Novel Terrain Relative Lunar Positioning System Using Lunar Digital Elevation Maps

Şamil TEMEL
Turkish Air Force Academy (TUAFA)
Aeronautics and Space Technologies Institute (ASTIN)
İstanbul, Turkey
s.temel@hho.edu.tr

Numan ÜNALDI
Turkish Air Force Academy (TUAFA)
Aeronautics and Space Technologies Institute (ASTIN)
İstanbul, Turkey
n.unaldi@hho.edu.tr

Fuat İNCE
Marmara University
Computer Engineering Department
Istanbul, Turkey
fuat.ince@superonline.com

Abstract—**The aim of Terrain Relative Navigation systems (TRN) is to augment inertial navigation by providing position estimates relative to known lunar surfaces. Also the purpose of TRN systems is to assist a lunar landing spacecraft with precise and safe landing. Such systems collect the height values from the lunar surface with the help of active range sensors which are then matched within a terrain Digital Elevation Map (DEM) database. Although lunar terrain elevation maps are rare and have low resolution quality, after Lunar Reconnaissance Orbit (LRO) mission is completed by 2010, maps of 20-25 m resolution will be gained. In this proposed work, a model of the lunar surface is developed with terrain generation algorithms. All the possible profiles (height values) and the slopes of the profiles that the sensor may collect during a position estimation phase are determined in advance. The DEM is pre-processed and reorganized into a Digital Profile Attributes Database (DPAD). DPAD records are organized in a way to optimize the lander's position estimation process. DPAD data is available as a function of lunar latitudes and longitudes. The DPAD over which the lunar lander is flying is loaded into the lander's memory. A novel TRN algorithm has been developed to estimate the precise location of the lander. This algorithm matches the determined slope values within the DPAD. Where only one match is found, the position of the lander is determined. When more-than-one matches arise, the system iterates until only one position solution is reached. In order to achieve accurate continuous navigation, the sensor should make measurements at specific intervals. The difference between the lander's estimate and the actual height that are measured by laser altimeter, can be used to calculate the position errors, thus providing the lander a continuous navigation solution as in TERCOM [7].**

Keywords - Lunar Landing; Terrain Relative Navigation; Precise Position Estimation;

I. INTRODUCTION

Beginning in 1959, United States and the Soviet Union sent a series of spacecraft to examine the moon in detail. The ultimate goal was to land people safely on the moon. United States finally reached that goal in 1969 with the landing of the Apollo 11 lunar module. The United States conducted six more Apollo missions, including five landings. The last of those was Apollo 17, in December 1972. After the Apollo missions, the Soviets sent four Luna robot craft to the moon. The last, Luna 24, returned samples of lunar soil to Earth in August 1976 [3]. Since the Apollo and Luna programs ended in 1976, over a period of 30 years, only four orbiter missions to the moon have been undertaken.

The world has recently turned its attention back to the moon. As we plan to send humans back to the moon, techniques must be developed to place humans and cargo safely and precisely on the lunar surface. Hazard Detection and Avoidance (HDA) and Terrain Relative Navigation (TRN) are onboard capabilities that combine sensing and computing to achieve autonomous safe and precise landing. The Autonomous Landing and Hazard Avoidance Technology (ALHAT) project is developing HDA and TRN capabilities for lunar landing [6]. Landing accuracies of perhaps 100's of meters will be required. Terrain sensing and navigation function of a lunar lander is shown on Fig.1.

The required landing precision for the upcoming lunar missions is much stricter than Apollo 11 where the landing ellipsoid was 18.8 km along-track by 4.8 km across-track. For Apollo 12, the expected landing ellipsoid was reduced to 4.2 by 2.6 km [4]. Apollo missions were able to achieve reasonably precise landings. However, the accuracy is not sufficient to meet the new objective, particularly for the unmanned missions that will not have benefit of astronaut-assisted navigation. To improve navigation precision, TRN is needed as inertial

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sensors alone, although improved since the Apollo missions, cannot achieve the necessary performance. The ALHAT program is examining a system using both passive optical (digital cameras) and active optical (lidar) systems to sense the lunar surface for determining instantaneous position and velocity with respect to known surface features.

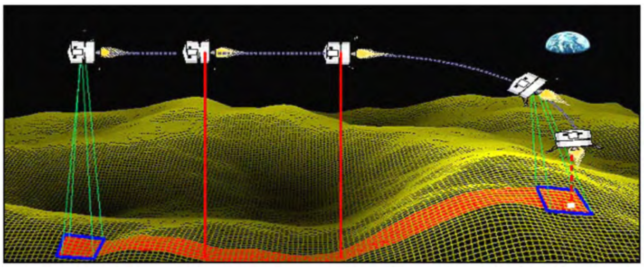

Figure 1. Terrain sensing and navigation function of a lunar lander

The primary objectives for ALHAT were to develop a system enabling precision landing of robotic, cargo, and human missions that will land autonomously anywhere, anytime within 10's of meters if there are lunar navigation assets in place and/or precise lunar maps and land autonomously anywhere, anytime within 1 km if there are no lunar navigation assets or precise lunar maps [6].

Obtaining repeatable precision landing without lunar navigation aids requires the availability of very good lunar surface maps. ALHAT is assuming that Lunar Reconnaissance Orbiter (LRO) maps will be available soon. The Lunar Reconnaissance Orbiter (LRO) represents the first mission from NASA's Vision for Space Exploration, a program to return to the moon and then to Mars. The LRO mission joins host of new orbiter missions to the moon that are likely to be followed by robotic landers and eventually with a return of humans to the surface. The LRO mission focuses on preparing for a future landing on the moon. Its primary goals are to search out safe landing sites near potential lunar resources [1].

