FUZZY-LOGIC BASED SELECTION OF SURFACE FEATURE OBSERVATIONS FOR SMALL BODY PROXIMITY OPERATIONS

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ABSTRACT

In this paper, we discuss the development of an autonomous system capable of maintaining surface feature references within sensor view by recommending spacecraft trajectory adjustments based on predefined criteria. The ability to localize with respect to terrain features is a necessary component for increasing the reliability of spacecraft position estimation during small body operations. The proposed algorithm uses the concept of fuzzy logic to maintain satisfaction of a number of feature selection criteria, which, when satisfied, allow consistent updating of feature observations. We provide details of the algorithm in this paper, and present results from integrating the algorithm into a small body descent simulator.

1. INTRODUCTION

The process of estimating a spacecraft's position during mission operations is a necessary function to ensure reliable control and maneuver capability of a spacecraft. Without accurate knowledge of where the spacecraft is, unsafe modes of operations can easily be created, resulting in surface collisions, undesirable fuel consumption levels, and/or unsafe maneuvers. One of the most successful systems for autonomously determining spacecraft position is AutoNav [1], an autonomous localization system used on Deep Space 1, which uses celestial references to determine spacecraft position. In the AutoNav system, celestial references are fixed for observation through a predefined sequence determined by on-ground personnel. In [2], Gaskell presented results from landmark-based navigation applied to an encounter with a simulated asteroid body to determine how well landmark maps could be reproduced from noisy image data and used for determining spacecraft position and orientation. In [3], a methodology for automatic feature tracking between pairs of descent camera images was presented for use in estimating rigid motion of a spacecraft during small body proximity operations. Finally, in [4], a vision system called DIMES, which used three spacecraft descent images to estimate lander velocity during planetary descent of the Mars Exploration Rover, was discussed. Although DIMES was not used to explicitly determine spacecraft position and orientation, the output from the system was used to ensure stable conditions were identified to allow spacecraft reorientation during descent.

In this paper, we focus on enabling science missions involving small body proximity operations, such as landing on a comet, asteroid flyby, etc. Due to the uncertainty in the environment, the limited communication bandwidth, and time delays, a key functional operation in these types of missions is autonomous spacecraft control. This requires the ability to autonomously localize with respect to the small body and estimate spacecraft position during small body operations. To enable this capability, we discuss a method that uses surface feature references located on the small body to recommend spacecraft trajectory adjustments necessary to maintain satisfaction of feature selection criteria, and thus maintain the capability to robustly estimate spacecraft position.

2. FUZZY FEATURE OBSERVATION PLANNER

The fuzzy feature observation planner is a system capable of selecting surface feature references, and maintaining them in sensor view, in order to provide reliable data for estimating spacecraft position. In this system, surface feature references are chosen based on four main observations: 1) surface features should maintain adequate terrain coverage (i.e. good geometric spread), 2) features should be of good quality (i.e. there should be high confidence that the features will be identifiable in subsequent sensor images), 3) there should be enough features to provide good position estimation (i.e. estimation algorithms should have enough reference points so as to minimize convergence error), and 4) features should be viewable during entire current trajectory path. The function of the planner is thus to recommend spacecraft traversal directions so as to maximally satisfy the four observations.

To develop the feature observation planner, we utilize the concept of fuzzy logic [2] to recommend directions for spacecraft motion during descent. Fuzzy logic allows us to reason about terrain features and extract corresponding adjustment rules for maintaining adequate feature coverage for spacecraft position estimation. Linguistic fuzzy sets and conditional statements allow the system to make decisions based on heuristic rule-base knowledge derived by engineering experts. Since small body operations of a spacecraft may occur over a short period of time, the computational speed of the fuzzy logic rule evaluation system involves simple arithmetic calculations that can be performed very rapidly. This allows implementation of the method to occur in real-time.

