Autonomous navigation and guidance scheme for precise and safe planetary landing

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Abstract

Purpose – The purpose of this paper is to discuss the autonomous navigation and guidance scheme for future precise and safe planetary landing.
Design/methodology/approach – Autonomous navigation and guidance schemes are proposed based on inertial measurement unit (IMU) and optical navigation sensors for precise and safe landing of spacecrafts on the moon and planetary bodies. First, vision-aided inertial navigation scheme is suggested to achieve precise relative navigation; second, two autonomous obstacle detection algorithms, based on grey image from optical navigation camera and digital elevation map form light detection and ranging sensor, respectively, are proposed; and third, flowchart of automatic obstacle avoidance maneuver is also given out.
Findings – This paper finds that the performance of the proposed scheme precedes the traditional planetary landing navigation and guidance mode based on IMU and deep space network.
Research limitations/implications – The presented schemes need to be further validated by the mathematical simulations and hardware-in-loop simulations, and then they can be used in the real flight missions.
Practical implications – The presented schemes are applicable to both future planetary pin-point landing missions and sample return missions with little modification.
Originality/value – This paper presents the new autonomous navigation and guidance scheme in order to achieve the precise and safe planetary landing.

Keywords Spacecraft navigation, Robotics, Programming and algorithm theory

Paper type Conceptual paper

1. Introduction

Future solar system exploration is filled with missions that require landing spacecraft on planets, moons, comets, and asteroids. Each mission has its own criteria for success, but all will require some level of precise and safe landing capability, possibly on hazardous terrain. In order to perform scientific region investigation or sample return missions, robotic spacecrafts have to land on the hazardous areas, such as big rock, crater, and steep slope. Autonomous landing spacecraft on the moon and planetary bodies, close to the pre-selected landing zone with high-scientific value, in an area of rough terrain, is a rather difficult and risky task. Because of the communication delay induced by the large distances between the Earth and targeted bodies, traditional spacecraft guidance, navigation and control (GNC) mode using the deep space network is not suitable for precise and safe planetary landing, all operations in the landing phase must be done autonomously using onboard sensors and algorithms (Scheeres, 1998). Current technology does not provide landers with the capability to land safely and precisely, so other new techniques must be investigated.

Issues of safe and precise landing spacecraft on target planetary bodies have been studied from the view point of conception since the 1990s. The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are pursuing vision-based relative navigation technologies to achieve pin-point planetary landings (PPL) within 10-100 m (Polle *et al.*, 2003; Mancuso, 2004; Paar *et al.*, 1994; Johnson and Matthies, 1999). Jet Propulsion Laboratory (JPL) is developing algorithms based on feature tracking that provide the surface-relative position and velocity that are required to generate accurate trajectory knowledge between position measurements (NASA, 2008). The Autonomous Precision Landing and Hazard Avoidance Technology (ALHAT) project will be jointly implemented by the Johnson Space Center, Langley Research Center, JPL and the Charles Stark Draper Laboratories. The ALHAT project will develop the new and unique descent and landing GNC hardware and software technologies necessary to achieve precise and safe planetary landing (Epp and Smith, 2007). The Navigation for Planetary Approach and Landing study has been proposed and performed by ESA (Silva and Parkes, 2004; Frapard and Mancuso, 2006). The main

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objective of the study is to develop a vision-based navigation system for the final descent phase of the landing, to allow soft and precision landing on a planet, based on a single optical navigation camera.

This paper proposes autonomous navigation and guidance scheme basing on inertial measurement unit (IMU) and optical navigation sensors for precise and safe landing spacecrafts on the moon and planetary bodies. Vision-aided inertial navigation (VAIN) scheme is suggested to achieve precise relative navigation; two autonomous obstacle detection algorithms, basing on grey image from optical navigation camera, and digital elevation map (DEM) form light detection and ranging (LIDAR) sensor, respectively, are proposed; flowchart of automatic obstacle avoidance maneuver is also given out.

