Hybrid Navigation System for GNC of Space Capsule Recovery Experiment (SRE): Development & Flight Performance

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Abstract

The Space Capsule Recovery Experiment (SRE) is the first Indian experiment in which a space vehicle is de-orbited from a low earth orbit and recovered from the Indian coastal waters on 22nd of January 2007. The main objective of SRE is to provide a microgravity platform for scientific experiments, demonstrate a host of new technologies for safe reentry of future manned modules into the earth's atmosphere and safe landing. One of the major challenges in SRE is the Guidance, Navigation and Control (GNC) system. In the SRE, a precision hybrid navigation system comprising of INS, fine sun sensor, magnetometer, satellite navigation receiver and robust navigation integration filter is designed, developed and successfully used to achieve the mission. As per the mission plan, the capsule is de-orbited under the closed loop GNC to achieve the re-entry pill- box at 100 km altitude very precisely. Below 100 Km, the aerodynamically stable capsule follows ballistic flight, terminal velocity reduction by parachutes for safe splash down within the specified impact zone for recovery. This paper presents the major design aspects and the flight performance of the Hybrid Navigation System and integration filter of the SRE.

Nomenclature:

SRE : Space Capsule Recovery Experiment, **GNC**: Guidance Navigation and control
INS: Inertial Navigation System, **GNSS** : Global Navigation Satellite System
IMU : Inertial measurement Unit, **DTG** : Dynamically Tuned Gyroscopes
EKF: Extended Kalman Filter, **DOF** : Degree of Freedom

1. INTRODUCTION

The 550 Kg Space Capsule of SRE is launched into 625 Km circular polar orbit on 10th January 2007 by the PSLV-C7 vehicle, the seventh operational flight of Polar Satellite Launch Vehicle (PSLV) of Indian Space Research Organization (ISRO) from the Shriharikota launch complex. The SRE Capsule is shown in Figure 2. On the 10th day the first de-boost is carried out under closed loop GNC to transfer the capsule to an elliptical orbit to have daily opportunity for final de-boost and recovery. On the 12th day the final de-boost is done for reentry and splash down in the Indian waters off the coast of Shriharikota. Figure 1 shows the overall mission profile. Figure 3 shows the final deboost ground trace.

