# Challenges in Navigation System design for Lunar Soft Landing

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**Abstract**

The moon is recognized as an important destination for space science and exploration. After the lunar missions in late 1950s and early 1960s, recently various countries started attempt to land in moon. Soft, precise landings of unmanned lunar spacecraft are needed for the logistic support for future manned lunar missions. The most critical driver for the mission is design and landing with 100% probability of success and hazard avoidance. The lander design requires a high level of autonomy, reliability and advanced GNC capability. The major technological objectives of a soft landing lunar mission are to assure precise landing, soft touch down and retargeting for hazard avoidance. This paper focuses on the navigation system required for the Lunar Soft Lander which is a complete, integrated, autonomous system with multiple sensor information for precise and soft landing.

## 1 Introduction

Exploration of the sole natural satellite of the Earth, the Moon, is gaining more importance in recent years. There are several types of missions to explore the surface of the moon viz., orbiting over moon, crash landing on moon, soft landing on moon etc. Among these, soft landing missions are becoming more important with respect to return to earth missions. Soft landing on the surface of the moon requires precise and autonomous Navigation, Guidance and Control (NGC). The NGC system must perform many functions that are critical to the soft landing on the terrain of moon. The purpose of this paper is to provide an overview of the complete and autonomous navigation system required for the Lunar soft lander. The overall mission profile for lunar soft landing is also provided. Key requirements that the NGC system must satisfy and functions it must perform in various mission phases are described. The NGC system configuration to support these requirements is then briefed. A system architecture based on Inertial Navigation System (INS) which is aided by ground tracking (Deep Space Network), star sensors, altimeter, velocimeter and Imaging sensors is addressed.

## 2 Mission profile

The mission starts with the Launch Vehicle injecting the combined lunar orbiter and lander module into a Transfer Orbit. The orbiter and lander are injected to a 170 x 36000 km typical transfer orbit by the launch vehicle. By series of mid-course orbit raising maneuvers and the final insertion maneuver, spacecraft is transferred to a 100 x 100 km circular lunar orbit. Based on mission planning, after achieving the desired initial conditions, the lander is separated from orbiter and a short burn de-boost is carried out to reduce the peri-lune to 15 km. After a long coast phase, the lander will reach the peri-lune. Near the peri-lune, a second long de-boost burn is carried out for horizontal braking. The objective of the braking phase is to efficiently kill the horizontal velocity to 0 at desired altitude. The lander will then follow a vertical descent, during which periodic firing shall be done to reduce the vertical velocity and achieve 0 m/s velocity, at 4 m height where the thrust will be cut off. The final phase is the free fall from 4 m to impact point with touch down velocity <5 m/s.

Summary of various mission phases are :

- Launch vehicle lift off and ascent phase.
- Transfer orbit.
- Circular Lunar orbit.
- Lunar de-boost phase.
- Coasting phases.
- Vertical descent phase.
- Terminal landing phase.

## 3 NGC Configuration

The key mission requirements driving the overall design of the lander module includes the need for an automated soft landing capability, the functionality necessary for lunar surface operations and the reliability which leads to the use of proven technologies. Soft and precise landings of unmanned spacecrafts require terminal guidance which would rely on information provided by the onboard instruments alone. Tasks that are extremely difficult, repetitive or require quick response are best performed automatically. Hence the guidance system should be autonomous.

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The lander operations from separation to touch down shall be carried out by a closed loop NGC system. The Inertial Navigation System (INS) alone will not be able to meet the stringent touchdown requirement of 5 m/s in vertical and horizontal velocity. The unbounded error growth in the INS with time is corrected with the help of other absolute external measurements. An external measurement can be any quantity that duplicates a navigation parameter such as velocity, position or orientation. An integrated navigation system consisting of an INS, star tracker, altimeter, velocimeter and image sensor is proposed. The initial attitude of IMU at de-boost is determined using star tracker. The accelerometer and gyro drifts are also updated before the first burn. The state vectors are established using Deep Space Network (DSN), Orbit Determination and ground uplink and transferred to the INS system. The lander NGC will be active before the separation from orbiter itself. The INS after updating the state vector is used for the first burn. During the long coast phase also, the attitude and gyro drifts are updated using star tracker. The accelerometer bias also is updated during the long coast phase. The INS state vector is used during the second burn. During the vertical descent phase, radar altimeter is used for the height information. Doppler velocity sensor is primarily used to measure the horizontal velocity in the terminal landing phase to ensure safe landing with a touch down velocity of <5 m/s. Vision aiding or terrain sensor using CCD camera is used to get the image of lunar surface to avoid the obstacles and re-targeting the landing surface.

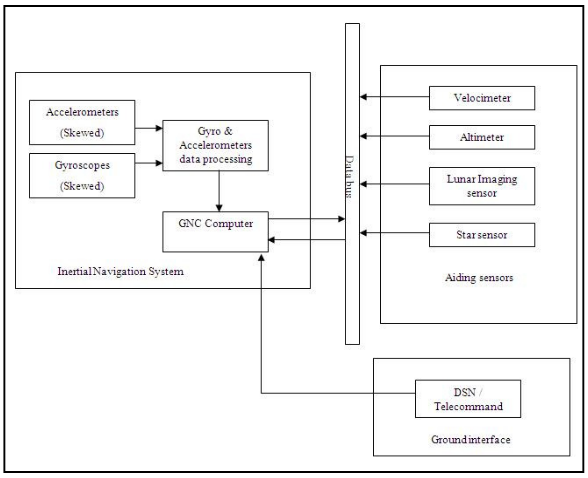



**Figure 1: NGC configuration**

**Table 1: Mapping of NGC functionality with sensors**

| NGC sensors and equipment | Ascent phase & orbit raising | Lunar orbit | Lunar deboost &horizontal braking | Coasting phases | Vertical descent phase | Terminal landing phase |
|---|---|---|---|---|---|---|
| Gyros | √ | √ | √ | √ | √ | √ |
| Accelerometers | √ | √ | √ | √ | √ | √ |
| Start tracker | | √ | | √ | | |
| DSN / Ground tracking | | √ | | | | |
| Altimeter | | | | | √ | |
| Velocimeter | | | | | | √ |
| Imaging sensor | | | | | | √ |