This paper is structured as follows. Section 2 describes the structure and function of the proposed autonomous navigation and guidance scheme. Precise relative navigation scheme is brought out in Section 3. Autonomous obstacle detection and avoidance algorithms are given in detail in Section 4. Finally, Section 5 contains the conclusions.

2. GNC architecture and function

Compared with the traditional planetary landers, the new generation smart lander should have the capability of autonomous precise relative navigation and automatic obstacle avoidance. The sketch of autonomous GNC for precise and safe planetary landing in our proposal is shown in Figure 1. The full GNC system structure can be divided into two blocks according to their functions: precise relative navigation (Block I) and autonomous obstacle detection and avoidance (Block II).

In our proposed scheme, navigation instruments include optical charge couple device (CCD) navigation camera, IMU and LIDAR. Optical navigation camera and IMU are widely used optical sensors for various deep space missions. LIDAR is recently developed optical sensors for planetary rendezvous and landing missions (Parkes and Silva, 2001; Hashimoto *et al.*, 2003). Navigation information, including position, attitude, image, and DEM, comes from optical navigation camera, LIDAR and IMU, respectively. The lander states (including position and attitude) is the autonomous relative precise navigation algorithm outputs, safe landing regions are obstacle detection and avoidance algorithm outputs. Guidance and control algorithm produce thrust command with navigation information and obstacle detection information taken into account.

In order to correct the bias and long-term drift of IMU, optical navigation camera is added up as accessorial vision navigation (VisNav) sensor. VAIN provides the relative state variables estimation between spacecraft and pre-selected landing site with high accuracy. The grey image and DEM data, coming from optical navigation camera and LIDAR sensor, respectively, are then processed and analyzed for autonomous obstacle detection and avoidance. Hazardous level is calculated to distinguish safe landing areas from hazardous regions. If the pre-selected landing site lies in the obstacle regions, obstacle avoidance maneuver is activated and new landing lying safe region is re-selected and re-targeted (Hoppa *et al.*, 2004; Matsumoto *et al.*, 2002, 2003).

3. Precise relative navigation

IMU is used as only navigation sensor in the traditional planetary entry, descent and landing process. Because of intrinsic inertial drift, IMU results in a larger navigation error. Optical CCD navigation camera, also referred to as VisNav sensor, provides position and attitude information through the direct observation of landmarks or feature points.