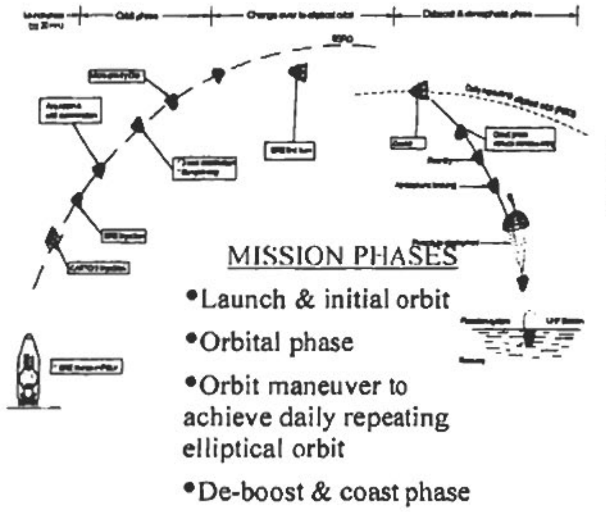

Fig 1, Overall mission

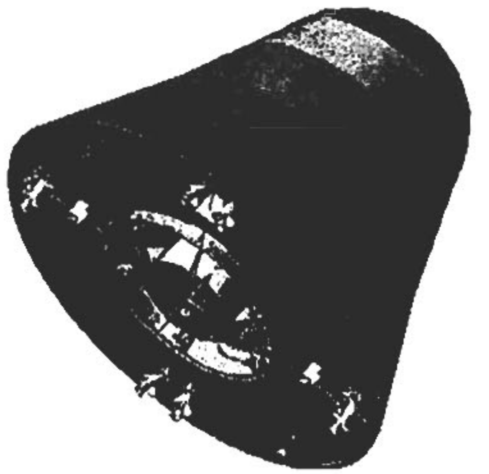

Fig 2 , Space Recovery Capsule

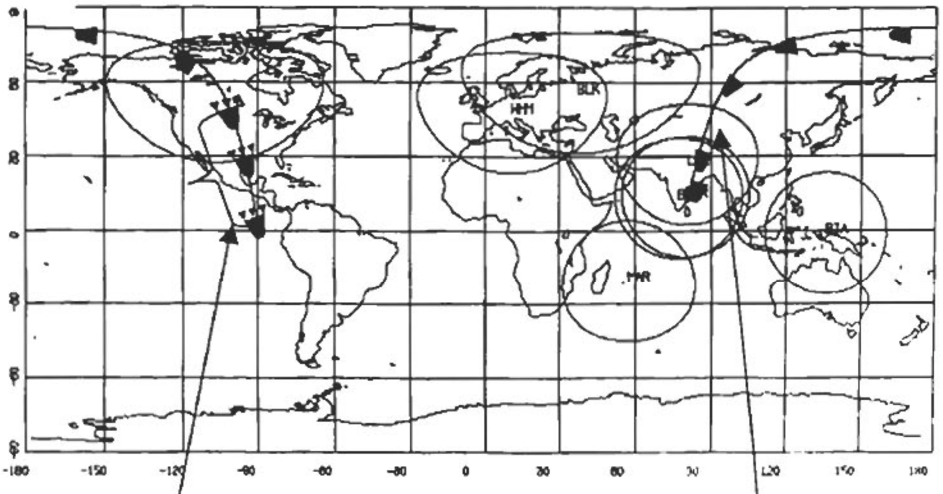

Fig 3, Deboost Ground Trace

The capsule has to be navigated to enter earth's sensible atmosphere (100 Km) with a precise position, velocity, Flight Path Angle (FPA) and angle of attack such that the reentry thermal loads are with in design limits. The state vector at the entry pill-box at 100 Km altitude has to be very accurate to achieve the desired impact point accuracy. This imposes major accuracy constraint on the navigation system design.

Even though the autonomous Inertial Navigation System IMU (Inertial Measurement Unit) had very good accuracy in terms of gyros and accelerometers, the uncertainties in the initial state vector and attitude for de-boost phase is very critical and hence Hybrid navigation (INS aided with GNSS) could only meet the mission accuracy. For this purpose, GNSS aided navigation algorithm based on optimal Kalman Filter was designed and developed.

Excellent navigation accuracy has been achieved using the Hybrid navigation in the orbit transfer and final de-boost phases. In the orbit transfer phase, perigee accuracy of 15m was achieved. In the final de-boost, the reentry pill-box has been achieved very accurately and the splash down point range error was only 4 Km from the planned location due to GNC.

2. MISSION OBJECTIVES

To design and qualify the following technologies for reentry missions:

- Navigation, Guidance and Control systems.
- Aero-thermo structure, thermal protection systems, materials and aero-thermo dynamic prediction methods.
- Parachute and recovery systems and operations.
- Carrying out microgravity experiments.

3. NGC SYSTEM

Overall GNC system consists of the following

- A precision INS and High dynamic GNSS receiver system.
- Mission management computer based on radiation-hardened processor.
- Fine sun sensors and Magnetometers for on orbit attitude determination and inertial attitude update and Magnetic torquers and thrusters for attitude control.
- Eight numbers of 22 N thrusters for de-boosting and attitude control operations.
- Hybrid navigation algorithm with elaborate error handling logics and software.
- Robust re-entry guidance algorithm and software for meeting large thrust perturbation of the thrusters and Telemetry, tracking and Tele-command systems.
- On orbit gyro drift estimation and accelerometer bias estimation
- Orbit Determination (OD) based on S-band tracking and GNSS, Orbit propagation.
- Ground link for telemetry and Tele-command.
- Software for Mission planning, trajectory design and GNC system design.