2.1 Defining Spacecraft Traversal Directions

The first step in designing the feature observation planner is to subdivide achievable x,y navigation directions into nine preferred traversal directions {NORTH-WEST, NORTH, NORTH-EAST, WEST, EAST, SOUTH-WEST, SOUTH, SOUTH-EAST, and CENTER} for the spacecraft. We assume that the z-traversal direction is based on a constant descent velocity profile. These traversal directions correspond to the following new coordinate spacecraft locations calculated in 3-D Cartesian space, as well as corresponds to a new desired landing location:

NORTH-WEST: $(x_{t-1} - \Delta x, y_{t-1} - \Delta y, z_0 + vt)$
NORTH: $(x_{t-1}, y_{t-1} - \Delta y, z_0 + vt)$
NORTH-EAST: $(x_{t-1} + \Delta x, y_{t-1} - \Delta y, z_0 + vt)$
WEST: $(x_{t-1} + \Delta x, y_{t-1}, z_0 + vt)$
CENTER: $(x_{t-1}, y_{t-1}, z_0 + vt)$
EAST: $(x_{t-1} + \Delta x, y_{t-1}, z_0 + vt)$
SOUTH-WEST: $(x_{t-1} - \Delta x, y_{t-1} + \Delta y, z_0 + vt)$
SOUTH: $(x_{t-1}, y_{t-1} + \Delta y, z_0 + vt)$
SOUTH-EAST: $(x_{t-1} + \Delta x, y_{t-1} + \Delta y, z_0 + vt)$

where $(x_{t-1}, y_{t-1}, z_{t-1})$ is the current position of the spacecraft, (x_{t-1}, y_{t-1}) corresponds to the current landing location on the surface, v is the spacecraft descent velocity, and t is the current time of descent.

2.2 Determining Spacecraft Traversal Direction

To determine a recommended traversal direction, we use a linguistic knowledge-base to calculate satisfaction of a set of feature selection rules, or criteria, for each traversal direction. Four rule sets are utilized, which are designed to satisfy the four observations mentioned above, corresponding to a *Quality* criteria, a *Quantity* criteria, a *Cluster* criteria, and a *Closeness* criteria. *Quality* determines the quality of the feature and typically corresponds to the confidence related to a frame matching criteria. For the *Quality* criteria, we prefer a selection of features having good quality, thus giving us confidence that features will be identifiable in subsequent images. *Quantity* determines the number of features resident in a specified region. We prefer a larger number of feature, thus giving us confidence that features will be present and available for matching in subsequent images. *Cluster* corresponds to the desire to have features that are in close proximity to each other, allowing for adequate geometric spread as the spacecraft descends closer to the surface. *Closeness* corresponds to the preference for minimal spacecraft adjustment, thus preferring directions in which features are clustered closest to the current designated landing location. We represent the satisfaction of feature selection criteria using a linguistic fuzzy set {POOR, GOOD, EXCELLENT}, corresponding to POOR satisfaction of criteria, GOOD satisfaction of criteria, and EXCELLENT satisfaction of criteria. The *Satisfaction* variable assumes a value in the range [0,1], with zero representing POOR satisfaction. Table I shows the rule sets linking each of the four criteria, and their corresponding *Satisfaction* output value.

Rule Set 1	
Quantity	**Satisfaction**
FEW	POOR
MEDIUM	GOOD
MANY	EXCELLENT

Rule Set 2	
Quality	**Satisfaction**
POOR	POOR
MEDIUM	GOOD
GOOD	EXCELLENT

Rule Set 3	
Closeness	**Satisfaction**
FAR	POOR
NEAR	GOOD
CLOSE	EXCELLENT

Rule Set 4	
Cluster	**Satisfaction**
DISTANT	POOR
AVERAGE	GOOD
CLOSE	EXCELLENT

Table I. Fuzzy rule base for determining criteria satisfaction

As an example, the following rule set corresponds to the Quantity criteria:

- If *Quantity* is FEW then *Satisfaction* is POOR
- If *Quantity* is MEDIUM then *Satisfaction* is GOOD
- If *Quantity* is MANY then *Satisfaction* is EXCELLENT

A satisfaction output value is computed for each rule set. Once all four output values are computed, they are fused together to provide a global satisfaction value for each traversal direction using the following equation:

$$S_i = \frac{\sum_{j=1}^{4} w_j p_{i,j} A_{i,j}}{\sum_{j=1}^{4} w_j A_{i,j}} \tag{1}$$

where i is one of the nine preferred traversal directions, j is one of the four feature selection criteria, S_i is the global satisfaction value, w_j represents the weighting factor associated with the jth criteria, $p_{i,j}$ is the degree of satisfaction (or strength) associated with the j^{th} criteria/i^{th} direction and $A_{i,j}$ is the area under the membership function associated with the satisfaction value. Figure 1 depicts combining the satisfaction values of two criteria having GOOD and EXCELLENT values, of varying strengths.

