Robotics and Autonomous Systems 78 (2016) 63–82

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Visual–inertial navigation for pinpoint planetary landing using scale-based landmark matching

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HIGHLIGHTS

- Future space missions require autonomous terrain navigation for pinpoint landing.
- We test a visual–inertial navigation filter that identifies generic mapped landmarks.
- The filter can efficiently predict position and scale of a landmark within the image.
- We demonstrate pinpoint landing performance on a lunar-representative test bench.
- We test the robustness to various parameter changes.

ARTICLE INFO

Article history:
Received 26 January 2015
Received in revised form
13 June 2015
Accepted 11 January 2016
Available online 29 January 2016

Keywords:
Navigation
Vision
Inertial
Landing
Precision
Moon

ABSTRACT

Landing an autonomous spacecraft within 100 m of a mapped target is a navigation challenge in planetary exploration. Vision-based approaches attempt to pair 2D features detected in camera images with 3D mapped landmarks to reach the required precision. This paper presents a vision-aided inertial navigation system for pinpoint planetary landing called LION (Landing Inertial and Optical Navigation). It can fly over any type of terrain, whatever the topography. LION uses measurements from a novel image-to-map matcher in order to update through a tight data fusion scheme the state of an extended Kalman filter propagated with inertial data. The image processing uses the state and covariance predictions from the filter to determine the regions and extraction scales in which to search for non-ambiguous landmarks in the image. The image scale management process operates per landmark and greatly improves the repeatability rate between the map and descent images. A lunar-representative optical test bench called Visilab was also designed in order to test LION. The observability of absolute navigation performances in Visilab is evaluated with a model developed specifically for this purpose. Finally, the system performances are evaluated at a number of altitudes along with its robustness to off-nadir camera angle, illumination changes, a different map generation process and non-planar topography. The error converges to a mean of 4 m and a 3-RMS dispersion of 47 m at 3 km of altitude on the test setup at scale.

1. Introduction

Robotic planetary exploration aims at improving our scientific knowledge about the other bodies in the solar system, to make discoveries hopefully useful here on Earth. The first missions to a target object usually study and map it safely from orbit. The data collected allows scientists to detect candidate areas for subsequent surface exploration with instruments placed on a static lander or on a mobile rover. A potential landing site must meet science objectives but also engineering constraints, e.g. being hazard-free, within an area large enough to ensure the lander can reach it. Therefore the greater the landing accuracy, the more places can be visited on the planet, the more science can be returned. The long term objective of precision landing research is to build an autonomous spacecraft capable of safely landing within 100 m of

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http://dx.doi.org/10.1016/j.robot.2016.01.007
0921-8890/

a target [1]. Landing with such an accuracy on an extraterrestrial body has only been achieved once in history by commander Alan B. Shepard and lunar module pilot Edgar D. Mitchell during the Apollo 14 mission to the Moon on February 5th, 1971. They landed within 50 m of the selected target and were able to do so by recognizing the craters below them, evaluating their trajectory and correcting it through the lunar module window system [2]. No unmanned robotic probe has ever reached this precision yet. Some future mission plans already assume such a capability though, while current inertial navigation technology only offers statistical accuracy of the order of the kilometer at best [3].

1.1. The navigation challenge

Entry, descent and landing is by far the most critical phase of a planetary exploration mission. It takes a spacecraft from traveling at tens of thousands of kilometer per hour through interplanetary space to landing safely on the surface of a planet. The size of the landing uncertainty ellipse depends on the performance of the guidance, navigation and control systems. These functions shall be autonomous on board as remote control from Earth involves communication delays which can reach several minutes even for planets as close as Mars, and thus prevent any efficient feedback. Current navigation technology has not changed much since the first landing attempts in the 1960s: the position and the orientation of the landing vehicle are estimated by integrating the specific force and angular rate data provided by an Inertial Measurement Unit (IMU). Localization is initialized in orbit from Earth-based range-rate radar measurements with an accuracy of several hundred meters at lunar distance and with even greater errors for more distant targets [4]. The spacecraft then commits to descent but, unlike on Earth, there are no GPS satellites nor radio beacons available to constrain the accumulation of position error due to the integration of noisy and biased inertial data during dead reckoning. Close to the ground, an embedded radar senses the height and the horizontal velocity using the Doppler effect to ensure soft landing, but it cannot correct the horizontal position drift with respect to the targeted landing site [2]. On missions flown up to date, the length of the major axis of the landing ellipse is of the order of a kilometer on the Moon, and tens of kilometers on Mars if guided atmospheric entry is performed [3]. These performances are not sufficient for pinpoint landing.