Figure 1 Sketch of autonomous GNC for precise and safe planetary landing

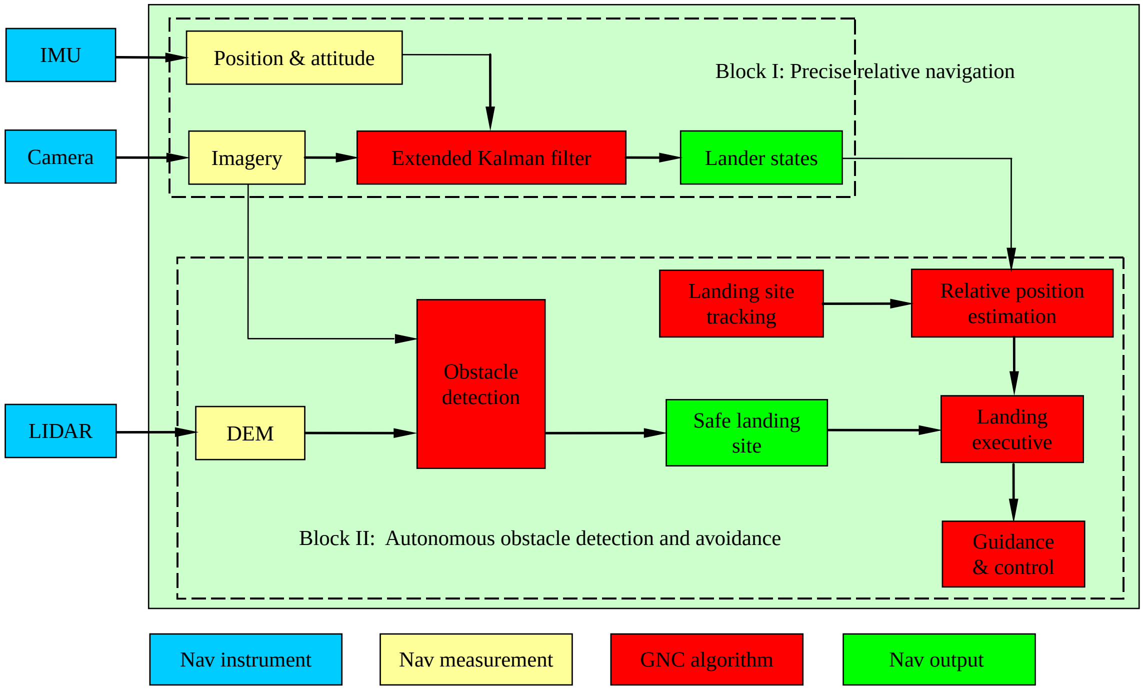
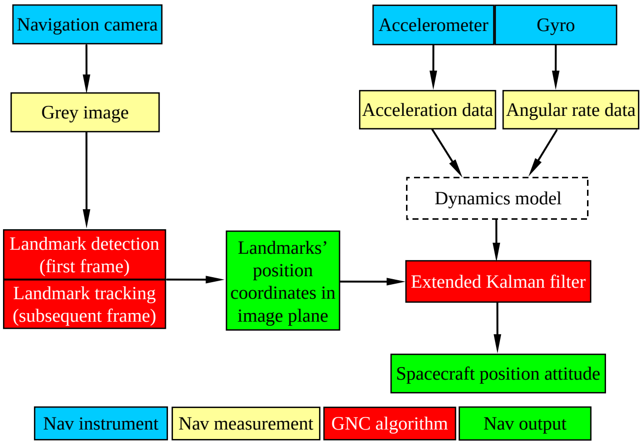


Image-based navigation systems that use CCD navigation cameras require a substantial burden for image processing (IP) or pattern recognition. So, these systems usually have slow data update rates and may suffer from occasional failures of the pattern recognition. The inertial navigation system (INS) provides densely measured linear acceleration and angular rate with high-bandwidth and high-sampling rate by three axial accelerometers and three axial gyroscopes. However, INS measurements are usually corrupted by initial condition errors, noise, bias, and drift variation, so that the navigation errors may be accumulated and lead to significant errors in the position, velocity, and attitude outputs. Therefore, the integration of optical and inertial navigation using the complementary provides a more precise and robust navigation solution.

In order to achieve precise relative navigation for PPL, we propose and implement VAIN algorithm which uses the image information of landmarks or feature points and INS measurements to estimate the relative position, velocity, and attitude between the spacecraft and pre-selected landing site (Li *et al.*, 2007). Vision system measurements serve to correct the long-term drift of INS, which leads to an extend Kalman filter which computes the optimal navigation solution by proper gains operating on the inputs from the VisNav and IMU (Figure 2). Thereby, this fused navigation system provides a continuous best estimate of the landing dynamic system's position, velocity and attitude vector, and is much more robust with respect to occasional VisNav data dropouts than forward propagation using INS outputs. At the same time, other GNC sensor data from other sensors, such as, lidar, or radar can be easily included in the filter to improve attitude and position estimation (Parkes and Silva, 2001).

Landmarks or feature points are pixel locations and the surrounding image intensity neighborhood (image window) which can be tracked robustly across multiple image frames. Surfaces of hazardous landing areas generally appear highly textured, so good features to detect and track are expected to be plentiful. Landmarks detection and tracking are the groundwork of VAIN algorithm. Since the processing speed of the IP algorithm is a very important design constraint for navigation application, the simple and robust IP algorithms should be selected for VAIN algorithm. The well-known Shi-Tomasi-Kanade feature detection and tracking algorithms are introduced at length in Li *et al.*(2006) and Robert(2002).