4. NAVIGATION SYSTEM DESIGN AND DEVELOPMENT

Major design and developments for the navigation system include

IMU, High dynamic GNSS receiver, Inertial navigation algorithm, Kalman filter design for hybrid navigation and optimization for onboard implementation and Flight software and system validation.

4.1 IMU

The IMU cluster is configured with three linear servo accelerometers and two Dynamically Tuned Gyroscopes. The sensor outputs in a fine range is used for navigation and a coarse range is used for re-entry measurements. The IMU cluster temperature control has the provision for three precise set points 50, 60 & 70 °C. The IMU is evaluated by special low acceleration input tests in addition to standard calibration to meet the mission specific requirements. The digital outputs of the accelerometers and gyros are interfaced to the Mission Management Computer. The IMU package is shown in Figure 4& 5. The sensors, accelerometers and gyros have been specially designed to operate in thermo vacuum condition for long duration and evaluated for their accuracy/stability under thermo vacuum.

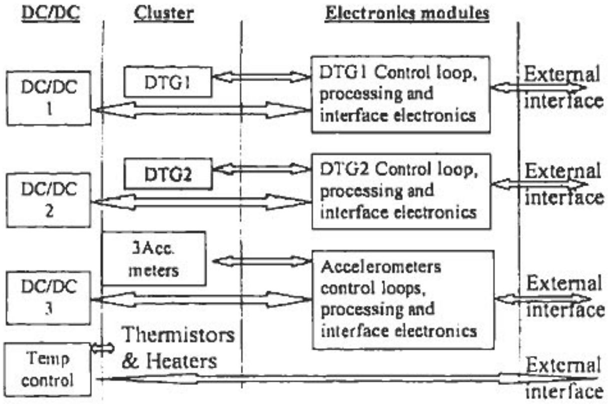

Fig 4, IMU configuration

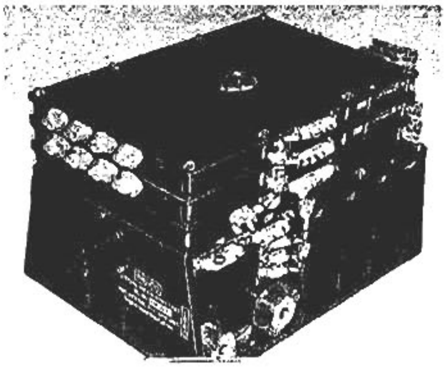

Fig 5, IMU Package

4.2 High Dynamic GNSS Receiver

An 8 - channel satellite navigation receiver is developed and qualified [1]. The receiver was interfaced to MMU through MIL 1553 B interface. Two patch antennae, one for the orbit and de-boost phases and another for the reentry phase are used with switching. The receiver is tested extensively with the de-boost trajectory and measured antenna pattern using a RF satellite navigation simulator. This study had a good bearing on the mission planning.

4.3 Kalman Filter Design for Hybrid Navigation

A 12 state (error state) EKF in feed forward configuration as shown in figure 6 is designed and developed. A full-fledged software simulator consisting of 6 DOF trajectory of the capsule integrated with the GNC model is used to design the EKF.

