Inertial Sensors and Navigation Systems

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1. Introduction

Highly precise and reliable indigenous Inertial Sensors and Navigation Systems, developed ab initio, have contributed immensely to the success of space launch vehicles of India. The venue of development was the erstwhile Space Science and Technology Centre, since outgrown into, Vikram Sarabhai Space Centre, VSSC, Indian Space Research Organization, ISRO, Trivandrum.

1.1 Background

Founding Fathers of the Space Program of India were deeply impressed by the potential of the emerging Space technology enabled Systems to upgrade the infrastructure for knowledge needed for taking India from backwardness to modernity. Their vision (1) encompassed Mass Communication, Telecommunication and Remote Sensing, among other vital systems, which existed in the country, but, in a minuscule level. They foresaw the potential much ahead of most of the professionals in advanced countries. They foresaw that Space Technology enabled infrastructure can be set up in much quicker time and at a fraction of cost compared to the then prevalent terrestrial systems. They insisted that India can skip many intervening technology related stepsfollowed by advanced countries and leap frog safely by going directly to Space technology.

At the same time, they stressed compliance with four cardinal conditions, namely,

(a) The Space Technology Enabled Infrastructure, STEI, should encompass the whole territory of the country,
(b) The infrastructure should remain contemporary at world level despite rapid advancements in systems and technologies,
(c) The program should be affordable, such that Return on Investment in India ought to be highly competitive, and
(d) The required human resources should be grown largely within the existing Indian educational system. It meant that large scale foreign training should not be required.

1.2 Options

Even with these postulates, two options existed to set up the needed systems, namely, (a) buy them out from the developed countries and operate them ourselves. This would be like what India has done in the field of Civil Aviation. The other option was (b) to develop, produce and deploy them indigenously, largely through Self-Reliance. Realizing that the needs of the country were huge and ever expanding, and also that the emerging technology will be advancing rapidly, the bought out technology would require frequent up-gradation. It precluded the bought out option. So, a courageous decision was taken to take up the challenge to develop, produce and deploy the whole range of technologies and systems indigenously. The cheering status after nearly fifty years of relentless efforts is that at present the country owns its own indigenously developed satellite based telecommunication and television system, which are comparable to the best in the World in respect of both the depth of penetration and performance. In addition, the country has satellite based advanced weather observation and warning system. Moreover, indigenously developed and sustained set up for seamless Remote Sensing of crops, forestry, floods and of a host of other natural resources are operational and have acquired great economic significance to the country. A significant piece of data is that just the Telecommunication service alone recovers the cost of satellite in about five years. The other services come virtually for free. So, what has been accomplished justifies amply the courageous decision of the founding fathers. Other significant by-products are concurrent emergence and utilization of enormously competent human resources, which were waiting to be employed in meaningful national tasks. Further, the Space program has put to use the investments already made and utilized fully by the country in non-space programs. Noteworthy examples are metals and special alloys, metal forming and machining, and Polymers and Composite materials.

It was in the context of aspiring to achieve total self- reliance in Space Technology that country ventured into the esoteric field of 'Rocket Science' and the associated fields of propellants, propulsion systems and Inertial Navigation systems. Here, we note that the major components of Space systems are Satellite Launch Vehicles, Satellites, Satellite borne payloads and Earth based tracking and data acquisition systems. The payloads include communication transponders, specialized multi-spectral cameras for observations of diverse natural phenomenon.

2. Placing a satellite in Earth orbit

A satellite Launch vehicle, SLV, lifts a satellite mounted on its top from the launch pad to the point of injection into orbit (1). It follows a pre-planned trajectory, which involves a vertical take-off, followed by a predetermined set of pitch manoeuvres, ending in a near horizontal path at a required altitude and with the required velocity. Control and Guidance system, stabilizes and steers the vehicle. Guidance and navigation system takes it to the destination. Actually, the SLV is a multistage rocket, with the first stage being ignited on the launch pad. When the propellant in the first stage burns out, the stage is jettisoned and the next stage takes over. This sequence continues till the penultimate stage reaches a predetermined altitude and velocity. At this point the velocity vector is parallel to the local horizon. Generally, after a brief coasting period the final stage gets ignited, imparting enough addition of velocity so as to give the satellite the required orbital velocity. A complex flight dynamics computer program determines and implements the multistage launch sequence. Inertial sensors and systems are integral to implementing these manoeuvres. As inertial sensors and systems are in a highly restricted category under advanced technology control regime practiced by developed countries, their indigenous development was critical to self-reliance in space launch vehicles.

We elaborate that the SLV lifts off vertically and reaches the desired point of injection in orbit following a predetermined steering program along a trajectory. To be sure, the SLV experiences destabilizing forces and moments originating from aerodynamics and propulsion systems. An autopilot, comprising angular rate sensing gyroscopes, stabilizes and steers it along the trajectory ,taking due care about the varying density of the air medium, prevailing winds and unpredictable propulsion related disturbances. The propulsion system has unpredictable variations requiring in flight corrections in order to reach the destination precisely. An Inertial Navigation system measuring the instantaneous orientation and sensors for measuring angular rates are integral components of the autopilot. An integrated Inertial Navigation System conjoined with an on-board digital computer measures the instantaneous altitude and relative velocity of the SLV and estimates its state at the end of the flight. The variations from the intended end conditions are corrected in real time by the closed loop guidance algorithm. Thus, the consolidated Inertial System of the SLV works in conjunction with its multistage propulsion system to impart the desired orbit injection conditions and orbital velocity with the required accuracy.