Figure 2 VAIN scheme



At the same time, low-cost large-scale integrated circuit, devoted to IP, has been developed in order to overcome the real time constraint of the IP algorithms in the planetary landing phases, which implements in hardware the IP algorithms (both for feature extraction and tracking; Bagnasco *et al.*, 2006).

In theory, the time development of the spacecraft position and attitude can be determined using dynamic models. However, dynamical modeling for spacecraft includes many difficulties in establishing valid torque and force models, which lead to inaccurate dynamic models. In practice, autonomous spacecraft can use inertial reference units as dynamic models replacement. In our proposal, the linear acceleration and the angular velocity of the spacecraft are provided by accelerometer and gyro output data, respectively. The evolution of the spacecraft position and attitude state in time are obtained from the kinematics equations. The accelerometer and gyro biases are state variables and the accelerometer and gyro data are not considered as observations, therefore, the accelerometer and gyro noises are considered as state noise rather than as observation noise (Li *et al.*, 2007).

4. Autonomous obstacle detection and avoidance

In order to explore the scientific site, the spacecraft has to land on the hazardous region. So, autonomous obstacle detection and avoidance is necessary for the next generation planetary lander. Obstacle detection algorithms can be divided into two categories: passive image- and active LIDAR-based obstacle detection algorithms. Each category has her advantage and disadvantage. Image-based obstacle detection algorithm is simple and the computation burden is low, but the process of camera acquiring image needs good light condition. By contrary, LIDAR-based obstacle detection algorithm is complex and the computation burden is heavy, however, which is reliable and free of light condition.

Because of the limited aboard computation capability, only simple and robust obstacle detection algorithm can be applied in the real flight mission. In our precise and safe landing navigation and guidance scheme, image- and LIDAR-based obstacle detection algorithms are combined to identify the potential obstacle and guidance the spacecraft to the safe landing site. At the entry and descent phase, the spacecraft is at the higher altitude which is larger than the working ranger of LIDAR, so image-based obstacle detection algorithm is applied to perform the coarse obstacle detection. The vertical descent and final landing phase commences at the lower height (about 3 km), the DEM can be obtained by use of LIDAR. Then, precise obstacle detection is performed using DEM.

4.1 Image-based obstacle detection

Obstacle detection avoidance is necessary for a safe planetary landing, and autonomous real-time obstacle detection using an imaging sensor is regarded as a promising means to achieve this goal, which has the potential to become a basic technology for future landing spacecraft on the moon and planetary bodies.

General speaking, obstacle means the severe rough region and it results in shadow. At the same time, the landing time is usually scheduled in the morning at local time to keep the daytime after landing longer. It means that sun elevation angular is very small and shadows are easy to made even small rocks or craters. When the sun elevation angle is known, the rough shape and size of the obstacle can be easily obtained. So, shadow information-based obstacle detection algorithm is very sensitive and reliable (Sawai *et al.*, 2003).

Image-based obstacle detection algorithm consists of the following three steps:

1. Shadow region is detection according to simple gray level threshold.
2. Hazardous area is defined along the solar light direction (Figure 3).
3. The hazardous area is then extended to the direction perpendicular to the solar light direction (Figure 4).

4.2 DEM-based obstacle detection

A LIDAR senses the 3D topography within its field of view by raster scanning a pulsed laser beam across the targeted surface. By measuring the time of flight of the laser pulses reflected from the surface the range to the surface can be determined for each scan. When combined with measurements of the angular position of a mirror that directs the scan, a 3D point or sample can be generated for each laser pulse. The output of the LIDAR is a cloud of 3D points that convey the topography of the scanned surface (Figure 5).

DEM-based hazard detection algorithm consists of the following three steps (Johnson *et al.*, 2002):

1. Local underlying horizontal plane is determined by least median square estimation (Figure 6).
2. Roughness map and slope map can be computed, respectively, basing on local underlying horizontal plane obtained in Step 1.
3. The hazardous level of the total landing area is then gained by weighting roughness map and slope map.

