Quality assurance challenges in testing and evaluation of reusable launch vehicle systems

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Quality assurance of the various reusable launch vehicle subsystems and the certification for flight involve many major and unique challenges compared to the conventional launch vehicle. This article highlights the major challenges faced by quality assurance teams during various phases of realization of the Reusable Launch Vehicle-Technology Demonstrator.

Keywords: Reusable Launch Vehicle, quality assurance challenges, testing and evaluation, mission design.

Introduction

REUSABLE launch vehicle-technology demonstrator (RLV-TD) mission was a grand success, achieving nominal flight performance meeting all mission objectives. This new project provided unique challenges to the quality assurance (QA) teams in the different areas of mission design, new subsystems realization, integration, software development and testing during the development phase. These challenges and their resolution are discussed in this article.

Mission design

The mission design process involves trajectory, guidance and Digital Auto Pilot (DAP) design as well validation of the above in six degrees of freedom (DoF) simulation beds. The mission design of RLV-TD HEX mission differed from the conventional launch vehicle design in two aspects. The vehicle configuration, consisting of the winged Technology Demonstration Vehicle (TDV) and the booster with fins was markedly different from the typical launch vehicle structure. It required extensive testing for aerodynamic configuration and also called for the development of different algorithms for mass property estimation. Again, the mission involved three distinct phases, ascent with the booster power, ascent with the TDV-alone configuration and descent of the TDV-alone configuration. Mission design had to cater separately to each of these three phases.

As the vehicle configuration changes during flight due to the separation of the booster stage as well as the deployment of aerodynamic control surfaces, the RLV aero data were classified into ten different subsets to ensure that flow features are correctly quantified in all configurations. Typical sets included liftoff aerodynamic data with tower effects, high angle of attack data for ascent configuration, etc. Wind tunnel data were used as baseline data over which corrections were applied utilizing Computational Fluid Dynamics (CFD) simulations. The RLV-TDV configuration was tested in three different wind tunnels in IIT Kanpur, NAL, Bengaluru, and VSSC, Thiruvananthapuram using eight different models in different scales in various flow conditions. This resulted in the generation of around 2000 tables of data. The two major challenges in quality assurance of aero data were to ensure the correctness of the data generated and also that they were correctly translated to inputs for simulation studies. Ensuring the correctness of data generation meant that the wind tunnel model used mimicked the flight configuration as close as possible. Major sources of error were identified like errors due to differences between vehicle configuration drawing and model configuration drawing, between model configuration drawing and actual fabricated model, and also differences due to model limitation like presence of sting, etc. All the error sources were identified by extensive audit and correction was applied on the data using CFD. Two CFD models were used, one being an exact replica of the flight configuration and other being a replica of the fabricated wind tunnel model. The simulations were carried out using both models and the difference between the two was applied as a correction to the base wind tunnel data. Once the data were generated, separate scripts were written to translate them into the formats required by simulation agencies as well as to verify the input.

System integration

The mechanical integration scheme of avionics in RLV-TD was intricate owing to the limited space availability. The packages were assembled to decks which were stacked one over the other with very little space for positioning, guiding and handling.

Detailed dynamic study of the avionics bay was carried out to check for any interaction between the isolated

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*For correspondence. (e-mail: pk_abrahamm@vssc.gov.in) avionics deck and hard-mounted ISU deck. Based on the tests, modifications had to be done in the integration scheme to delink the two systems and isolate the ISU deck from the other parts of the avionics bay.

The Centre of Gravity (CG) measurement of the TDV provided a different set of challenges due to the winged-body configuration. For mission requirements, it was necessary to accurately determine the lateral and axial CG of RLV. A different method of CG estimation, similar to the one used for racing vehicles (Formula 1), was evolved for this purpose. Detailed evaluation was carried out for the scheme before certification for flight. The final estimated CG values matched well with those prediction, which was critical for the mission.

As the ISU package for RLV-TD was assembled on the deck of the avionics bay for which a direct sighting of the porro prism for alignment was not possible at the launch pad, a transfer alignment method was implemented. The scheme was evolved on the assumption that no relative motion takes place between the ISU package and the structure. In this method, measurement was carried out in two phases – at the vehicle assembly bay and at the launch pad. An additional secondary prism was mounted on the aft end bulk head of RLV-TD in yaw (+) side and the azimuth for the ISU prism was derived from two independent measurements for secondary and ISU porro prisms. The INS azimuth value thus computed was finally provided to the mission after a thorough verification of the computations.