**Table 2 : Typical Power and Mass budget**

| Subsystem | Quantity (Nos.) | Mass (kg) | Power (W) |
|---|---|---|---|
| INS | 1 | 20 | 100 |
| Star tracker | 2 | 6 | 15 |
| Altimeter | 2 | 1.5 | 8 |
| Velocimeter | 2 | 1.5 | 8 |
| Imaging sensor | 2 | 2 | 5 |

## 4. NGC subsystems

The Inertial Navigation System proposed for use in Lunar soft landing mission is chosen based on the requirements of improved accuracy, reduced mass and better reliability. Considering the simultaneous requirements of reliability and accuracy, a typical configuration invokes in-flight sensor redundancy. Accordingly, the proposed INS consists of gyroscopes and accelerometers mounted in skewed configuration. This configuration detects any single point sensor failure and isolates the failed channel. The system will be re-configured to meet the navigation computation requirements. The mass of the system is estimated to be 20 kg and requires a power of 100 Watts. The INS will be required during all phases of the mission. The navigation state vectors obtained from the INS is used for the closed loop guidance and control. However, the INS has a time growing error characteristic and also suffers from initial attitude errors. This leads to the requirement of external aiding sensors.

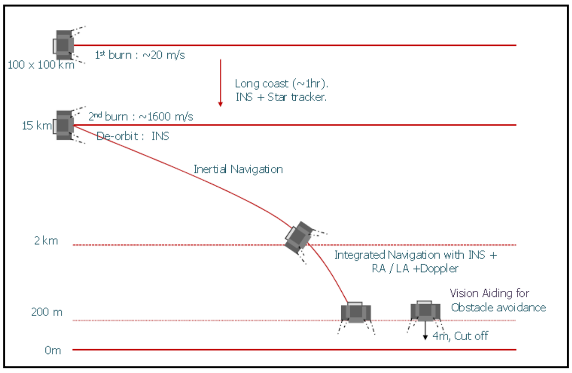


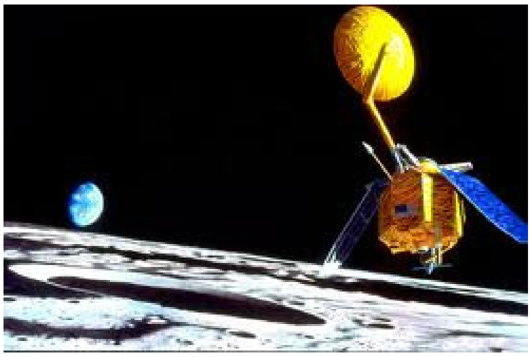

**Figure 2 : Lunar landing profile and NGC Configuration**

For precise attitude determination, aiding with star sensors is used. Two star sensors are planned for redundancy. Star sensors are used for attitude update and gyro drift update during the on-orbit and intermediate coast phases. Periodically, the gyro drifts are calibrated with star sensor and the drifts are updated, if necessary. Star sensors planned in the proposed mission weigh around 6 kg and requires a power of 15 watts.

Radar Altimeter is used in the vertical descent phase to get an idea of the height of the lander from the terrain so as to have a proper guidance to the surface. Radars do not perform well in the near terrain range. To eliminate this performance gap, the other NGC sensor, imaging sensor is used in the final phase of landing.

Doppler velocity sensor is used to measure the horizontal velocity during the terminal landing phase to ensure safe landing. The undesirable horizontal velocity of the lander, if any, is to be cut off after finalization of the landing site.

The landing terrain may have hazards which include craters, slopes and rocks that may be challenging for smooth landing. Final navigation and guidance under consideration of hazard avoidance aspects has to be processed fully autonomously on-board during final descent to the lunar surface. This leads to the requirement of imaging sensor using CCD camera at the time of landing. The obstacles can be identified and avoided by using the surface feature tracking.



## 4 Challenges ahead

Apart from the basic NGC functions, a number of challenges are faced in ensuring safe, precise landing. The lunar surface is covered by granular materials, leading to the development of dust clouds during the descent phase of landing. The performance of the NGC sensors must be robust to tackle the dust prone environment of moon. The imaging sensor which is very essential for landing must be protected from the dust particles. The NGC design should be flawless as tasks are required to be done repetitively and require quick response time.

The most challenging aspects of a lunar exploration mission is the survival of the extreme thermal conditions associated with the lunar day and night which varies from -150 deg C to +123 deg C. Appropriate technology development and proper testing is to be planned for surviving these conditions.

High quality DSN updates and improved lunar gravity modeling are essential for accurate navigation computations.

## 5 Concluding remarks

The challenges in the navigation system design for safe, precise, soft and autonomous landing on the moon's surface are discussed. The NGC system has to perform many functions that are critical to the soft landing. The NGC configuration during various phases of the mission is described. The mission profile including the navigation plan from the time of lift off till landing on moon's surface is briefed. The NGC sensor suite was selected catering to the functional requirements of the mission. The selection of specific sensors during various phases also is described.

**References**

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