Figure 3 Obstacle definition in the solar light direction

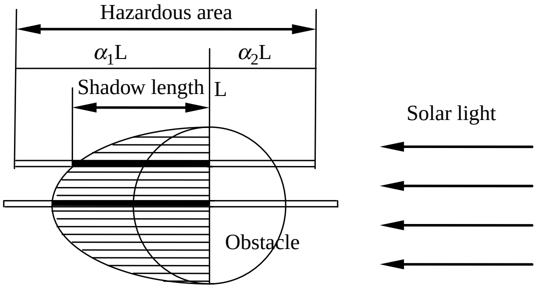


Figure 4 Obstacle expansion to the normal direction of the solar light direction

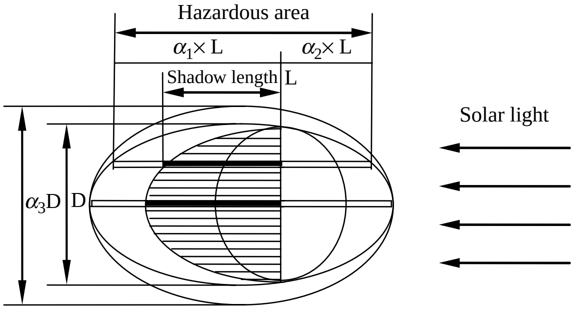


Figure 5 Sketch of DEM from LIDAR

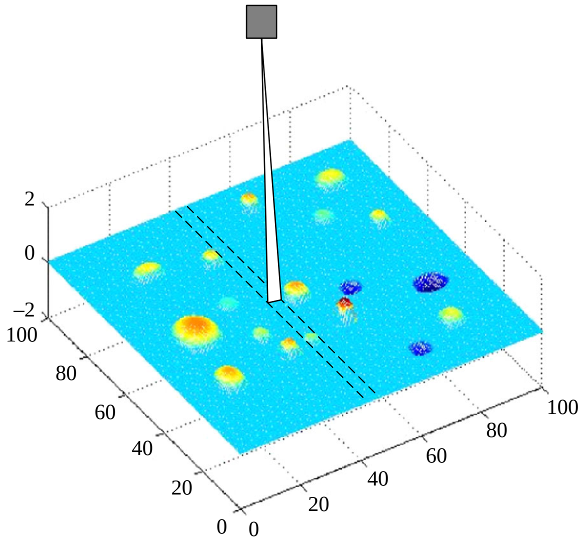
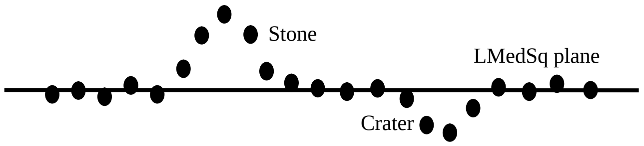


Figure 6 Sketch map of obstacle detection



Here, a simple roughness and slope weighted algorithm is used to estimate the potential obstacle. The hazardous level H is defined as follows: $H = aD + bS$, where D denotes roughness hazard information; S denotes slope hazard information; a and b are the weighted factors.

4.3 Information fusion-based obstacle detection

Information fusion is the process of using information derived from multiple sensors and combining them at the information level. Compared with single sensor (such as camera or LIDAR) based obstacle detection algorithm, the reliability of information fusion-based obstacle detection algorithm is getting much better.

Information fusion-based obstacle detection algorithm consists of the following three steps:

1. Roughness map and slope map are, respectively, derived using image- and DEM-based obstacle detection algorithms described aforementioned.
2. Safe landing area and hazardous landing area are computed basing on roughness map and slope map obtained in Step 1.
3. The final safe area and hazardous area are derived by information weighting fusion (Figure 7).