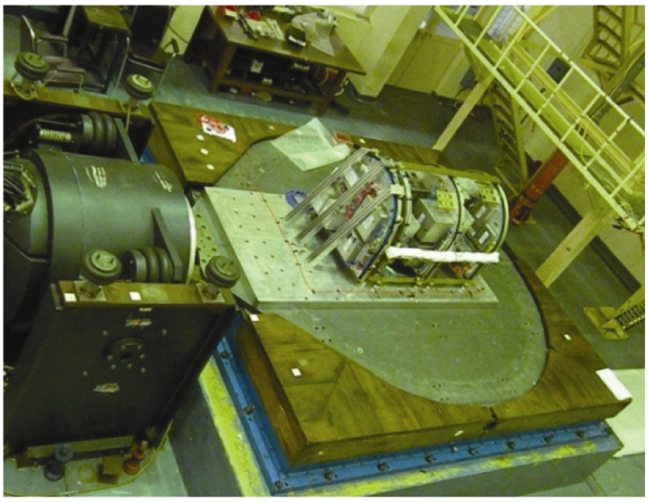

Figure 1. Dynamic characterization of avionics bay.

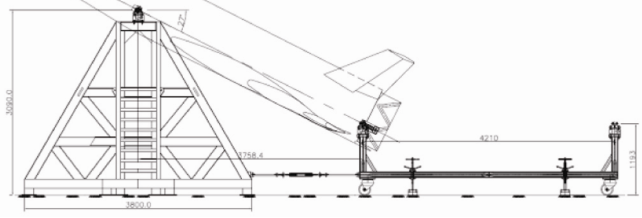

Figure 2. RLV-TD Centre of Gravity measurement.

Structural and environmental testing

The structures in RLV-TD were tested for the loads due to structural and thermal environments. Evaluation of the test set-up for qualification requirements was a challenge in itself.

All major hardware, viz. fuselage, wings, inter stage and base shroud were subjected to structural tests to 1.25 times the design loads and vertical tail, rudder, elevon, wing leading edge and nose cap were qualified for both thermostructural and structural loads.

The TDV and interstage were also subjected to acoustic tests. The base shroud which houses the major control systems was subjected to vibration tests for which the levels were derived based on the results of acoustic dynamic characterization test.

The vibration responses at all critical locations were monitored and acceptability with respect to package survivability was ensured.

Control actuation systems

The RLV-TD actuation system consisted of eight servo actuators; four for booster stage fin controls and four for TDV-winged body controls. The actuators were powered using a hydraulic power pack consisting of a pump, Brushless DC (BLDC) motor (prime mover for pump), accumulator, reservoir and other elements of the hydraulic circuit.

A common distributed control actuation system driven by a common hydraulic power source was a unique concept proven in RLV-TD. Detailed evaluation of the control systems was carried out in the different test beds, including actuator in loop simulation (ALS). Different test cases for evaluating the flight control actuation systems were identified and an extensive test was carried out for the hydraulic powered system. Interlocks were also devised for safe operation of high-power BLDC system. The Linearly Variable Differential Transformer (LVDT) sensor's connector failure and failure of hydraulic hose were adequately addressed and detailed evaluation carried out before induction in flight.

As the separation of hydraulic lines – high pressure and low pressure was involved during flight, criticality existed with respect to immediate sealing of the interfaces in order to avoid leakage.

Hydraulic loop stiffness was also a concern as the length of the hydraulic line was large. This was addressed through re-tuning of control electronics compensator.

Controlling contamination and air entrapment due to lengthier hose and more number of joints posed high risk.

Natural frequency of the plumbing system was taken care of using additional combination of flexile hoses, wherever required.

For addressing the above criticalities, a detailed test matrix was evolved and all aspects were validated before flight.

Software systems

The software used for the RLV-TD mission was an integral part of the overall scheme of success of the mission. The on-board software had to perform the navigation, guidance and control functions during the ascent, re-entry and guidance phases of the mission, unlike a regular lunch mission where these functions are performed only during the ascent phase. Hence, the software had to be newly developed and extensively tested. Quality assurance had to ensure that all the failure modes and errors in the software are properly addressed and taken care of through independent verification and validation (IV&V).

To evaluate software performance at ground level, special test beds were developed which enabled systematic testing of the packages and the software functional chain, thus ensuring that a reliable and defect-free software was used for the mission. Special test beds such as 'a testbed for evaluation of checkout software (TECS) and on-board software simulators were used to perform these test and evaluation (T&E) functions.

On-board software systems

The salient features of the software were the i960-based mission management computer (MMC) in both prime and redundant chains which does the navigation, guidance and control (NGC) functions, microcycle (10 ms periodicity) task scheduling for navigation and control during ascent phase, and flight control and bank angle computation using air data parameters. GPS Aided Inertial Navigation Sector (GAINS) data were used for aiding inertial navigation sensor (INS) position and velocity and radar altimeter data from 2 km to 10 m during descent phase were used for enhanced vertical accuracy.

The flight software of RLV-TD was developed according to the 'on-board software development life cycle model' and underwent all QA protocols and independent verification and validation, similar to the software of regular missions. As the software was newly developed, the IV&V activities were carried out for the entire software and the full IV&V cycle was repeated even for incremental changes from the baseline version. The software was subjected to thorough reviews at system and requirements levels, and all recommendations were implemented and documents revised and released as a new version.

