This phase starts after booster separation and includes TDV coasting and reorientation. Here elevons are used to control pitch and roll dynamics, and RCS is used to control yaw dynamics. At the end of reorientation, the vehicle starts descending at a high angle of attack. Time-based gain scheduling is adopted during this phase. As the angle of attack reduces, rudder effectiveness improves.

Phase 2: Once the rudder becomes effective (comes out of the shadow of the fuselage), it is used for active yaw control. TDV is completely controlled using aerodynamic control surfaces and RCS is used in backup mode. MIMO design is carried out for the stabilization of coupled yaw–roll dynamics. Two-dimensional gain scheduling based on Mach number versus dynamic pressure is used.

Phase 3: This phase starts when Mach number reduces below 2 and altitude below 20 km. During this phase, wind velocities significantly influence the estimation of aerodynamic angles. So, in place of aerodynamic angles, accelerations are sensed and commanded by guidance for attitude control. Pitch plane design is done as in a conventional launch vehicle. MIMO design is carried out for stabilization of coupled yaw–roll dynamics. Gain scheduling is based on Mach number vs dynamic pressure.

Trim requirement and its scheduling: TDV is intended to follow a defined angle of attack trajectory based on Mach number and hence there is a known requirement of control surface deflection (trim control requirement). Since this Mach versus angle of attack profile is non-monotonic, 2D trim schedule is adopted in all the three phases.

Figure 3 shows the overall control guidance strategies.

Control power plants

Three types of control power plants are employed during various phases of the mission are: (i) Electrohydraulic actuators for deflecting aero control surfaces – four fins (ascent twohase), two elevons and two rudders (descent phase). (ii) SITVC system for pitch and yaw control during liftoff phase. (iii) RCS for roll control during liftoff phase; yaw control during rudder ineffective regime, and pitch, yaw and roll control as back-up during descent phase.

All the eight electrohydraulic actuators are powered from a common power source – hydraulic power pack. High-power brushless DC (BLDC) motor is used to drive the hydraulic pump and high energy Li-ion battery unit is used for powering the BLDC motor.

NGC system configuration

The overall NGC system includes MMC, which computes the navigation information from the sensor data and generates steering, control and sequencing commands. The control commands are routed through the stage processing system to the actuators through the control electronics package. NGC is configured as a dual redundant cross-strapped system to handle subsystem failures. MIL-Standard 1553B bus is used for communication between MMC and other elements in the NGC system. The performance of the subsystem is assessed from the telemetry data acquired through the integrated data acquisition and processing systems.

The mission requires a higher sampling rate of vehicle states and control during the ascent phase. Hence the NGC algorithms are scheduled in three periodicities, viz. micro cycle (10 ms), minor cycle (20 ms) and major cycle (500 ms) in the ascent phase. The 1553B communication bus utilization is also double compared to the existing launch vehicles, due to the presence of increased number of subsystems.

NGC validation plan

NGC validation begins with autonomous simulations, where on-board algorithm assessment and design finalization are carried out. On-board software clearance starts with validation in software in loop simulation (SILS) test bed, where on-board software is executed in closed loop along with trajectory simulation software. No on-board hardware packages are required in this test bed and closed loop simulations are carried out in pseudo real time.

NGC validation in real time with actual systems in flight configuration starts with on-board processor in loop simulation (OILS) test bed, where on-board processors are in loop with the trajectory simulator. These tests help in the validation of the integrated system, validation of the on-board software components, validation of the hardware interfaces, end-to-end data flow and clearance of flight-loadable initialization data.

Hardware in loop simulation (HLS) test has the objective to validate the sensor performance under nominal vehicle conditions as well as with dispersions. Effect of actual sensor dynamics and errors on mission performance can be assessed through these simulations.

In actuator in loop simulation (ALS) test, evaluation of the mission, subsystem performance and design adequacy with control power plant hardware in the loop for different flight environments is achieved.

6D trajectory simulation software

The dynamic behaviour of the vehicle, subsystems and on-board systems has to be studied in detail under various dispersion conditions (propulsion dispersion, aerodynamic dispersion, etc.) before the real flight. Hence trajectory simulation software is developed incorporating all features, for validation of the NGC system and for mission performance analysis.

The digital trajectory simulation software, SITARA (software for integrated trajectory, analysis with real-time applications) simulates the six degrees of freedom (6-DOF) motion, both translational and rotational motion of the reusable launch vehicles along with vehicle subsystem characteristics.

The software simulates the environmental conditions such as earth's gravity, atmosphere and wind characteristics. It simulates the vehicle characteristics such as propulsion, aerodynamics and mass properties. The vehicle subsystem includes control power plants, on-board software models and sensor models. In order to handle the implementation of complex models and other subsystems, with good maintainability and re-usability, the software is developed with an object-oriented approach.