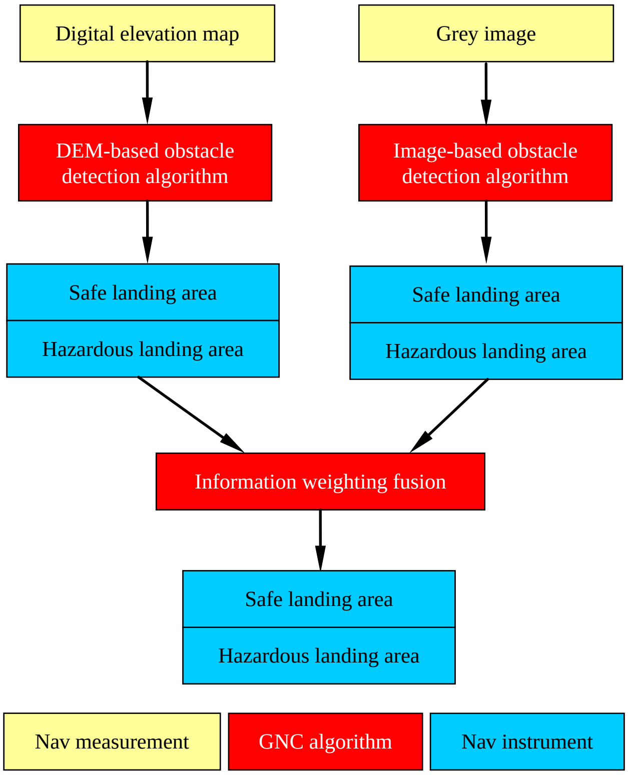
4.4 Autonomous obstacle avoidance maneuver

After the safe landing site and potential obstacles have been detected, the obstacle avoidance maneuver is initiated. The new landing site is re-selected and the spacecraft is re-targeted (guidance) to the new landing site.

Two factors must be taken into account in the new landing site selection, the:

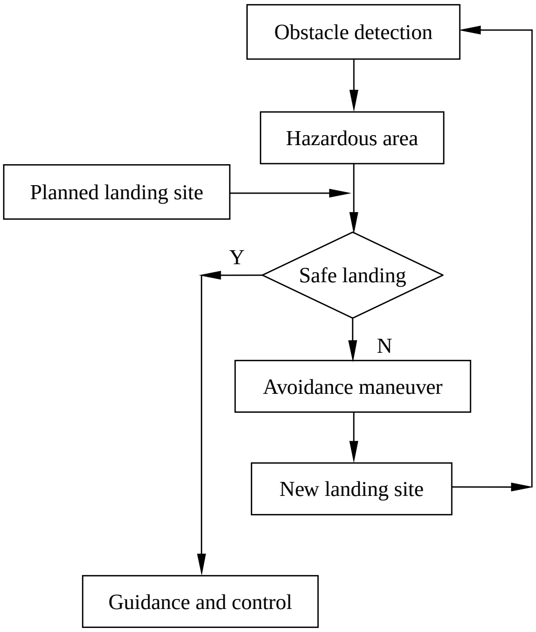
1. local hazardous level; and
2. distance between the spacecraft and the new landing site.

Figure 7 Information weighted fusion hazard detection



The landing sites with the lower hazardous level are relatively safe regions. At the same time, the spacecraft consumes lower fuel to maneuver to the landing sites are near the spacecraft. The flowchart of autonomous obstacle avoidance maneuver is shown in Figure 8.

Figure 8 Flowchart of autonomous obstacle avoidance maneuver



5. Conclusion

In this paper, the autonomous navigation and guidance scheme for precise and safe planetary landing is conceptual designed, which is necessary for future sample return and manned planetary exploration missions. VAIN algorithm is presented in order to achieve the aim of precise planetary landing. Two autonomous obstacle detection algorithms, basing on grey image form optical navigation camera and DEM from LIDAR sensor, respectively, are conceptual designed to achieve the goal of safe planetary landing. The flowchart of autonomous obstacle avoidance maneuver is also presented.

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