A Fuzzy Rule-Based Safety Index for Landing Site Risk Assessment

Ayanna Howard   Homayoun Seraji
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109, USA

ABSTRACT

This paper presents a Fuzzy Rule-Based Safety Index that quantifies the ease-of-landing a spacecraft on a planetary surface based on sensor-derived measurements of terrain characteristics. These characteristics include, but are not limited to, slope and roughness. The proposed representation of terrain safety incorporates an intuitive, linguistic approach for expressing terrain characteristics that is robust with respect to imprecision and uncertainty in the sensor measurements. The risk assessment methodology is tested and validated with a set of simulated data. These tests demonstrate the capability of the algorithm for perceiving hazards associated with landing on a planetary surface.

KEYWORDS: *safe landing, terrain analysis, fuzzy logic*

1. INTRODUCTION

Safe landing of a spacecraft on a planetary surface is of critical importance for the success of NASA exploration missions. The selection of an appropriate landing site for a spacecraft touchdown is therefore of fundamental significance. The current practice for site selection is only performed *off-line* in which mission scientists visually examine hundreds of pictures of potential sites obtained from previously acquired orbital imagery. Based on this examination, the appropriate site is then selected by considering both engineering and science goal criteria. For example, in selecting the Pathfinder landing site, the Ares Vallis landing site was selected because it appeared reasonably safe for landing and also offered the possibility of analyzing a variety of rock types. Landing sites are considered safe if they have minimum slope, are free of hazards, and have acceptable roughness constraints [1].

Typically, engineering criteria established for ensuring success of the mission are constructed by analyzing terrain characteristics that affect the ability of the spacecraft to land safely on a planetary surface. The roughness of the terrain and the size/concentration of rocks must be minimal. The surface slope must be within acceptable limits because the spacecraft can become unstable at certain landing angles. In most cases, the following are the major terrain-based characteristics affecting the landing site selection:

- Smoothness: Relatively few craters and boulders
- Approach: No large hills, high cliffs, or deep craters
- Slope: Less than 2° slope in the approach path and landing site

Currently, there is no comprehensive system capable of real-time terrain risk assessment necessary to enable a safe spacecraft touchdown on a planetary surface. To address this issue, a robust rule-based technique is presented for determining terrain quality using sensor-derived measurements of multiple terrain characteristics. Based on the physical properties of the terrain, the suitability of the terrain for landing is inferred using a Fuzzy Rule-Based Safety Index. The following sections describe this algorithm in detail. Section 2 describes the terrain assessment algorithms. Section 3 describes the Fuzzy Safety Index and Section 4 presents typical test results.

2. TERRAIN CHARACTERISTICS

To enable autonomous spacecraft touchdown on natural terrain, the risk associated with landing must first be evaluated. This is accomplished by identifying the underlying surface characteristics that directly contribute to landing difficulty. The terrain characteristics associated with ensuring spacecraft survivability and mission success are determined by analyzing the following engineering criteria used in evaluating the safety of prospective landing sites [2]:

- *Elevation*
  - Spacecraft subsystems (aeroshell, parachute, etc.) constrain the maximum elevation acceptable for the landing site. For example, the spacecraft needs adequate time to stabilize the parachute before touchdown or there must be sufficient time available to separate the Lander from the backshell. As such, a site is considered safe if it is positioned below a predetermined elevation level.
- *Latitude*
  - The surface latitude affects the performance of the spacecraft thermal control and solar power systems. Latitudes located farther from the subsolar latitude require additional power for heating to maintain thermal balance. Thus, the latitude constraint becomes dependent on the energy and temperature profiles required by the system.
- *Dust*
  - The accumulation of airborne particles onto solar panels and spacecraft instruments can potentially limit the power output and expected data return, therefore reducing mission lifetime. This can lead to situations in which mission success cannot be realized due to power unavailability.
- Slope
  - Extreme tilts of the surface with respect to the spacecraft can aversely impact science operations and data return. The spacecraft can also become unstable at certain landing angles, thus causing situations in which the spacecraft may inadvertently tip over.