Challenges involved

This mission is aerodynamically intensive, as the winged body flies over the atmosphere during most of its flight duration. The highly complex nonlinear aerodynamic model (~3000 tables) with 3D and 4D interpolation schemes along with other vehicle and subsystem models

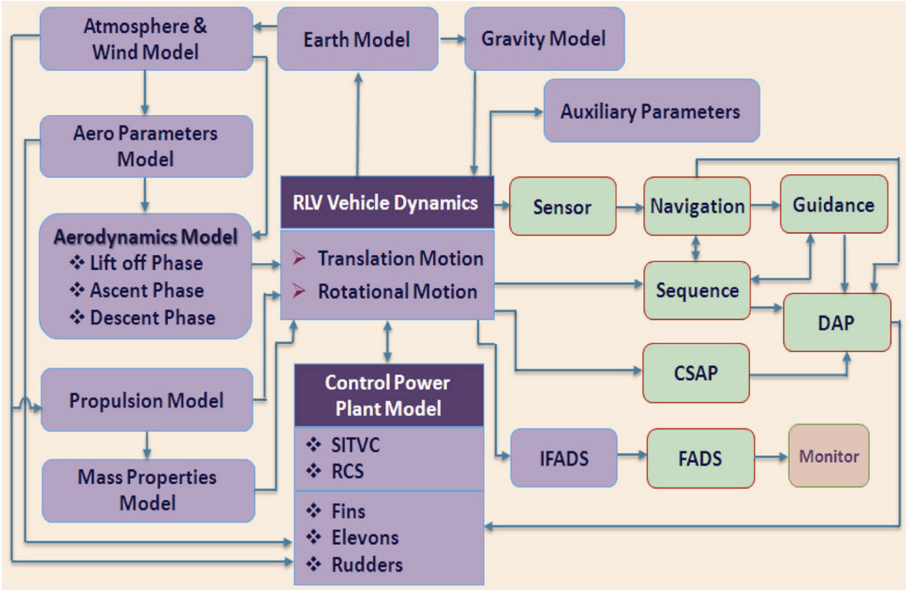

Figure 4. Block schematic of SITARA.

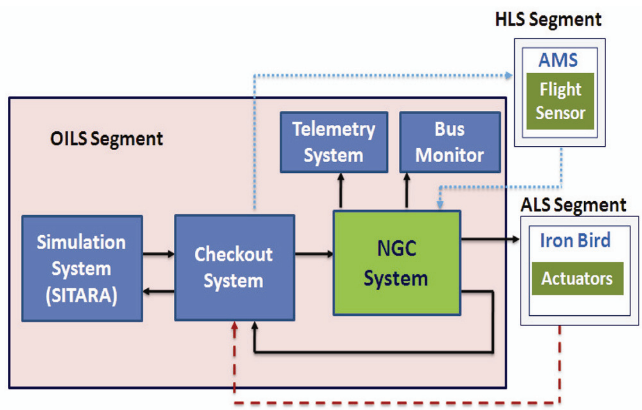

Figure 5. Block schematic of NGC test-bed configuration.

has been implemented. Figure 4 shows the block schematic of SITARA.

The trajectory simulation software is developed with features for carrying out real-time simulations. The software has to run in a closed loop with the on-board NGC packages and software. Hence the software should be capable of synchronizing with the on-board systems, generating the necessary inputs to the on-board systems, establishing proper communication interfaces with the on-board packages, acquiring the on-board outputs for closing vehicle loop while meeting the on-board timing constraints.

Test-bed configuration

The RLV simulation facility is designed to meet the requirements of OILS, ALS and HLS phases of simulation tests.

The on-board NGC processor is integrated with other packages for meeting its input and output requirements over MIL-STD-1553B bus in dual-redundant cross-strapped configuration. The processor is the bus controller (BC), while all the other systems are the remote terminals (RTs). These are integrated on the test set-up according to the package electrical interface definitions (EIDs). The functional inputs and outputs of the packages as well as monitoring from on-board are interfaced to the checkout computer with proper isolation.

The test set-up basically consists of the on-board segment and ground segment, viz. simulation system, checkout system, telemetry system and simulation facilities. Figure 5 shows the overall block schematic of the test-bed.

On-board segment

The on-board packages include MMC, inertial sensing unit, navigation interface module, RA, GAINS processor, flush air data system, CSAP and sequence command execution module. The control system includes control electronic packages, electrohydraulic actuation system with eight actuators, BLDC motor and pump, battery, accumulator and reservoir.

Electrical integration

OILS segment: The interfaces realized for avionics hardware in the simulation test bed replicate the flight integration in all aspects. The packages are linked to the common communication 1553 bus.

Dual redundant cross-strapped topology is implemented in the interconnection of communication bus to the on-board devices. The transmitter and receiver of these devices are linked to each of the main buses through transformer-coupled stubs. The dual, viz. prime and redundant data buses are extended to the checkout console through a repeater. The bus monitor system captures digital traffic from the communication buses through transformer-coupled stubs. Relays introduced between the bus coupler and device stub are utilized to simulate communication failure of various on-board devices. The checkout to simulation system communication is made via a separate MIL-STD-1553B bus.

