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# A multilayer perceptron hazard detector for vision-based autonomous planetary landing

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**Abstract**

A hazard detection and target selection algorithm for autonomous spacecraft planetary landing, based on Artificial Neural Networks, is presented. From a single image of the landing area, acquired by a VIS camera during the descent, the system computes a hazard map, exploited to select the best target, in terms of safety, guidance constraints, and scientific interest. ANNs generalization properties allow the system to correctly operate also in conditions not explicitly considered during calibration. The net architecture design, training, verification and results are critically presented. Performances are assessed in terms of recognition accuracy and selected target safety. Results for a lunar landing scenario are discussed to highlight the effectiveness of the system.


*Keywords:* Autonomous landing; Hazard detection and avoidance; Artificial Neural Networks

## 1. Introduction

In recent years, a renewed interest in space exploration had brought to the development of several missions in which the Entry Descent and Landing phase fulfills a critical role. Such phase can be often considered as a bottleneck in space missions: a failure encountered during the landing would lead with high probability to the complete loss of the spacecraft. In these cases, safety is the main driver in mission analysis and design process. Historically, high uncertainties in attainable position at touchdown had always imposed severe requirements on the landing site choice. The selection process is very complex, with the strong limitation of fitting the absolute landing site dispersion ellipse in a safe area (Masursky and Crabill, 1976; Arvidson et al., 2008; Spencer et al., 2009; Golombek et al., 2012; Ulamec et al., 2015). In spite of that, in many cases scientifically relevant places are associated with hazardous terrain features or confined in small areas; in other cases there is no possibility to completely characterize an interesting region with the required accuracy. The possibility to adapt the trajectory during the descent would reduce the landing dispersion, making possible the execution of absolute correction maneuvers. At the same time, in conjunction with the capability to distinguish hazardous from safe landing areas, the safety criteria during the mission analysis could be relaxed, leaving to the system the task of hazard detection and avoidance (HDA). Such a system should be able to scan the area around the landing site, to verify if the nominal target can be reached with the required level of safety and, if not, to seek for an alternative safe and reachable one. Then, a new relative landing path toward the updated target should be computed, followed by the execution of a divert maneuver avoiding in this way local obstacles and slopes.

Hazard detection studies were carried out in parallel with the development of affordable trajectory computation

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methods. One of the first systems capable of retargeting was introduced in the Apollo Program: in that case, the target selection relied on human intervention (Klumpp, 1974). In subsequent years, with the increase of the available computational power, more complex and optimal guidance algorithms were investigated. A derivative of the Apollo lunar descent guidance was later proposed by Wong et al. (2002) for the Mars Science Laboratory (MSL), while another variant of this explicit scheme based on a polynomial formulation of the acceleration – called *E-Guidance* – has been recently considered by Parreira et al. (2007) to accomplish HDA tasks. Direct numerical methods for trajectory optimization were widely investigated, not requiring the explicit consideration of the necessary conditions and with better convergence properties (Betts, 1998). These methods were used together with Chebyshev pseudospectral techniques, to allow the reduction of the number of the optimization variables (Fahroo and Ross, 2002). Açikmeşe and Ploen (2007) considered convex programming to guarantee the convergence of the optimization; this approach, coupled with direct collocation methods, has proved that the size of the region of feasible initial states, for which there exist feasible trajectories, can be increased drastically (more than twice) compared to the traditional polynomial-based guidance approaches, but at the price of a higher computational cost. This method was coupled with a minimum-landing-error approach, in order to compute a landing trajectory even in case a feasible solution for the selected landing site is not found (Blackmore et al., 2010). Lunghi et al. (2015) extended the polynomial formulation leaving a limited number of parameters free to obtain a suboptimal solution and to cope with trajectory constraints, maintaining at the same time a light computational weight. Wibben and Furfaro (2016) augmented a zero-effort-miss/zero-effort-velocity with sliding mode control to obtain a guidance algorithm robust to uncertainties.

Investigations on hazard detection algorithms followed a similar development. Early studies on HDA systems exploited very simple principles: Pien (1991) considers local variance over an intensity image as criterion to estimate surface roughness, together with surface major irregularities detection performed by a scanning ranging laser. Later, the development of more powerful systems and specialized hardware paved the way to the development of more complex and accurate hazard detection methods. In the frame of the autonomous landing and hazard avoidance technology (ALHAT) project, carried out by NASA since 2006, extensive studies have been conducted on the hazard estimation based on a Digital Elevation Map (DEM) obtained by active ranging sensors, such as Doppler LIDAR and flash LIDAR, as shown by Trawny et al. (2013). A proposal to include also scientific criteria in the selection process is done by Furfaro et al. (2012) exploiting soft computing techniques. Other methods to reconstruct a DEM of the landing area through image processing techniques, such as shape from shading (Parreira et al., 2008), stereo-vision (Woicke and Mooij, 2014) and shadow analysis (Matthies et al., 2007) have been widely investigated.

Four main criteria concur to determine if a landing site can be classified as safe: visibility by sensors, surface roughness, slopes, and size of the safe area. Areas that cannot be analyzed by the sensors system should be classified a priori as unsafe; considering systems based on visual information, areas in shadows are included in this category. At the same time, the actual architecture of the lander touchdown system (legs, airbags), determines which are the maximum allowed dimensions of local obstacles and slopes that maintain the probability to avoid damages over tolerable values. Finally, the landing site dimension must be compatible with the lander footprint plus expected uncertainties due to Guidance, Navigation and Control (GNC) system. Plus, also if a target is found safe, it could be impossible to be reached, due to the limited control authority of the spacecraft. Then, also the probability to find a feasible trajectory to the target should be taken into account in the selection process.

Recently our research group proved the feasibility of an HDA system based on Artificial Neural Networks (ANNs) (Lunghi and Lavagna, 2014). ANNs appear particularly attractive for their generalization properties: in fact, once trained with proper data, this kind of systems is able to autonomously determine "fading" rules that describe the phenomenon under investigation (Hornik, 1991). This property is very relevant for hazard detection. In fact, during algorithms development, it is impossible to consider in advance all the types of terrain morphological structures that a landing spacecraft could potentially deal with during operations. At the same time, ANNs working principle relies on a long series of elementary mathematical operations (sums and multiplications), giving them a high computational efficiency, compatible with real-time systems.

In this paper, a major step in the development of an affordable ANN-based hazard detection system is presented, with an optimized architecture and the development of a full objective method to train and test the system. It is assumed that the system receives as input only images from a monocular camera and some basic telemetry, including spacecraft altitude and attitude. The aim is to demonstrate the robustness and the effectiveness of a neural networks based system with minimal available information. In a real case, ANNs can be provided with additional input from different sources (LIDARs, feature tracking systems, stereo cameras etc.), making the system even more effective.

The paper is structured as following: first, in Section 2, the system architecture is described; two different structures of ANNs are considered. Then, the generation of ground truth models for system training and validation are explained in Section 3, and obtained results and performances are assessed in Section 4. Finally, conclusions and suggestions on future developments are expounded.