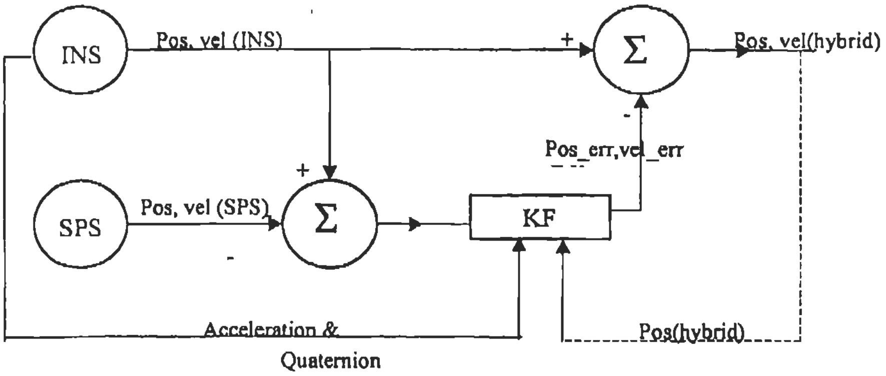

Fig 6. Feed forward filter confuration

4.3.1 Model Validation, Process & Measurement Noise Estimation

By conducting perturbation studies using the simulator and comparing the model state and true state the INS error dynamics model of the EKF is validated. The process noise is estimated by conducting Monte Carlo study. Based on the RF simulation studies with the SPS receiver, statistics of the navigation errors were analyzed and the measurement noise covariance determined for Kalman Filter design.

4.3.2 Kalman Gain and Robustness studies.

The real time KF gain computation was implemented and computation time measured. Since single processor was used for all onboard tasks, real time computation of Kalman gain was not feasible. Instead, an offline Monte Carlo analysis of the Kalman gains is carried out and optimal gain scheduling strategy based on time and events are adopted for onboard implementation. This novel scheduled gain scheme could meet the mission accuracy with ten fold decrease in computation load.

This design is validated for robustness with respect to Wild measurement noise (uniform distributed and bursts), Data loss (intermittent and continuous), Extreme levels of measurement noise (1/2 σ to 12σ), Gain sensitivity studies ($\pm$6dB) and Q sensitivity (0.1 to 10).

4.3.3 Filter Initialization, Convergence and Error Handling Logics

To achieve faster convergence, a novel scheme of initializing the filter states has been developed. Few consecutive differences between INS data and satellite navigation data are averaged for initializing the states of the filter. The initial state error covariance P_0 is conservatively chosen to speed up filter convergence and optimality is ensured by controllability analysis [3]. Error handling logics are built in to detect and manage wild samples, data loss, poor PDOP etc. Observability studies [3, 4] and analysis carried out to ensure filter performance in prediction mode after convergence.

5 Flight Software Development

The overall configuration of the software is presented in figure 7. The software is partitioned in to the following major modules, Gyro and accelerometer processing, Attitude estimation from Sun sensor & magnetometer for orbital phase, gyro & accelerometer bias estimation, Quaternion propagation, Navigation computations, and Aided navigation Kalman filter. The software is realized in ADA language. The integrated software is tested in closed loop with OILS (onboard processor in loop simulation), HILS (hardware in loop simulation) where IMU is mounted on angular motion simulator and acceleration and GNSS by digital simulation.

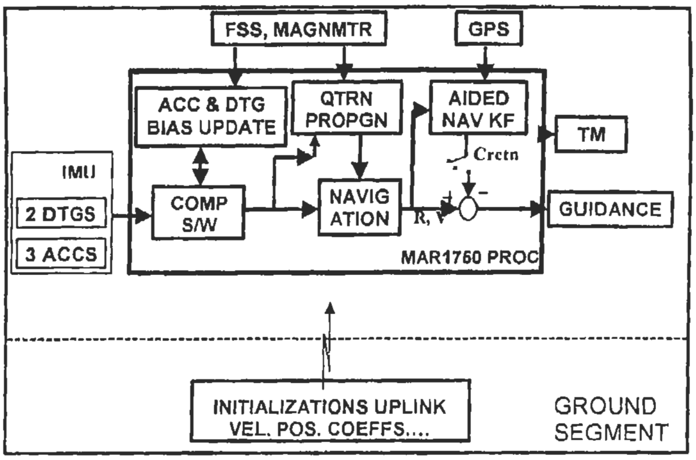

Fig . 7, Overall software configuration

6. Conclusion

The robust design of hybrid navigation system has met all mission requirements in the first flight itself. The first orbit transfer is achieved to an accuracy of 15m in perigee. The final de-boost reentry pill-box and splash down point is achieved with a range error of 4 Km.

7. References (Books)

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