The avionics hardware in the test segment is powered by regulated DC sources. Separate power supplies are allotted for the prime and redundant packages. The power drawn by individual packages is monitored by routing the respective power lines through Hall effect current sensors. The built-in communication features present in the power supplies allow interconnection through RS485 link and remote control over an RS232 link.

The beat frequency signal to the RADAR altimeter is fed from the simulation system through a beat frequency simulator using coaxial cable of appropriate MIL standard. The transmitter output is connected to the measuring head of the microwave power altimeter. The transmission lines are kept short and cables are routed appropriately to reduce the electromagnetic interferences.

Precision low-voltage signals emulating the strain gauge pressure transducer outputs, for simulating air data system inputs, are achieved by proper scaling of the full-scale DAC output. The in-house developed circuitry brings down the DAC output to the desired signal range. The active circuit also shields the sensitive electronics connected to the output terminal from any spurious signals by clamping the output signal to either side of the specified range. The circuit acts as a buffer by preventing any accidental electrical stress to the flight hardware.

The checkout system is equipped with interfaces to acquire digital as well as analog data generated by the on-board systems. The digital sequence commands are acquired through digital input interface cards in the checkout. The on-board and checkout ground terminals are isolated from each other using optical isolation. The analog signals are acquired in true differential format. Figure 6 shows the block schematic of the OILS test bed with on-board and ground segments.

HLS segment: The HLS segment features simulation interfaces required for the inclusion of actual navigational sensors with the OILS segment. The attitude dynamics of the vehicle is simulated by imposing the angular motions to the inertial navigation sensors. This is achieved by mounting the inertial sensors and associated electronics onto the angular motion simulator (AMS). The AMS is a tri-gimballed platform capable of vectoring to any possible attitude.

The inertial sensors are mounted on a levelled platform on AMS designed to maintain the precise alignment of the body axes of multiple sensors. Signals to and from the AMS are routed through slip rings provided in the AMS interfaces. The digital communication bus from the on-board segment has been extended to the AMS and connected to the sensors through stubs. The test bed has provision to generate simulated acceleration signals which are loaded onto the sensor interface module. HLS simulations are carried out in a safe operational limit for flight navigational sensors through proper software and hardware limits on the AMS gimbal rates.

ALS segment

The ALS test segment integrates the actuation elements with the OILS segment. The actuation elements include electromechanical injection valves as well as electro-hydraulic fin actuators for the boosting phase, and electrohydraulic rudders and elevons for the re-entry and descent phase. The actuators are mounted on a mild steel rigid frame called Iron Bird. The data acquisition system (DAS) captures the health parameters of the control electronics and sensor outputs of various transducers mounted on the test rig.

The analog commands issued from the OILS test segment are routed to the control electronics circuitry in the ALS test segment. The control electronics, tuned for the actuator dynamics, provides the necessary driving force to the actuator to achieve the commanded position. The position feedbacks from actuators are fed back to the trajectory simulation software to compute the resultant change in trajectory.

The integration of the ALS test segment follows a distributed rack-oriented stacking scheme, to simulate the harness lengths to various actuation elements located at different stages. Interfaces of individual control electronics are built on sub-racks and each rack is equipped with power distribution points, power supplies and associated current sensors. The racks are positioned based on safety and harness length requirements.

The drive circuit and control circuitry are powered separately to ensure electrical isolation of the power grounds from the signal grounds of control electronics. The actuator outputs are routed through relays/contactor-based circuits to prevent accidental powering of the drive circuitry. Diode OR-ing strategy is also implemented for redundancy in powering the critical control electronics.

The motor control electronics generates the three-phase output that powers the BLDC motor, which in turn drives the pump. The control electronics is powered by two power supplies connected in an OR-ed configuration to ensure uninterrupted power to the control electronics even under one supply failure. The output of the supply is controlled remotely from the checkout system. The hardware interlock implemented can also affect the state of the motor supply output. A capacitor of sufficient

