A Novel Information Fusion Methodology for Intelligent Terrain Analysis

Ayanna Howard
NASA-Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109, USA

Abstract. This paper presents a novel information fusion methodology for intelligent terrain analysis. In our application, we define information as terrain characteristics derived from sensor data extracted from on-board spacecraft sensors. The fuzzy-logic construct allows us to represent the terrain characteristics using an easily understandable, linguistic approach. Once derived, these fuzzy terrain characteristics are blended together using a fuzzy rule base to produce a coherent representation of terrain safety. The fused information is then used to autonomously select a safe landing site for spacecraft touchdown. The fuzzy terrain analysis and fusion methodology is explained in detail in this paper. Computer simulation results are provided to show the viability of the approach.

I. INTRODUCTION

In future NASA exploration missions, safe landing of a spacecraft on an unknown planetary surface is of significant importance. Landing sites must be analyzed during spacecraft descent to verify the ability of the spacecraft to land safely on the planet's surface. This analysis must be performed in real-time, while ensuring robustness with respect to noise and variations in system parameters. In determining the ideal landing site location, major terrain-based characteristics that affect the safety of the spacecraft must be assessed. A safe site must have relatively few craters and boulders, possess no large hills, high cliffs, or deep craters, and have less than 20° gradient slope [1].

In order to intelligently analyze the terrain to ensure a safe spacecraft landing, data from multiple heterogeneous sensors must be utilized by the system. Fusing this diverse data, which is extracted from sensors having different field-of-views, resolution, pointing location, and data representations, requires a fusion methodology capable of robustly handling the variations in multiple sensor devices. Fuzzy logic [2] provides a flexible 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. As such, our approach models terrain information using a fuzzy representation that allows the integration of imprecise sensor data extracted from multiple sensors. The fusion of this fuzzy terrain information allows the system to robustly analyze the safety associated with a spacecraft touchdown on a planetary surface.

The following sections are arranged as follows. Section 2 discusses the issue of deriving fuzzy terrain information from sensor data. Section 3 explains how the terrain information is blended together to provide a coherent representation of terrain safety and Section 4 provides example results from a computer simulation used to test the algorithm.

II. INTELLIGENT TERRAIN ANALYSIS

In our application, we have focused on using two sensors to obtain terrain information: namely camera and lidar sensors. Each sensor images the planet's surface and data values are collected based on terrain features. The data values are used to intelligently evaluate the physical characteristics of the terrain, as discussed in the following sections. These derived terrain characteristics are then used to compute the terrain safety map, which represents the difficulty of the terrain for spacecraft landing. The terrain map is represented by a grid of cells in which values are represented by the linguistic fuzzy set {*SAFE, RISKY, VERY-RISKY, UNSAFE*} and the membership functions shown in Figure 1. The terrain safety information (extracted from the different sensor devices) is then blended together by the fusion algorithm in order to provide a unified assessment of the terrain.

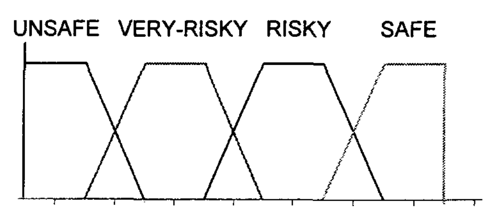


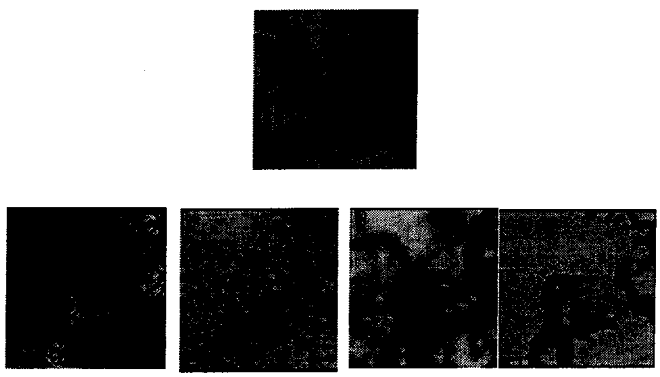
Figure 1. Membership functions representing difficulty of terrain for landing

A. Deriving Terrain Information from Active Sensors

The lidar sensor provides range data that is subsequently converted into an elevation map for extraction of terrain characteristics. 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 plane fit. Once calculated, the slope and roughness values are fed into a fuzzy-logic rule base [4] to compute values for the terrain safety. The roughness is represented by the linguistic fuzzy set *{SMOOTH, ROUGH, ROCKY}* whereas the terrain slope parameter is represented by the fuzzy set *{FLAT, SLOPED, STEEP}*. The membership functions of these sets are input into a set of fuzzy logic rules (Table I) used to construct the terrain safety map. Figure 2 shows example images of computing the terrain safety using this fuzzy-logic construct.

Slope	Roughness	Terrain Safety Information
FLAT	SMOOTH	SAFE
FLAT	ROUGH	RISKY
SLOPED	SMOOTH	RISKY
SLOPED	ROUGH	VERY-RISKY
STEEP		UNSAFE
	ROCKY	UNSAFE

Table I. Fuzzy rule base for terrain safety map construction[1]



(a) (b) (c) (d)

Figure 2: First row: terrain; Second row: (a) elevation map, (b) roughness map, (c) slope map, (d) terrain safety map[2].

B. Deriving Terrain Information from Passive Sensors

We extract terrain information from camera sensor data by utilizing a simple texture-based algorithm [5] that determines roughness based on average pixel intensity variations for a given region. In essence, the rougher the surface area becomes, the larger the increase in the pixel variation value. We represent roughness using the linguistic fuzzy set *{SMOOTH, ROUGH, VERY-ROUGH, ROCKY}*. Furthermore, since terrain roughness is directly related to terrain safety, we can use Table II to convert the calculated roughness values to an equivalent terrain safety representation.

Roughness	Terrain Safety Information
SMOOTH	*SAFE*
ROUGH	*RISKY*
VERY-ROUGH	*VERY-RISKY*
ROCKY	*UNSAFE*

Table II. Table relating roughness to terrain safety

III. INFORMATION FUSION METHODOLOGY

There are several research efforts focused on multi-sensor data fusion [6], with a primary focus on statistical methods (Kalman Filters) and probabilistic techniques (Bayesian network). Probabilistic techniques focus on combining data from multiple sensors by using weighting factors based on how accurate the sensor data is, whereas statistical methods concentrate on minimizing errors between actual values and predicted values. In contrast, we have focused on the process of multi-sensor information fusion in which the terrain information itself, rather than the actual sensor measurement values, is integrated together to provide a coherent representation of terrain safety.

To perform the information fusion process, we must first align the terrain maps so that they reference the same viewable areas of the terrain surface. This is accomplished by using a data transformation process that accounts for variations in sensor operating parameters such as different fields-of-view, resolutions, and pointing locations, and thus allows the formation of a map that represents a global view of the terrain. The data transformation process uses a combination of rotation, translation, and scaling in order to correctly align the different terrain information sets. Once transformed, individual maps are then combined into a fused representation of the terrain.

A. Data Transformation

The first step in the data transformation process is to calculate the centroid offset of each sensor's terrain map based on sensor pointing direction. This is accomplished using the following equations:

$$o_y = h \tan\theta_y + o_y'$$

$$o_x = h \tan\theta_x + o_x'$$

where (θ_x, θ_y) is the angle offset of the sensor from the spacecraft normal, h is the distance of the spacecraft from the planet surface, (o'_x, o'_y) is the position offset of the sensor from the spacecraft reference origin, and (o_x, o_y) is the new centroid offset for each sensor. Once calculated, the sensor offset is used to translate each sensor terrain map into the same reference coordinate system by adding border grid cells

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

[2] where safe cells in 2d are represented by white, unsafe cells by black, and gray-level cells represent terrain safety values in-between.

to enlarge the image and translate the map centroid location. In this case, border cells are given values of *UNKNOWN* since terrain safety values are not actually calculated for these added cells. Once translated, each map is then scaled to equivalent resolution and size constraints. This is accomplished by enlarging each terrain safety map to account for lowest resolution and the maximum image size. Due to differences in resolution, size, and sensor offsets, data may not be available from the original map to populate the newly enlarged terrain map. In this case, newly added cells are given the value of *UNKNOWN*.

B. Information Fusion

Each terrain map is created independently of one another and generates values based on sensed data obtained from the on-board spacecraft sensors. We combine this terrain information by utilizing crisp certainty factors to create a fused representation of the terrain. We use the concept of 'behavior integration' in which recommendations from different behaviors are integrated to form a unified control action [7]. In this same way, we blend together the values derived from each sensor so that the final terrain map allows each sensor to influence the final representation. The final map values are computed using the following equation:

$$T_{i,j} = \frac{\sum_{n=0}^{S}\left(\alpha_{i,j}^{n} \sum p_{i,j}^{n} A_{i,j}^{n}\right)}{\sum_{n=0}^{S}\left(\alpha_{i,j}^{n} \sum A_{i,j}^{n}\right)}$$

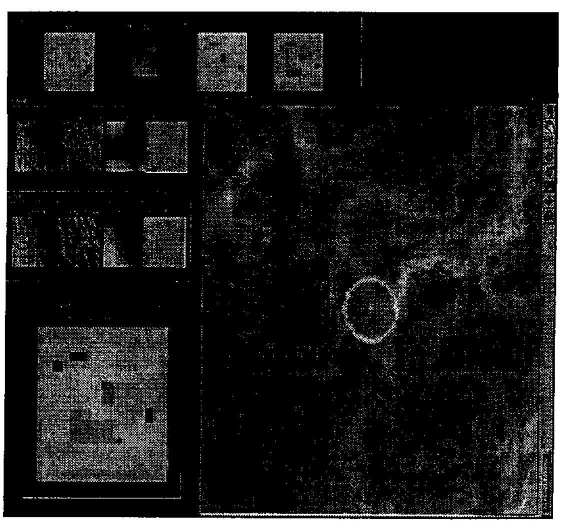
where i,j is the index of each cell in the terrain safety map, $T_{i,j}$ is the fused terrain map value computed for each cell, S is the number of on-board spacecraft sensors, $\alpha_{i,j}$ represents the certainty factor associated with each cell, $p_{i,j}$ is the peak value associated with fuzzifying the terrain map values ($t_{i,j}$) for each sensor and $A_{i,j}$ is the area under the membership function associated with the terrain safety value.

This information fusion framework allows data from additional sensors to easily be combined. Once the final terrain safety map is constructed, the fused map is used to select a safe landing site for spacecraft touchdown. In our current application, the safe landing site is chosen as the safest site located near the current landing location.

IV. EXPERIMENTAL RESULTS

A graphical simulation for controlling a spacecraft landing on a planetary terrain was used to simulate the descent and landing phases of a spacecraft touchdown. This simulation package is used for evaluation and testing of the fuzzy terrain analysis and information fusion approach. The visualization tool can incorporate a wide variety of Digital Elevation Models (DEMs) that represent different terrains and automatically updates current spacecraft dynamic parameters during EDL[3] operations. Figure 3[4] shows results from a spacecraft landing simulation run on a sample Mars terrain while Figure 4 provides a close-up of the corresponding fused terrain map representation depicted in Figure 3a.

The sensor data and individual terrain safety maps are shown in the top left-corner of Figure 3, whereas the fused map output is displayed at the bottom left-hand corner. The terrain located on the right-side of the image shows the fused fuzzy terrain map as an overlay on the terrain, with the white circle designating the landing site location. We ran approximately 20 simulation runs on various terrain segments and observed qualitatively good performance in choosing safe landing sites. As work progresses, we will be able to provide a quantitative assessment of system performance. Based on our current efforts, we have verified that the methodology for terrain analysis and fusing information from multiple heterogeneous sensors allows the terrain assessment algorithm to perform in a robust and autonomous manner. By enabling the incorporation of a diverse set of input data from redundant and complimentary sensors, the system can reduce and correct errors that may be produced by a single sensor.



(a)

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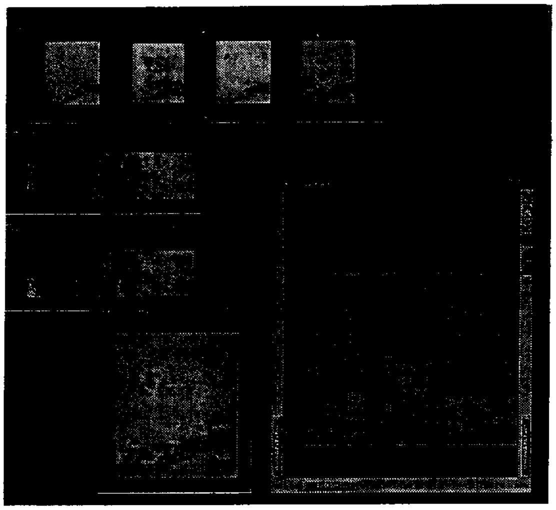
[3] Entry, Descent, and Landing

[4] where safe cells are represented by white, unsafe cells by off-black, and gray-level cells represent terrain safety values in-between.



(b)

Figure 3: Graphical simulation results: (a) initial descent profile, (b) final landing selection

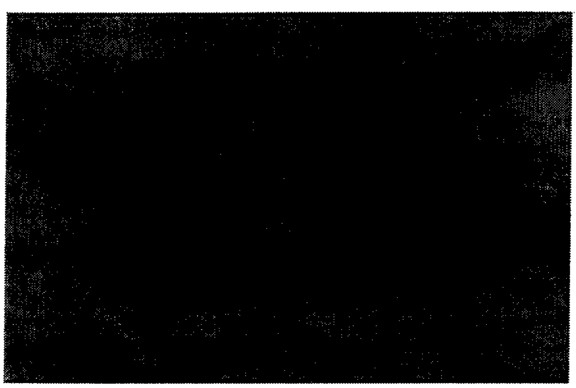


Figure 4. Close-up of fused terrain safety map overlay on terrain

V. CONCLUSIONS

This paper presents a multi-sensor information fusion methodology for intelligent terrain analysis. The fusion strategy discussed directly incorporates information regarding the terrain characteristics derived from data extracted from heterogeneous sensors. The implementation of the fuzzy logic methodology for fusing sensed data is shown to provide a natural framework for providing a unified assessment of the terrain. Through experimentation, it is shown that the integration of fuzzy logic rules for terrain assessment allows the construction of an autonomous fusion strategy for safe landing that deals with the real-world uncertainty inherent in natural environments. Future work will focus on enhancing the sensor certainty rules for fusing terrain information and incorporating additional sensor devices.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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