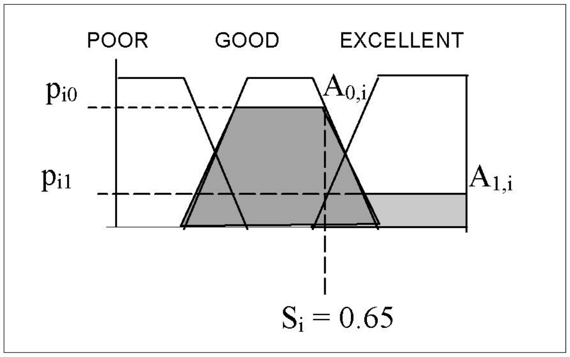

Figure 1. Combining satisfaction values for two criteria

The weighting factors used are extracted based on the current distance between the robotic spacecraft and the ground surface. The system uses adjustable weighting factors to combine recommendations provided by each criteria. The rationale for determining the weights is as follows: 1) when the spacecraft is closer to the surface, the *Closeness* criteria should increase in importance since the spacecraft has less time to maneuver, 2) the *Cluster* criteria should decrease in importance because we are near landing impact, and 3) the *Quantity* and *Quality* criteria should remain at a constant value to maintain the ability to return to a hovering position above the surface. This motivation is reflected in the following linguistic rule set:

If *Distance_to_Surface* is FAR then $Weight_{Closeness}$ is LOW
If *Distance_to_Surface* is MEDIUM then $Weight_{Closeness}$ is MED
If *Distance_to_Surface* is CLOSE then $Weight_{Closeness}$ is MED

If *Distance_to_Surface* is FAR then $Weight_{cluster}$ is HIGH
If *Distance_to_Surface* is MEDIUM then $Weight_{cluster}$ is MED
If *Distance_to_Surface* is CLOSE then $Weight_{cluster}$ is LOW

$Weight_{Quantity}$ is HIGH, at all times
$Weight_{Quality}$ is HIGH, at all times

Once the global satisfaction value is computed for each direction, the last step in the reasoning algorithm is to incorporate historic preference for direction. In other words, to minimize spacecraft jitter in the trajectory path, the system should maintain a preference to select directions that are comparable to the currently traversed direction. Thus, once a direction is recommended, subsequent recommendations must exceed a threshold as compared to the current Satisfaction value. Thus, the final recommended direction for traversal is calculated based on the following logic:

- Let k represent the previous direction of traversal
- Compute the global satisfaction value S_i for N directions
- Select the direction d associated with the maximum S_i
- If $S_d > S_k - \varepsilon$ then recommend new traversal direction d

3. SIMULATION RESULTS

The small body descent simulator allows testing/visualization of the feature observation planner, which determines recommended traversal direction to ensure sufficient feature coverage for spacecraft estimation during small body proximity operations. The small body descent simulator processes a terrain descent image and the corresponding feature set as input parameters to the feature observation planner. Given the viewable feature set, the feature observation planner determines a suitable location for subsequent spacecraft traversal, and feeds it to the simulator. The new x,y,z coordinate location of the spacecraft is then used by the descent simulator to extract the next terrain image in the descent sequence.

The original terrain image is a 1024x1024 sized image covering a surface area of 100m x 100m with 5 cm pixels. Descent images are retrieved by scaling the original image as a function of the percentage of z-distance traveled, such that:

$$\text{Pixel Size of Image at time } t_n = R_0 \frac{z(t_0) - z(t_n)}{z(t_0)} \tag{2}$$

where R_0 is the resolution of the original image, which is currently equal to 5 cm, and $z(t_0)$ is defined as 1km (Figure 5).