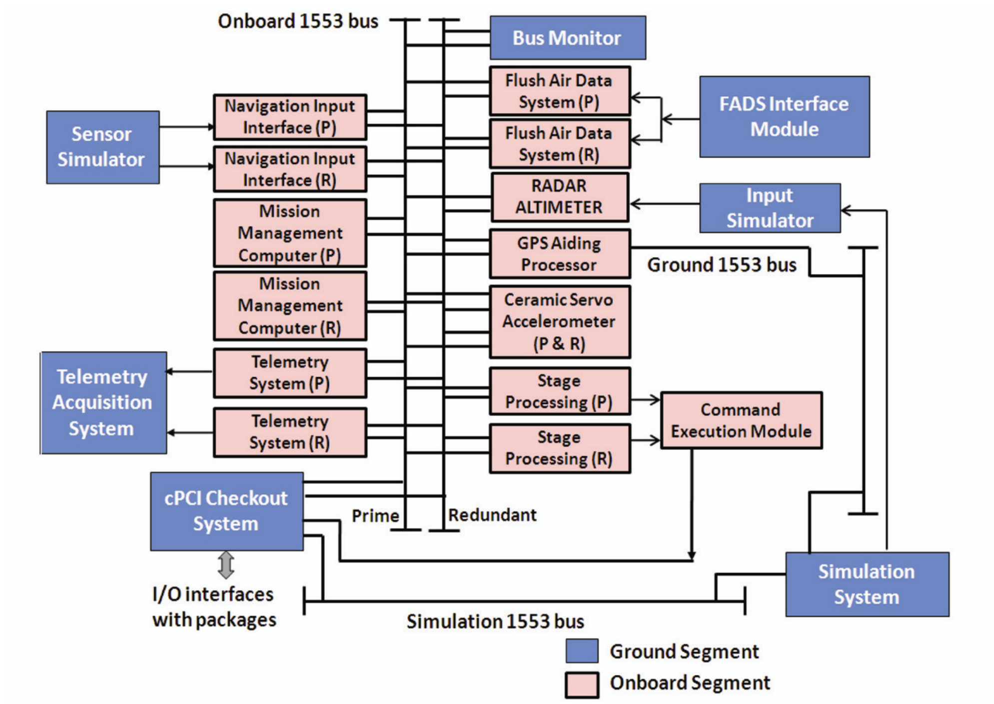

Figure 6. Block schematic of OILS test bed.

capacitance is connected at the motor supply terminals to act as an energy buffer.

The DAS comprises of multiple signal acquisition modules linked by a digital bus connected in daisy chain topology. The digital link is extended to a PC interface unit to acquire the data. The interface unit is programmed to raise an abort signal in the event of a critical parameter crossing a pre-defined range. The abort signal is extended to the checkout system to initiate the abort sequence. The low-voltage digital pulse from the PC interface unit is level-shifted to match the checkout digital input range.

The actuator feedback signals from different control electronics are wired to the mutually isolated checkout ADC modules.

Iron Bird facility

In order to validate the control power plant, a ground test facility is required where all sub-systems can be integrated. For this, a full-size representative system integration test rig known as Iron Bird has been designed and built with the primary focus to validate flight actuation systems and associated electrical systems.

The facility consists of a mild steel structure representing the vehicle in size and shape (Iron Bird structure), support structure and mounting plates, flight equivalent actuation system, on-board elements, flight equivalent electrical integration, checkout systems, simulation and data acquisition systems. The structure is designed and built to have no interaction with the actuation system. Separate support structures are designed to accommodate the hydraulic line as in flight, and specialized brackets are designed to mount the actuators on the Iron Bird.

The test segment not only reduces the development risk by testing the fully integrated systems prior to the integrated vehicle-level tests, but also provides a platform for exhaustive evaluation of the system and subsystem to the maximum possible extent. Figure 7 shows the overall facility.

The checkout system

The entire simulation interface to the avionics hardware is managed by the checkout system. This system is responsible for powering the avionics packages, generating simulation inputs, acquiring the control and sequencing outputs and transferring data between the on-board and simulation systems for closing the vehicle loop.

A compact peripheral component interconnect (cPCI)-based checkout system is used to interface with the on-board system. All the interfaces for the NGC system reside on the cPCI system. These include digital to analog cards, analog to digital cards, digital input/output cards, relay cards and 1553 cards. The system works in RT-Linux operating system (OS).

The system design considerations are as follows: *Selection of checkout system:* While considering the system to be chosen for checkout, the system attributes considered

Figure 7. Iron Bird test facility.

included an open industrial standard and architecture, with support for scores of interfaces and with the standard PCI signalling and protocols.

Compact PCI computer bus interconnect fits all this, combining a Eurocard-type connector and PCI signalling and protocols. The system has high noise immunity and provides bandwidth of 132 Mbytes/s for 32 bits data transfer.

With multiple interfaces to be handled in checkout with more than a dozen sets of packages, the cPCI system with 21 slots was chosen. The cards were chosen such that they have proper isolation with external interfaces.

Selection of real-time OS: For a real-time simulation to be valid, the real-time simulator used must accurately produce the internal variables and outputs of the simulation within the same length of time as that of its physical counterpart. Data flow schemes and sizes must be as close to flight as possible.

The RT-Linux OS was chosen for the deterministic response required of the checkout system. RT-Linux is a hard, real-time OS that runs within the framework of the Linux OS. It has the advantages of Linux which is open source and has an architecture which is less prone to viruses. The real-time OS along with the real time drivers for the add-on cards ensures that the time criticality required on-board by to maintain data flow as in flight is met.

Checkout software requirements: These include two major modes of operation – monitor mode and flight mode. In the monitor mode, software is used for clearance of all on-board software functionalities and interfaces prior to the actual tests. Checkout carries out powering the on-board packages with safety interlocks and surveillance, and prepares on-board packages for flight-mode entry.

The flight mode demands execution of a real-time module to maintain data flow as in flight with logging and real-time display.

A user-interactive graphical user interface (GUI) is also essential for carrying out operations smoothly incorporating automation, wherever possible.

Software design considerations: Based on the above stated requirements, checkout has the following features to be met: (1) Synchronization with on-board and simulation system. (2) Data exchange between on-board and simulation systems. (3) Ensuring safety of on-board systems through periodic surveillance and monitoring of critical parameters. (4) Scheduling of various tasks, including optimization of i/o intensive tasks to meet on-board timing requirements. (5) Supporting error injection according to test case requirements. (6) In-built error-handling and automation features. (7) Simulation of RTs, not currently participating in the test. (8) Posting inertial angles of vehicle to an angular motion simulator in real time when sensors are used in the closed loop simulations. (9) Calibration of actuator feedbacks and control of simulation based on real-time monitoring of the health of the actuation set-up.

Design challenges: (1) Allocation of tasks to carry out various activities every 10 ms: Checkout synchronizes with the on-board broadcast message, acquires control outputs from on-board, transfers the required data to the simulation system, gets the rate and acceleration for the next cycle from the simulation and posts the rate and acceleration to on-board packages before 7 ms. (2) Synchronization every 10 ms: A high-precision internal clock timer provided in RT-Linux is used to generate the 10 ms cycle sync in checkout. (3) Task optimization: the tasks in checkout are scheduled and code-optimized so that the checkout data acquisition is completed within 2 ms. (4) RT simulation: When checkout is needed to simulate an RT on 1553 bus, interrupt handling in block modelled to checkout task completion with sufficient time margin. (5) Monitoring features: Checkout acquires logs and displays the health of both the on-board systems and the communication links.

Implementation aspects: Based on the timing requirements, the tasks in checkout software have been categorized as real-time and non-real-time tasks.

Non-real-time tasks – These include powering the on-board packages with surveillance of currents and verification of on-board interfaces invoking test utilities from checkout. The processor function test ensures health of the on-board packages. The tests are equipped with real-time displays in user-friendly format and logging for off-line analysis. An effective error handler captures any operational or on-board performance-related deviations. During closed loop simulations, the real-time display notifies the progress of the simulation. Any deviation in the health of on-board packages or any of the participating systems is immediately notified to the operator.

The GUI communicates with the real-time module through a real-time first-in-first-out (FIFO). The RT-Linux FIFO is visible to both real-time and non-real time modules, and is read and written by each of the tasks at either ends.

Real-time tasks – The real-time module is developed using RT-Linux calls. The on-board NGC timing between the elements requires that the present vehicle rates and acceleration are to be simulated to the system in the current cycle, to ensure data flow as close to flight. The on-board cycle time is 10 ms. In this cycle time, the data of the current cycle are sampled by the input RT at 7 ms. Hence, the first and foremost real-time requirement is to post the vehicle rate and acceleration information on-board well before 7 ms, even in the worst-case scenario simulated. The on-board output RT posts the control information to the stage processing electronics towards the end of the frame time. These data are to be sampled by the ground segment for control force computation of the vehicle.

The checkout system acts as the master during simulations. It synchronizes with the on-board system and maintains communication link with the simulation system.

Simulation system

This is an industrial PC-based computer system working in Windows OS with real time patch (Intime kernel), where SITARA simulating the trajectory of the vehicle runs in real time during closed loop simulations. It synchronizes with checkout every 10 ms. It receives data from checkout, carries out the trajectory computations and sends the next set of inputs to checkout to be simulated on-board. It uses the on-board outputs, control and sequencing commands for closing the vehicle loop.

Simulation computer has the following constraints to be considered: (1) Carry out vehicle states computation so that data get posted on-board before the required time, even in the worst-case scenario simulated. (2) Input simulation to the on-board GPS processor according to the protocol. (3) Simulate the beat frequency input for RA simulation. (4) Scheduling the different tasks to meet the on-board cycle time.

Data acquisition and analysis computer

This monitors, logs and analyses all the activities in the on-board 1553 bus. It shall validate the results of the closed loop simulation test.

Simulations for validation of NGC system

Test conditions and scenarios

In order to validate the NGC system under different flight scenarios, test conditions are defined by perturbing vehicle and subsystem performance within 3σ limits or beyond. These include the booster propulsion perturbations, thrust misalignments, mass properties dispersions, aerodynamic parameter perturbations, control surfaces effectiveness dispersions, degradation in sensor performance, inter-package communication failures, etc. Since the vehicle is a winged-body configuration and is controlled by aerodynamic control surfaces, wind variations, atmospheric perturbations and aerodynamic parameter dispersions play a significant role in validating the entire system.

Autonomous simulations

In this test set-up, all on-board algorithms are implemented in the trajectory simulation software for validation of the algorithms and on-board designs. The mission design, on-board design and sequencing logics are thoroughly validated for different flight conditions. Extensive simulations are carried out for different versions of on-board design and based on simulation studies, mission and on-board designs are finalized. Autonomous simulation results are the reference for further simulations.

Software in loop simulations

This test set-up allows full verification of the integrated on-board application software in loop with the trajectory simulator. The total system is in the software, and runs in general purpose computers. The test bed primarily ensures the correctness of the application software performance with various vehicle dispersions and scenarios of failure. Probable software or computational failures are simulated to evaluate the recovery or salvage operations. The test case suite includes the suite used for on-board computer in loop simulation and additional software-specific test cases. Exhaustive simulations are carried out in this test bed for different on-board software versions of on-board and corrections are implemented in the flight software based on SILS analysis.