- Roughness
    - Impact on sharp, angular rocks can cause spacecraft failure in that the spacecraft's support structure can snap, or supporting air bag material can rip. An acceptable rock density, or roughness factor, is constrained by the probability calculated for landing on a rock of a given height.

In analyzing the terrain characteristics associated with landing site risk assessment, we have chosen to focus on two primary features: namely slope and roughness characteristics of the surface.

2.1 Terrain Assessment

We define terrain roughness as the irregularity of the surface upon which the spacecraft is to land. Slope is accordingly characterized as the average incline/decline of the corresponding ground plane. For analysis of the terrain, we have chosen to utilize data extracted from a Lidar sensor. The Lidar sensor provides range data that can be converted into an elevation map for extraction of terrain characteristics such as slope and roughness. The derived elevation data is used to extract slope and roughness characteristics of the terrain using a least-squares plane fitting algorithm [3]. The slope of the plane which best fits the elevation points is used as the terrain slope value and the roughness is then computed as the residual of the fit. In order to compute values for the safety index, the terrain characteristics are first converted into a linguistic representation using fuzzy logic sets. The roughness is represented by the linguistic fuzzy sets *{SMOOTH, ROUGH, ROCKY}* with the membership functions shown in Figure 1. The terrain slope parameter is converted into the linguistic representation *{FLAT, SLOPED, STEEP}* with the membership functions shown in Figure 2.

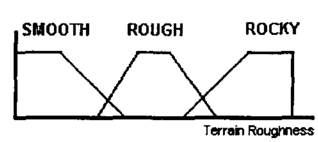

Figure 1. Terrain roughness fuzzy sets

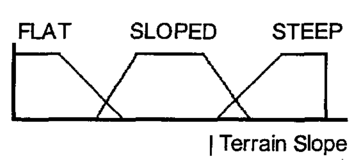

Figure 2. Fuzzy membership functions for slope

Figure 3 shows a sample terrain image and the corresponding fuzzy slope and roughness parameters calculated by the algorithm. In the slope image, black denotes steep regions of the terrain, gray denotes sloped terrain, and white denotes flat areas. In the roughness image, rocky is denoted by black pixels, gray denotes rough areas, and smooth is denoted by white areas.

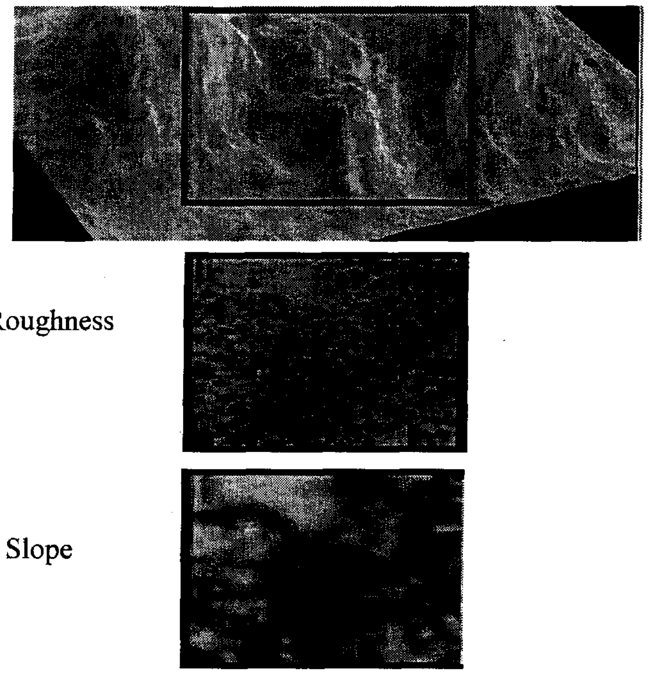

Figure 3. Top: terrain image, Bottom: associated roughness and slope terrain characteristics

3. FUZZY RULE-BASED SAFETY INDEX

Once the characteristics of the viewable scene are extracted, the terrain safety must be assessed and classified. To accomplish this task, we have developed a set of fuzzy logic rules which classify the safety of the terrain based on the characteristics present in the given sensor data set. The Fuzzy Rule-Based Safety Index thus obtained succinctly quantifies the ease-of-landing a spacecraft on the terrain based on the terrain physical characteristics.

Fuzzy logic [4] provides a powerful tool for modeling the relationship between input and output information and is distinguished by its robustness with respect to noise and variations in system parameters. Linguistic fuzzy sets and conditional statements allow fuzzy systems to make decisions based on imprecise and incomplete information. Fuzzy logic can inherently handle the uncertainty in data and can emulate the imprecision that exists in a natural language. Fuzzy logic allows the management of heuristic rule base knowledge, imprecise information from sensors, and the uncertainty in the knowledge about the environment.

In order to assess terrain safety, the terrain characteristics are first converted into linguistic representations using fuzzy sets. These sets allow the terrain characteristics to be represented based on *grades* of membership, as opposed to the conventional 0 or 1 value. The membership functions of these sets are then used in a set of fuzzy rules to infer terrain safety. The output from the rule base is the Fuzzy Safety Index which represents the relative level of safety associated with landing the spacecraft on the surface. This index is represented by the linguistic fuzzy sets *{POOR, LOW, MEDIUM, HIGH}*. These fuzzy sets correspond, respectively, to the four terrain classifications *{UNSAFE, MODERATELY-UNSAFE, MODERATELY-SAFE, SAFE}*. By utilizing fuzzy logic, a mission engineer can specify rules that are not dependent on *exact* measurements of the terrain characteristics, thus allowing *robust* analysis of the terrain. The rule-based definition of the Safety Index in terms of terrain slope and roughness is summarized in Table I[1].

Slope	**Roughness**	**Safety Index**
FLAT	*SMOOTH*	*HIGH*
FLAT	*ROUGH*	*MEDIUM*
SLOPED	*SMOOTH*	*MEDIUM*
SLOPED	*ROUGH*	*LOW*
	ROCKY	*POOR*
STEEP		*POOR*

Table I. Rule base for Fuzzy Safety Index

4. EXPERIMENTAL RESULTS

For testing purposes, sensor data is retrieved by imaging simulated terrain environments. Figure 4 shows two typical example images and the derived output representing the Fuzzy Safety Index. In the images, dark-gray denotes UNSAFE regions of the terrain and light-gray denotes SAFE areas. Gray colors in-between represent the range of safety values.

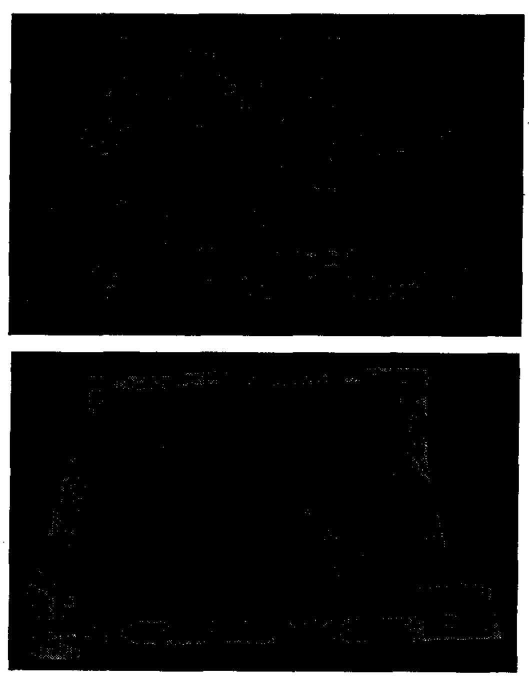

Figure 4. Risk assessment output overlaid on terrain.

[1] Empty fields in the fuzzy rule base indicates the specified input parameter has no effect on the rule outcome.

5. CONCLUSIONS

This paper presents a methodology for real-time risk assessment for spacecraft touchdown on a planetary surface. The implementation of the fuzzy logic assessment algorithm is shown to provide a natural framework for representing the characteristics of the terrain. The proposed safety classification method is particularly suitable for spacecraft, which have limited on-board computing power and carry imprecise sensors. Through simulation tests, it is shown that this methodology can lead to a simple assessment algorithm capable of real-time computation of landing site safety. In addition, the structure of this methodology allows the robust incorporation of additional terrain characteristics. Future work involves integrating other terrain features into the risk assessment process.

6. ACKNOWLEDGMENTS

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