Pinpoint landing requires autonomous and accurate absolute terrain navigation with a dedicated sensor. The sensor plays the role of the astronauts' eyes during the Apollo missions. The data coming out of it is matched with an on-board map to estimate the pose, i.e. the position and orientation, of the vehicle with respect to the global frame of the planet in which the landing site was designated. Error contributions from guidance and control account for less than 3 m, which is usually negligible compared to the pose estimation uncertainty [5]. Thus at first order, the 100-m pinpoint landing requirement can be translated into a 100-m absolute terrain navigation error requirement. To achieve this accuracy, both active or passive sensors have been proposed. Active sensors such as altimeters or lidars have a limited range which is related to the available power on board. They are also mainly useful for measuring topography gradients, and cannot be exploited for navigation over flat terrains [6–8]. On the contrary, passive cameras are able to operate at any distance from an illuminated terrain, and are not dependent on the topography. Furthermore, cameras can come at lower mass and cost than active sensors, and their use for planetary landing was already validated by NASA on the Mars exploration rovers in 2004 when it replaced the traditional Doppler radar for horizontal velocity estimation [9]. As most missions need to land in daylight areas due to payload power generation constraints, the requirement for a passive sensor to have a sunlit terrain is not considered an onerous constraint. The absolute terrain navigation system proposed in this paper is based on a camera.

1.2. Reference mission: pinpoint landing at the lunar south pole

The ESA lunar lander is a mission project by the European Space Agency, for which the key science objectives are to analyze the plasma and dust environments at the south pole of the Moon to prepare for human exploration, as well as to look for resources [10,11]. This is the first planetary robotic exploration mission to call for a pinpoint landing. The lunar lander can only survive in daylight by relying on its solar panels as a power source and thus the candidate landing sites are the very few peaks in the mountainous lunar south pole area which are continuously illuminated for several months. These illuminated areas are small, in the order of 100 m in radius and hence drive the need for precision landing [12]. This mission was selected as the reference test scenario for vision-based navigation in this paper.

Fig. 1 shows the reference scenario of a lunar descent. The spacecraft is on Low Lunar Orbit (LLO) at 100 km of altitude when it commits to descent with a Descent Orbit Insertion burn (DOI). Thereafter, it starts coasting along a half ellipse down to a 15-km altitude where Powered Descent is Initiated (PDI). The powered descent braking phase lasts about 10 min and aims at cutting the orbital velocity before the Approach Gate (AG). The target landing site is visible during most of the approach phase, between High Gate (HG) and Low Gate (LG). The terrain can be analyzed for hazards and the guidance system will proceed to a retargeting if necessary. It will finally command a final vertical descent at Terminal Gate (TG) above a safe area for TouchDown (TD).

Absolute visual navigation may be employed from LLO to TG. It starts to be important on orbit as DOI burn errors propagate through the descent phase resulting in a high fuel penalty if they are to be corrected at PDI. Therefore the more accurately the DOI burn can be performed, the more efficiently the landing can be executed. Absolute visual measurements are crucial during the braking phase as the main engines firing on full thrust can lead to a rapid and large accumulation of position errors without accurate navigation and guidance feedback. The use of IMU measurements only during this phase can be hampered by errors accumulated due to the effects of engine induced vibrations. Finally, map-based camera measurements may still be used during approach. Indeed the closer to touchdown that the navigation sensor can operate and provide good measurements, the more accurate the landing.

There are two key moments of a lunar descent when absolute visual navigation is required but the scene has a significant 3D aspect: at DOI and at low altitude. At DOI, the terrain appears spheric and not flat in the field of view of a landing camera on orbit. At low altitude the camera perceives the relief of the lunar south pole [13].

This lunar scenario is representative of landing on a body with no atmosphere. We shall note that the time window to perform absolute terrain navigation and trajectory correction is significantly shorter on planets which do have an atmosphere. Indeed the lander must then go through an entry phase during which the terrain sensor is necessarily covered by a heat shield and no data is acquired. In a standard Mars scenario, there is less than two minutes between the moment the sensor starts to see the ground after the heat shield is jettisoned and the actual touchdown [14]. Dust and clouds might also be an issue on planets with an atmosphere.

1.3. Related work

Absolute visual navigation relies on a terrain map usually built from orbital images and Digital Elevation Models (DEM) of the landing area acquired before the mission. It can be divided in two steps: