Landing Dispersion Analysis for Hazard Avoidance Capable Flight Systems

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Introduction

Hazard detection and avoidance (HDA) capability – realized through dedicated imaging sensors, control authority and adequate propulsive capability – is regarded as a key enabler for a safe access to topographically challenging landing sites. It thus enlarges the set of meaningful and scientific important sites. On the other hand this technology comes at the price of significant added design and qualification effort as well as its share in the system's overall mass and power budgets allocation.
To support landing site assessments of such systems and to facilitate trade studies between the potential HDA architectures versus the yielded probability of safe landing for a site of interest already in early mission study phases, a stochastic landing dispersion model has been developed. Hereby the HDA maneuver is modeled as a stochastic decision process based on Markov chains to map an initial dispersion at an arrival gate to a new dispersion pattern affected by the divert decision-making and system constraints. This model approach allows for a quick implementation of different architecture options or landing scenarios and is regarded complementary to the "classical" high-fidelity engineering simulator approach.
This poster outlines the modeling techniques and describes its application to landing site and system studies.

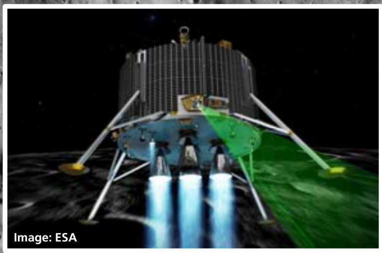
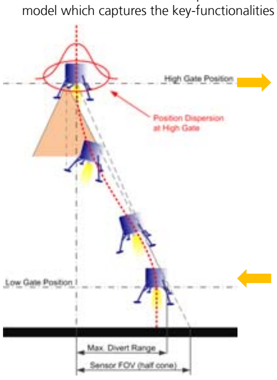


Image: ESA

Rationale & Problem Statement

The landing site assessment as part of the mission engineering process requires an analysis of the probabilities of terrain related failures. The state-of-art for open-loop flight systems (e.g. Mars Phoenix [1]) is the superposition of landing dispersion ellipses on terrain maps to make such probability estimates of an encounter with certain terrain features. In case of HDA-equipped flight systems the terrain properties „drive" the dispersion pattern.
The current state-of-art technique shall be supplemented by a suitable model which captures the key-functionalities of an HDA-subsystem.



Grid decomposition of landing area with „per grid-cell" initial likelihood p_0 to land in that area.
This is the state of the art method for current landing missions.

Need to propagate initial dispersion pattern to post HDA maneuver pattern, such as:

$$p_1 = T \cdot p_0$$

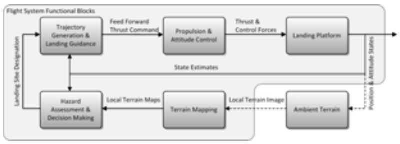
Idea: use (Semi-) Marcov chains.
This method requires a transition matrix T, which captures the flight system technical properties.

Math. Method and Model Fidelity

The macroscopic dispersion pattern is determined by the site selection of the onboard decision-making entity. HDA subsystem key functionalities considered are:

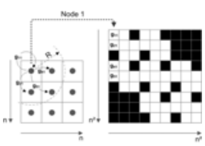
- Terrain Mapping (sensor FOV, sensor errors),
- Trajectory Generation (considering Time-to-go, propulsion constraints)
- Hazard Assessment & Decision-Making (Cost or Score Function, error propagation into the divert-decision)

Not considered: Inner loops of the control cascade and thus the „fine dispersion" around the commanded trajectory is neglected.



Modelling Visibility & Divert Range Constraints

The landing area is resolved by n × n grid. From each node and at height H certain other positions are in view / range R (see figure right). An n² × n² adjacency matrices store the visibility and divert range capabilities. The terrain properties Slope, Roughness as well as Shadows visible within the field of view determine the hazard situation as seen from each position (node). The hazard map is the base for a divert decision. The full mathematical framework is published in [2].

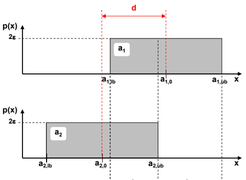


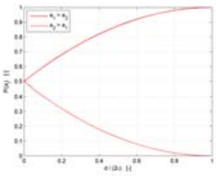
Decision Making under Uncertainty

Relevant for HDA: what is the likelihood that actually the safest spot is targeted and which are the odds that a less safe spot is mistakenly selected as safest spot?

Example

A score value measures the safety of a particular spot through a score or cost criterion. For example two alternatives a_1 and a_2 are assumed. The alternative a_1 is the truly better choice (score $a_1 > a_2$). In an ideal world with absence of any measurement errors it is certain that a_1 is targeted. In the presence of errors the score values become random numbers here assumed as rectangular distrbution (Figure below, left). The width of the interval is determined by the sensor error propagation through the score or cost function.
The probability that a_1 is correctly identified as best alternative and the probability that a_2 is incorrectly chosen as best alternative depends on the difference d between their nominal values (Figure below, right).





$$P(a_1 > a_2) = P(a_1 \in I_1) + P(a_1 \in I_2) \cdot P(a_2 \notin I_2) + P(a_1 \in I_2) \cdot P(a_2 \in I_2) \cdot P(a_1 > a_2)$$

$$P(a_2 > a_1) = P(a_1 \in I_2) \cdot P(a_2 \in I_2) \cdot P(a_2 > a_1)$$

Application Example

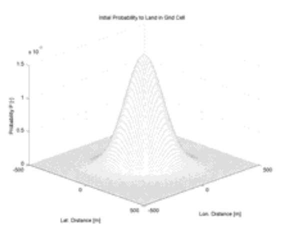
Flight System

This section shows an illustrative example of the application of the stochastic HDA model. A generic case study has been set up, assuming a medium sized, robotic landing system. The specific functional and performance properties taken as input to the model are tabulated below. The landing scenario assumes here one decision gate at the High Gate position at 1000m height above the surface.
Two variants A and B of this scenario are calculated differing only in the illumination conditions.