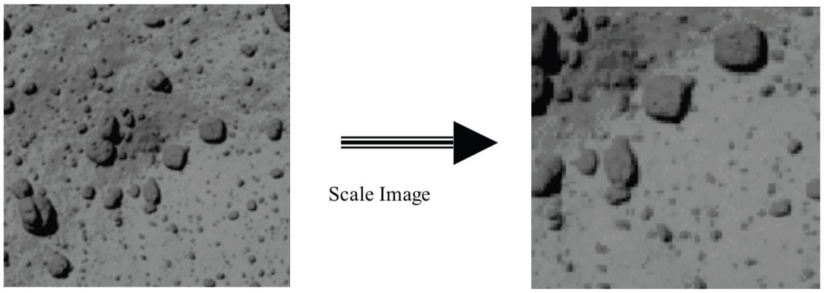

Figure 5. Scaling a descent image

The origin of the spacecraft coordinate system is specified in pixel space as the position located at the center of the original image (x,y,z) = (25.6m,25.6m,1km) = (512,512,20000). The z coordinate value is determined by translating the 1km defined height value into pixel space. This origin is also designated as the original landing site located on the small body. Subsequent images in a descent sequence are thus extracted by specifying a landing site relative to the original center. It is assumed that the new landing location can be achieved instantaneously, and that the vehicle descends to the surface at a constant z-velocity. For the simulation, each cycle is equivalent to a one second iteration and we assume that the z-velocity is equivalent to 50m/sec (or 1000 pixels/sec). After descent, the original image is translated such that the new landing location becomes the center point of the new image in the sequence (Figure 6).

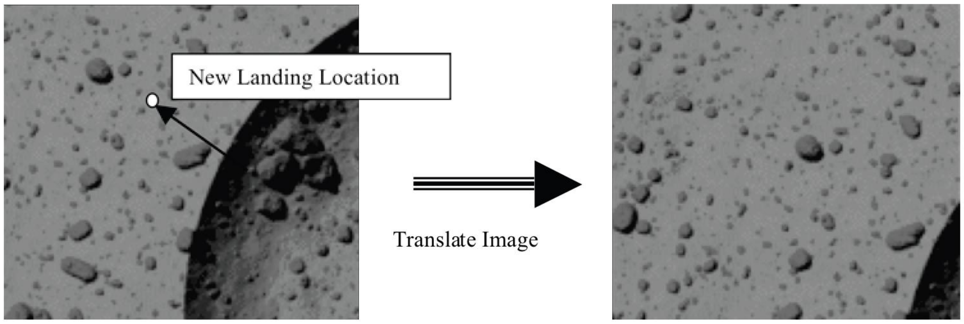

Figure 6. Translating a descent image

The feature set is currently determined by random selection at the beginning of the descent cycle. During descent, these features can be randomly removed/added to allow further testing of the robustness of the feature observation planner. Assumptions are also made that spacecraft control parameters, such as velocity, acceleration, torque, etc., are held at a constant value. These assumptions through are a limitation of the simulator in determining the visualization components of the descent sequence, and not of the feature observation planner itself.

Figure 7 depicts a snapshot of the small body descent simulator with the integrated fuzzy observation planner. The left figure displays the original terrain image, cropped to a size of 512 x 512. The right figure depicts the scaled terrain image extracted from the descent sequence, with features designated by white squares. During the descent cycle, the right image is updated to reflect the relative change in spacecraft position.

From the implementation results, our goal was to verify that the fuzzy observation planner is able to maintain surface feature references within sensor view by recommending spacecraft trajectory adjustments based on satisfaction of the four necessary criteria. By using the concept of fuzzy logic, the system should provide a robust process for the mission designer to revise criteria, modify weighting factors, and allow consistent updating of feature observations. A number of various scenarios were run, with different initial feature sets randomly determined. Figure 8 depicts snapshots of one descent sequence, with associated traversal directions recommendations by the feature observation planner in the labeled caption.