On-board computer in loop simulations

The main objective of OILS is to evaluate the mission performance with flight systems in loop for dispersions and disturbances within and beyond specified limits, and also for the evaluation of software integrity to confirm that it does not fail even under extreme conditions of mission failure.

This configuration includes the onboard computer system from the sensor interface elements to the sequencing and control interfaces running in closed loop with the trajectory simulator in real time. This requires sensor simulators to provide inputs to the corresponding sensor interface packages. The sensors to be simulated are gyros and accelerometers, pressure simulation for flush air data computation, RA, CSAP and GAINS.

The simulations are carried out in two phases:

Phase 1: Stress cases – The main objective is to assess the software performance in 3σ environment, ensure software integrity in high-stress environments, and test all logics, failure modes and their impacts on the mission and flight software clearance.

Since the mission considered is totally new, vehicle, mission, subsystems, on-board algorithms and on-board software were evolving. There were seven different iterations or versions for the on-board flight software. Table 1 shows some of the major observations and corrections implemented in the on-board software/design/algorithms based on simulations. The results show that closed loop simulations are successful in bringing out a rugged on-board system capable of satisfying stringent mission requirements. Figures 8–10 show the typical OILS results in comparison with reference, for nominal flight conditions.

Phase 2: Performance cases – Flight initialization datasets are evaluated within 3σ dispersions of subsystem performance with final version of design and vehicle data. Based on the results, initialization data are cleared for flight loading.

Hardware in loop simulations

The main objective is to evaluate the mission performance, subsystem performance and design adequacy with actual flight sensors in the loop. It also includes sensor performance assessments, end-to-end verification of hardware links, signal flow, sign verifications and electrical checks, performance evaluation under simulated failure of sensors.

The configuration includes integrated flight NGC system with sensors in the loop. The sensors are mounted on the AMS which includes three-axis gimbals for simulating the pitch/yaw/roll motion of the vehicle. The vehicle acceleration is not simulated and the respective signal is fed to the on-board navigation interface from the simulator as in OILS configuration. The test conditions include propulsion dispersions, aero perturbations, and separation disturbances. The performance of inertial systems is evaluated under simulated failure of sensors, sensor performance repeatability, drift characteristics assessment and sensor warm-up period performance.

Detailed analysis was carried out for the test conditions. The following are the major highlights: (i) The impact of sensor performance on mission is assessed. (ii) Trajectory parameters such as altitude, velocity, Mach number, etc. match well for all dispersion cases with reference.

Figure 10 shows the body rate comparison of reference and actual sensors. The integrated navigation system performance and landing point accuracy for different flight conditions were assessed. Based on the simulation results and analysis, all NGC flight hardware, including sensor packages were cleared for flight.

Actuator in loop simulations

The configuration includes integrated NGC system with actuators and associated electronics in the loop. The trajectory simulation software provides the inputs for on-board NGC system. The control commands generated on-board are given to actuators through control electronics packages and the actuator feedbacks are used to close the vehicle loop of the trajectory simulation software. The elements in addition to that of OILS set-up include electrohydraulic actuators, flight equivalent hydraulic system, control electronics, external power supply and battery. Flight equivalent hydraulic system consists of accumulator, BLDC motor and pump reservoir, hydraulic plumbing lines and manifolds.

The test conditions include booster propulsion dispersions within $\pm 3\sigma$ level, aero-perturbations in ascent

Table 1. Major observations and corrections based on onboard processor in loop simulations

Typical observations from OILS	Corrective actions
Unexpected variations observed in guidance commands due to single precision computations using the on-board computer.	Computations modified to be in double precision format.
Aiding of altitude with radar altimeter showed sudden jump at aiding start.	Fusion algorithm implemented at aiding start period to smoothen the transition.
On–off control calling in back-up mode during descent phase adversely affected controllability of the vehicle for certain flight conditions.	On–off control in back-up mode option modified.
Control insufficiency due to rudder ineffectiveness at high angles of attack during descent phase for high dispersion cases.	Descent trajectory reshaped to make rudder more effective.
Control design inadequacy for extreme performance cases beyond the limits for multiple parameter combined dispersions.	Control design tunings/updates for more variations in trajectory.
Guidance and control interaction issues during landing phase.	Guidance algorithm modified to have real-time decision of landing point based on vehicle performance.