2.2 Significance of Orbital Parameters

It is clear that the function of a satellite launch vehicle is to place its passenger satellite in a desired orbit of Earth. The Earth orbits are generally elliptical in shape. The main parameters of an orbit are its Apogee, Perigee, orbital period and the Inclination angle. The Apogee and the Perigee are respectively the farthest and the nearest points to Earth in the orbit. Orbital period is the time taken to complete one Orbit around the Earth. Inclination angle is the angle between the Plane of the orbit and the equatorial plane of the Earth. These as well as orbital parameters play crucial role in the utilization of satellite as explained in the following.

A satellite in orbit traverses Earth below it. Inclination angle of the orbit determines the portions of Earth it visits during an orbit. The footprint of such visit is limited by the swath coverage of the camera. Through successive visits the satellite covers the entire area of Earth, accessible for a given inclination angle. For Polar orbits the inclination angle is 90 degrees enabling access to the entire surface of Earth. Thus it is the preferred inclination angle for remote sensing application. Further point to be noted is that a satellite in polar sun-synchronous orbit returns at the same time of the day. It covers the whole of Earth in 22 days enabling repeated collection of data over the same place. This characteristic helps in keeping track of changes in target features on Earth.

When the inclination angle is zero it becomes an equatorial orbit and with orbital period of 24 hours it becomes the geo-synchronous orbit with the property that it appears stationary with respect to earth. This property is used as a technical simplification for direct-to-earth, D2H, connection to fixed orientation antennas on Earth, making them simple and inexpensive and accordingly widely employed.

A satellite borne camera gets an exceptionally large field of view, the size being related to the altitude of the satellite. The camera collects gigabytes of photographic data in selected bands of the spectrum. Additionally, depending upon the inclination angle the satellite visits nearly the whole of Earth during its orbits. With the inclination angle of 90 degrees a polar orbit provides view of the entire Earth. Thus, gigabytes of data on the state of plant, water and or minerals on Earth is collected within a few days, aiding scientific analysis of state of agriculture, forestry and soil conditions. In comparison, an airborne camera will take several months to collect similar data on a small portion of Earth.

Likewise, a geosynchronous satellite borne communication transponder can communicate with points located on nearly one third of Earth, replacing thousands of terrestrial repeaters. Three properly located geo-synchronous satellites can cover nearly the whole of globe. Only the regions located near the North and South poles and in the high latitude zones are inaccessible from the equatorial plane due to the spheroid geometry of the Earth. The satellite borne communication links can be set up as soon as the satellites are placed in orbit and a suitable Earth station is established. Consequently, the speed of setting up a space technology based system is incredibly high, demonstrating the validity of the expectations of the speedy establishment.

3.0 Satellite Launch Vehicles of India

The Polar Satellite Launch Vehicle, PSLV, and Geosynchronous Satellite Launch Vehicle, GSLV are the current operational vehicles of India. A more powerful vehicle under development is GSLV Mark 3.

Owing to its reliability and orbit imparting accuracy the PSLV has become the work horse of ISRO. The launch on April 4, 2014 of the second Indian Regional Navigation Satellite – IRNSS-1B was its 25^{th} consecutive successful mission. The injection was so precise that the subsequent insertion in the final orbit by the satellite borne Liquid Apogee Engine required 7 kg less fuel, extending the service life of the satellite by more than 6 months. The precision came from the performance of the indigenous on-board Inertial Navigation System.

Some of the other missions accomplished by PSLV are IRNSS – 1A, Chandrayaan-1, MARS Orbiter. PSLV has placed in its 26th mission on 30th June 2014 the French Earth Observation Satellite SPOT-7 and four more commercial passenger satellites in the intended orbits. Thus far PSLV has launched 40 commercial satellites, signifying its reliability and cost effectiveness. Micro satellites built in Indian academic institutions have received piggy back rides. Its Inertial Guidance and Navigation system is programmable such that it can guide satellites to Polar orbits as well as Geo-synchronous Transfer orbits. Thus, PSLV is a versatile vehicle.

4.0 Anatomy of Inertial Navigation Systems

A cluster of gyroscopes to detect the movements in three inertial aspect angles, three accelerometers to measure orthogonal components of rectilinear accelerations and an on-board digital computer to process data make up the basic Inertial Navigation and Guidance System (2). Currently, two numbers of two - axis Dynamically Tuned Gyroscopes, DTG, serve as angular position sensors.DTG have replaced the single-axis Rate Integrating Gyroscope, RIG, as the former does not require as stringent precision in its parts as does an RIG. Heart of both types of gyros is an in-house developed Hysteresis Synchronous Motor, which maintains constant speed under severe launch vehicle environment of high acceleration and vigorous vibration, thus assuring the accuracy of the gyro. Participation of specialists in Material Science enabled development of the hysteresis synchronous motor. Extremely low internal loss materials for flexures employed in Accelerometers and DTGs contribute to precision in measurements. Ultra high precision, of the order of one micron, in machining and assembly in super clean environment assure stability in the characteristics of errors in sensing. This stability in the characteristics of hardware permits further reduction of final errors by sophisticated software compensation. The outcome is the world class precision in orbital injection of satellites in their desired orbits, thereby enhancing the class of PSLV (3) among the satellite launch vehicles. Chandrayaan and Mars Orbital missions depend on the precision of the Inertial Measurement System. Thus, the ab initio development has fulfilled its mission.

Supplementary Information

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