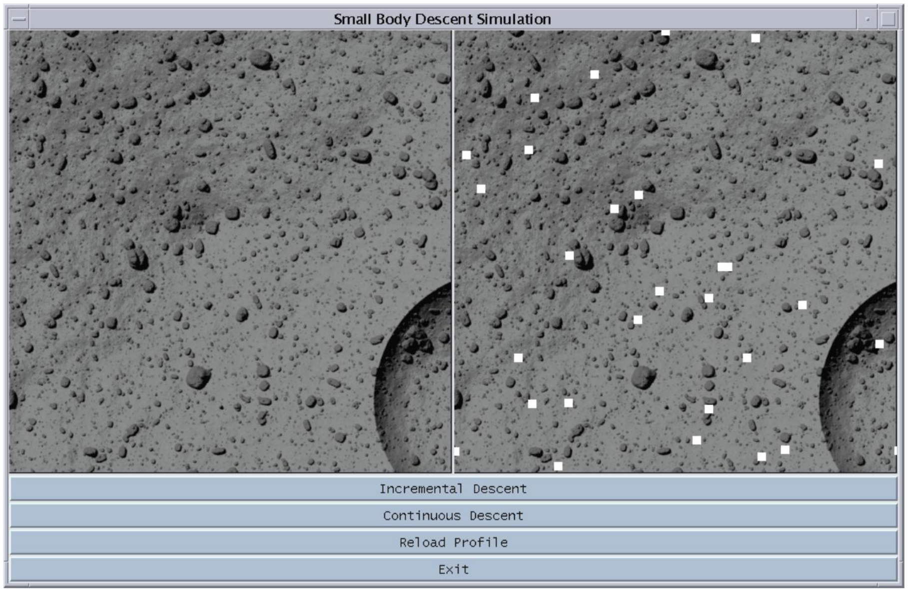

Figure 7. Snapshot of Small Body Descent Simulator

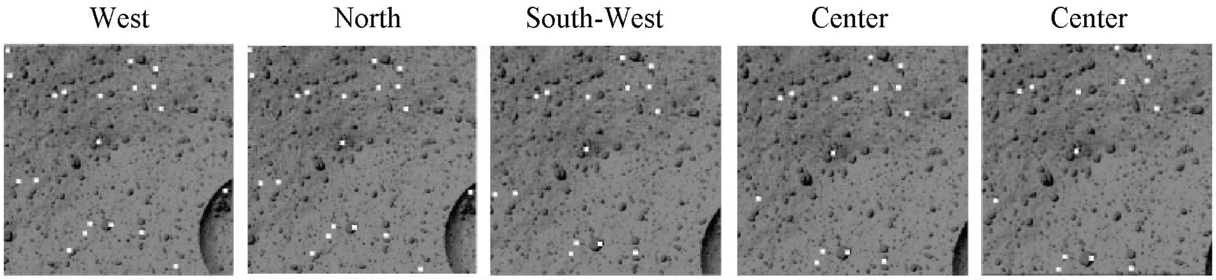
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Figure 8. Example descent profile with recommended spacecraft traversal direction

4. CONCLUSIONS

In this paper, we present a fuzzy-logic based methodology for selecting surface feature references, and maintaining them in sensor view, in order to provide reliable data for estimating spacecraft position. Future work will involve integrating the fuzzy observation planner directly into a GN&C simulation system for documenting performance in improving the position estimation calculations during small body proximity operations. Thanks are due Dr. David S. Bayard of NASA's Jet Propulsion Laboratory for providing insight and motivation for this research.

5. REFERENCES

[1] NASA, Deep Space 1 Asteroid Flyby Press Kit, July 1999.
[2] L.A. Zadeh, "Fuzzy Sets", Information and Control Journal, vol. 12, pp. 338-353, 1965.
[3] R. Gaskell, "Landmark Navigation and Target Characterization in a Simulated Itokawa Encounter," AAS/AIAA conference, Tahoe, NV. 2005.
[4] A. E. Johnson and L. H. Matthies, "Precise Image-Based Motion Estimation for Autonomous Small Body Exploration," 5th Int. Symp. AI, Robotics and Automation in Space, 1999.
[5] Y. Cheng, et. al. "The Mars Exploration Rovers Descent Image Motion Estimation System," IEEE Intelligent Systems 19 (3), 2004.