Parameter	Value
Landing Site Coordinates Lat/Lon [°] (Lunar SP »Connecting Ridge«)	-89.442 / -137.298
Mean of Initial Dispersion at HG (X_0, Y_0) [m]	(0, 0) (1)
Along Track Error (3σ) at High Gate [m]	360
Cross Track Error (3σ) at High Gate [m]	240
Ground Track Azimuth [°]	180
Divert Distance Capability, omnidirectional [m]	170 (2)
LIDAR Field of View [°], resolution [px]	20, 700x700
Slope Determination Error [°]	2.5 (2)
Roughness Determination Error [m]	0.35 (2)

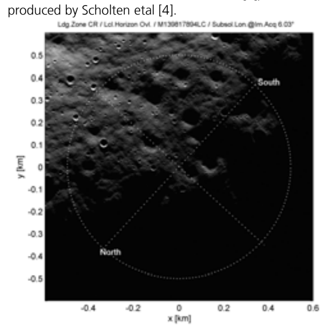
(1) Centered at nominal landing site coordinates
(2) At 1000m above the surface

Navigation Precision / Initial Position Dispersion

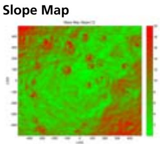


Landing Site Characterization

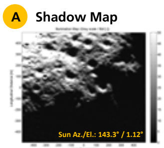
The application example uses a digital terrain model (DTM) of the Lunar South Pole site »Connecting Ridge«. This site is a candidate for the ESA Lunar Lander [3]; the DTM was produced by Scholten etal [4].



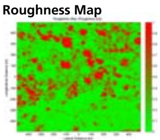
Slope Map



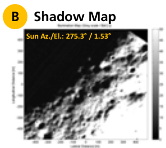
A Shadow Map



Roughness Map



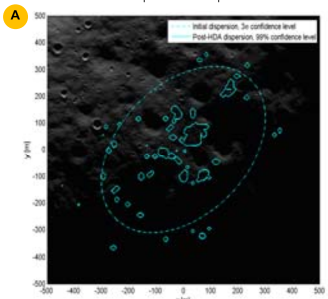
B Shadow Map



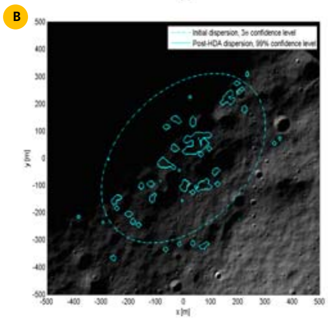
Landing Dispersion Pattern

The landing position dispersion pattern is obtained by propagating the initial dispersion pattern through the transition matrix to the post-HDA dispersion.

A



B



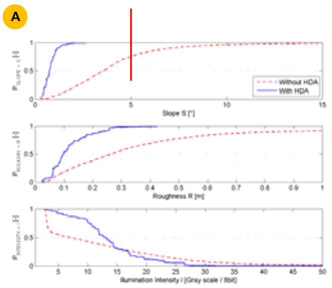
HDA-System Effectiveness

The effectiveness of an HDA architecture and the landing safety gain compared to the non-HDA case is measured by the probability to encounter a potential hazardous terrain property.

Example A:

The probability to land on a 5° or less sloped position improves from **74.9% (w/o HDA)** to **99.9% (with HDA)**.

A



Conclusion

In this poster a stochastical model to estimate the landing dispersion of a landing system with HDA functionality is presented. It considers the macroscopic dispersion from the safe site selection in the decision-making entity of the vehicle. The overall concept extends the stochastical analysis methods already used for the purpose of landing site assessment.
The use of this method is however deemed either in an early mission study phase to analyze mission requirements or system baselines and their effect on the risk of terrain related failure, or in later study phases and, after being validated by or calibrated against high-fidelity simulations, as efficient tool to demonstrate landing success probabilities by analysis.

References

[1] E. Bonfiglio et.al., Landing Site Dispersion Analysis and Statistical Assessment for the Mars Phoenix Lander, Journal of Spacecraft And Rockets, Vol. 48, No. 5, September – October 2011 , doi: 10.2514/1.48813
[2] Witte, L., Stochastic Modeling of a Hazard Detection and Avoidance Maneuver – The Planetary Landing Case, Reliability and System Safety 119 (2013) 259-269, doi: 10.1016/j.ress.2013.06.033
[3] D. De Rosa et al., Characterisation of potential landing sites for the European Space Agency's Lunar Lander project. Planetary and Space Science (2012), doi:10.1016/j.pss.2012.08.002
[4] F. Scholten, et.al, NAC_DTM_ESALL_CR1, Connecting Ridge Potential Landing Site for ESA Lunar Lander, [http://wms.lroc.asu.edu/lroc/view_rdr/NAC_DTM_ESALL_CR1], 2012