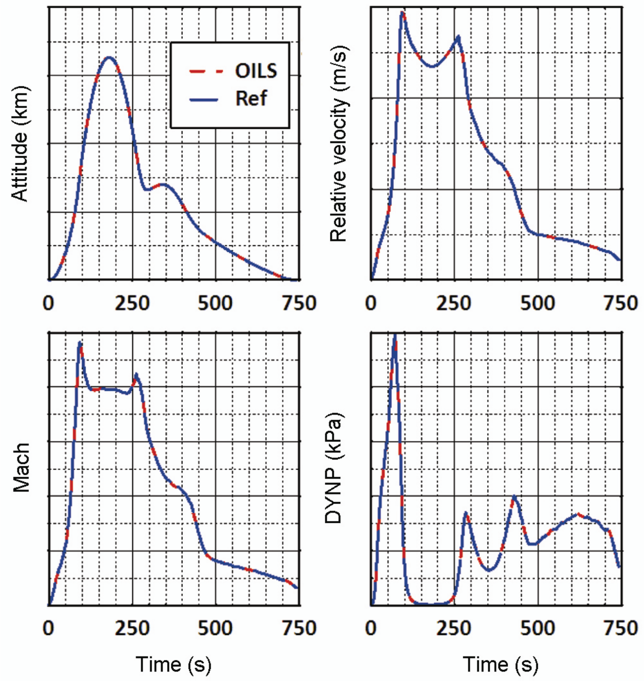

Figure 8. Flight parameter comparison.

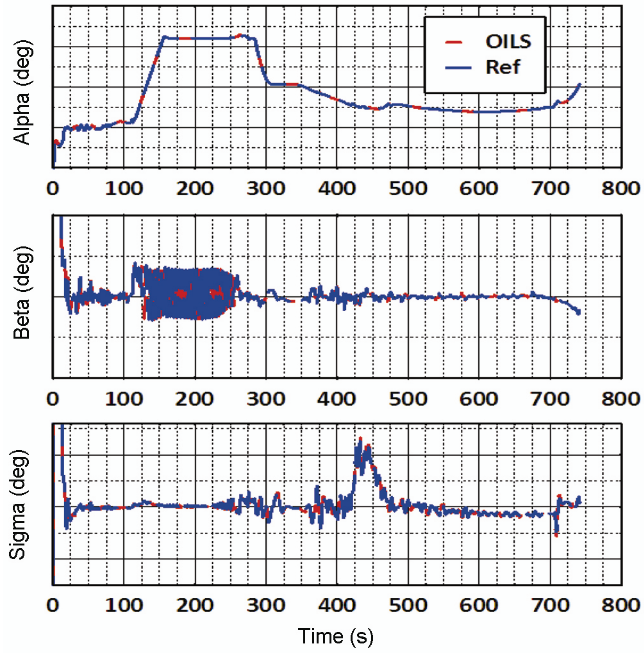

Figure 9. Flight angles comparison.

and descent phases within $\pm 3\sigma$ level, disturbances like thrust misalignment, separation dispersions and aero-parameter perturbations such that the control surfaces are saturated, step/sinusoidal disturbances to check the sign convention, test cases to evaluate mission performance under degraded and partial failures, simulations with reduced system pressure, reduced power supply voltage.

Simulations were carried out with flight systems for nominal conditions and with protosystems for identified dispersion conditions. Based on simulations, design iterations/modifications were carried out. Table 2 provides some of the major highlights of the results.

Closed loop simulations with GPS RF simulator

The mission uses GPS aiding for the entire flight duration to improve navigation accuracy. This necessitates integrating and testing the GPS receiver and GPS processor in closed loop NGC simulations, to evaluate the performance of aiding systems and logics. For OILS simulations, GPS receiver is simulated through ground system. For integrating GPS receiver and low-noise amplifier in loop, real time GPS radio frequency (RF) simulator system was integrated with the rest of the NGC simulation test bed. Figure 11 shows a block schematic for the test set-up with GPS RF simulator.

Table 2. Major observations and corrections based on actuator in loop simulation

Typical observations from ALS	Corrective actions
At BLDC power-on, the actuators hit mechanical limit due to initial transients in control electronics (CE) output.	CE compensator design modified to avoid initial transients.
Intermittent saturation of FIN actuator feedback	LVDT wire hook joint replaced with splice joint for all actuators
For additive 3σ aero perturbations, yaw and roll rate oscillations (2 Hz, Y: 1°/s and R: 7°/s P–P) in descent phase at 280 s and simulation fails at 380 s	Descent phase yaw–roll channel control margin improved.
Roll rate oscillations for nominal and off nominal cases in ascent phase during high dynamic pressure regime.	Ascent phase roll gain after transonic regime updated. No oscillations observed with modified design.