As part of independent verification and validation, static analysis, code inspection, module-level test and software fault injection test (SFIT) were carried out before the software was cleared for NGC simulations. Absence of dead codes, redundant/extra codes and type inconsistency in the software was ensured as part of static analysis. Adherence to Ada Language for Flight Applications (ALFA) design guidelines was also verified as part of static analysis. The logical correctness of the software was verified through code inspection and re-inspection was carried out for the corrected software.

The software has been thoroughly validated at module level as part of software testing. Both black box and white box tests were conducted. About 2000 test cases were designed to provide 100% coverage for functional

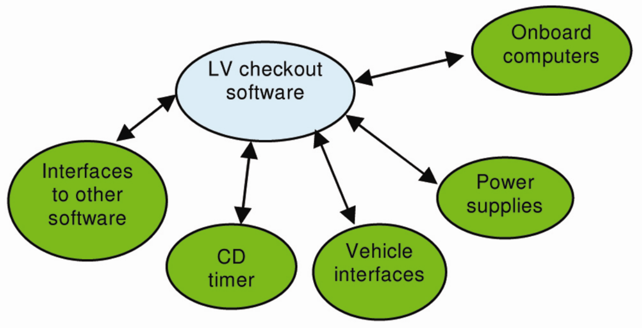

Figure 3. External interfaces of Launch Vehicle checkout software.

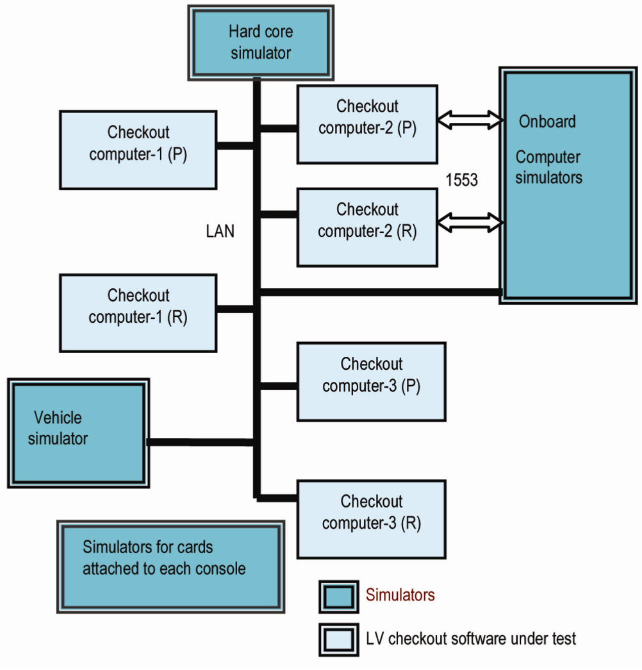

Figure 4. Configuration of test bed for evaluation of Checkout Software for Automatic Launch Sequence.

and error handling requirements, basis paths and condition/decision coverage. Profile-based tests were also carried out in open loop at component level. The hardware-specific error handling features implemented in the software were validated through SFIT. About 82 test cases were designed as part of SFIT based on memory errors, arithmetic error, processor self-check error, task incompletion, communication errors and others like integrity failures, RGTM failures and EEPROM checksum failure.

The software underwent extensive simulations in various test beds like simulated input profile (SIP), integrated processor test (IPT), on-board in loop simulation (OILS), ALS and hardwrae in loop dimulation (HLS). In OILS test, the performance of the software was evaluated under various dispersion/failure modes and software design limits. All system error handling features were validated in IPT. A total of 525 test cases were designed and executed as part of the total simulations.

Checkout software

The reusable launch vehicle checkout system is a real-time fault-tolerant distributed system that carries out critical activities of the count down, culminating in the launch. The software logic is implemented across several computers providing specific functionality as well as redundancy. This distributed real-time nature, and failure detection and isolation capabilities add to the complexity of the software, making its evaluation a challenging task.

The conventional methods of software evaluation include reviews, code inspection, module-level testing, and system-level test and evaluation. However, these verification processes do not fully capture the temporal aspects of the cooperating software and its constituent threads. The system-level tests are limited in their capability to simulate exact error conditions. Hence, a platform to perform software-specific evaluation is required to ensure dependability.

Considering the criticality of the software, a test bed has been developed to evaluate ALS along with the associated software elements. This platform, called the test-bed for evaluation of checkout software (TECS) provides a framework to execute the checkout software as in launch configuration without the hardware interfaces.

On-board checkout computer (OBCC) is a new concept introduced in RLV-TD. Conventional checkout systems are ground-based systems used to ensure the health of the vehicle during checkout phase. OBCC resides on-board the RLV, thereby reducing the connection complexities between vehicle and ground. Verification and validation of the OBCC software was carried out exhaustively to ensure the desired performance.

Conclusion

The RLV-TD was a prestigious mission for Indian Space Research Organization in many aspects. Several novel techniques and implementations could be developed and tested during the mission. The quality and reliability levels required to achieve a successful mission posed unique and characteristic challenges to the QA teams in all the associated areas. The set standards of reliability were achieved through exhaustive verification and validation of all systems. The mastering of the new technologies at subsystem as well as integrated vehicle level has been an excellent learning experience for the QA teams.

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