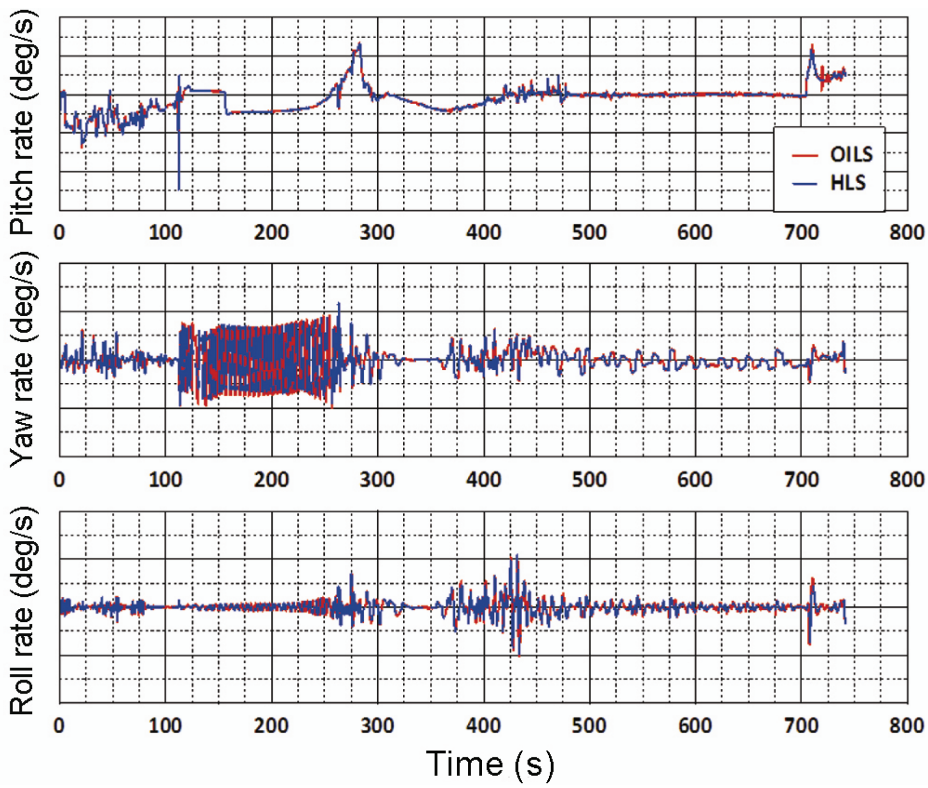

Figure 10. Body rate comparison.

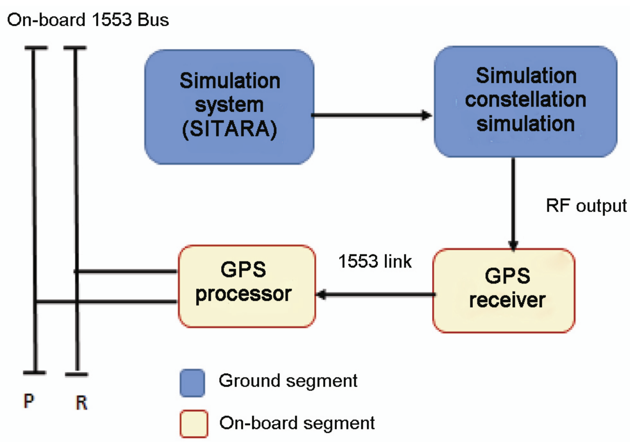

Figure 11. Test set-up with GPS RF simulator.

The GPS simulator includes a GPS satellite constellation simulator which simulates the orbital motion of the satellites for a given epoch, and a signal generator which generates the RF signal. By providing real-time vehicle motion parameters to the GPS simulator, it generates the ranging codes and navigation data messages as RF signal, which is received by the GPS receiver and generates the position and velocity information as 1553 messages to GAINS processor. For real-time closed loop simulation, the GPS simulator needs to be synchronized with the NGC simulation test set-up so that the simulator generates the RF signal corresponding to vehicle motion. With the INS position and velocity information and GPS information, sensor errors can be estimated using Kalman filtering techniques.

Test bed for closed loop real-time simulations with GPS receiver in loop was realized. Analysis of closed loop simulation results revealed good match between INS and GPS data. GPS data quality metrics such as position dilution of precision (PDOP), time dilution of precision (TDOP) and Kalman filter residues were found to be comparable with the data observed in recent missions.

Conclusion

Integrated simulation facility was designed and established to meet the validation requirements of the NGC systems of RLV-TD, and enabled the performance assessments of the system, including software and final initialization of data leading to the clearance for flight.

Digital simulations were carried out to finalize the vehicle, mission design and validate the on-board algorithms. On-board software including navigation, guidance, control and other subsystems software embedded in the actual flight hardware were thoroughly validated in the integrated configuration using processor in loop simulation test bed. The anomalies observed in the flight software were corrected and re-validated to ensure expected performance.

HLS tests ensured that the INS and navigation software provided designed performance for the mission under nominal conditions as well as sensor isolation conditions. The repeatability, drift characteristics and performance of inertial sensors were critically evaluated across days and found acceptable.

Through ALS simulations in Iron Bird, actuator performance was assessed in closed loop environment with vehicle dynamics, for different flight conditions. This ensured adequacy of end-to-end control performance.

1. Etkin, B., *Dynamics of Atmospheric Flight*, John Wiley, 1972.
2. Regan, F. J., *Re-entry Vehicle Dynamics*, AIAA Education Series, American Institute of Aeronautics and Astronautics, 1984.
3. Zipfel, P. H., *Modeling and Simulation of Aerospace Vehicle Dynamics*, AIAA Education Series, American Institute of Aeronautics and Astronautics, 2000.
4. LaPlante, P. A., *Real-time Systems Design and Analysis*, John Wiley, New Delhi, 2004, 3rd edn.

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