Because LRO will make global observations, the altimetry data can be used to develop TRN systems. In this proposed work a novel terrain relative lunar landing system is developed using 20, 25, 30 and 40 m resolution digital elevation maps, which have almost the same resolution with the oncoming LRO maps.

The main drawback of the TRN systems is that they cannot work on plain areas. In order to find a position match, the system needs undulating terrain or some specific terrain features like well known craters, hills or mares. When the height values which are determined from LIDAR are constant, the slope values will remain constant too. In order to attain a terrain that is rough enough to navigate on, we can use an automated terrain analysis system. With "Automated, on-board terrain analysis for precision landings [12]" the flight path can be automatically determined by examining the results of the smoothness-based segmentation which shows the areas in the image that surpass a degree of smoothness.

An important assumption underlying the TRN approach is that the altitude of the spacecraft is either constant or can be estimated using an onboard INS device adjusted to work under lunar gravity. Thus variations in LIDAR measurements can be attributed purely to variations in the lunar surface.

II. REVIEW OF THE TRN SYSTEMS

The TRN approaches can be split into two categories based on the type of sensor supplying the terrain data: *passive imaging* or *active range sensing*. Passive imaging has the advantage that the sensors (visible cameras) are mature and easy to accommodate on the lander (i.e., low power, mass and volume). Some of the passive imaging approaches can provide navigation measurements from any altitude. However passive imagers have the distinct disadvantage that they cannot operate in the dark. They require solar illumination or an illumination source on the lander. The high altitude for TRN operation makes the illumination source approach impractical and requiring solar illumination places excessive constraints on landing time of day. The active range sensing approaches have the advantage that they operate under any illumination conditions. However, space qualified active range sensors are less mature than passive imagers and they have a limited maximum operating range which places constraints on the altitude at which TRN measurements can be made available [2].

The TRN approach can also be broken down based on the structure of the algorithm used to compare surface measurements to the map, *correlation approaches* and *pattern matching approaches* [2]. In *correlation approaches*, a contiguous patch of the surface is acquired using the onboard sensor. If a passive imager is used, then the patch is essentially a subset of the image; for a range sensor, the patch is elevation map or contour. This patch is then correlated, in the image processing sense, with the onboard map. Correlation algorithms place the patch at every location in the map and then measure the similarity between the patch and the map values (This process can be visualized as raster scanning the patch across the map.) If the values are similar, then the location is given a high score; if they are not similar, then the location is given a low score. The location in the map with the highest score is chosen as the best match location for the patch in the map. Interpolation of the correlation scores is used to obtain a sub-pixel estimate of the match position. The orientation (and altitude for imagers) is then used to compute the position of the lander in the map coordinate system [2]. Some famous correlation TRN methods are: Image to Map Correlation for Position Estimation (e.g. DSMAC) [13] and Altimeter to DEM Correlation (e.g. TERCOM) [7].

Pattern matching approaches use landmark matching instead of patch correlation. Landmarks are locations that can be extracted reliably from map and surface data and also have distinct characteristics (i.e., the pattern) that make them amenable to comparison to other landmarks [2]. For example, craters are often used as landmarks because they can be extracted reliably from image data over a broad range of image scales and illuminations and the diameter of the crater is an identifier that can be used for matching. The relative distances and angles between landmarks are also used during the matching procedure. [2] Some famous pattern matching TRN methods are: Scale Invariant Feature Transform (SIFT) [14], Shape Signature Pattern Matching, Onboard Image Reconstruction for Optical Navigation (OBIRON) [15].

Development of TRN systems for Earth started in the 1970s and a number of systems have been produced commercially over the years. By these systems, the height of the terrain below the air vehicle is estimated with the help of a radio altimeter and a barometric altimeter. As shown on Fig. 3 the height of the terrain h_t is calculated by subtracting the altimeter height from barometric altimeter height.

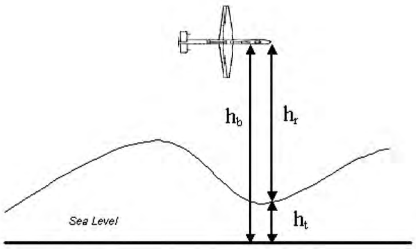

Figure 3. Estimating the terrain height on earth

Where, h_b: Barometric Altimeter Height h_r: Radar Altimeter Height h_t: Terrain Elevation

$$h_t = h_b - h_r \tag{1}$$

Measurements are taken periodically and these are then compared within a terrain height map A range of different techniques have been developed to obtain position fixes from the comparisons of measured and database terrain heights. TERCOM [7] and TERPROM [8] are such examples. In these systems, the difference between the radar altimeter generated and database indicated terrain height is input as a measurement to Extended Kalman Filter (EKF). The principal advantage of the EKF approach is relative simplicity and comparatively low processor load. However, it relies on accurate knowledge of the terrain gradient below the aircraft, which is a demanding requirement.

III. OPERATION OF THE PROPOSED SYSTEM

The proposed system is designed in order to provide a lunar lander with precise location information. The system works in two phases: *Preparation Phase* and *Locating Phase*. The block diagram of the proposed system is shown on Fig. 2. As shown on Fig. 2, when there is only one location solution, the program stops, otherwise continues until only one location solution is reached. If the number of probable locations of the landers is zero, the process is repeated all over.

Hutton and Evensen classified the lunar surface into four terrain types: smooth mare, rough mare, hummocky uplands and rough uplands [10]. In this proposed system we have developed four types of terrain structures which are Type-1, Type-2, Type-3 and Type-4. Each terrain type has a roughness constant where Type-1 is the smoothest and Type-4 is the roughest areas. Examples of these terrain maps are given in Fig. 5.

An algorithm for matching slope values of the altimeter swaths to a DPAD has been developed using components of computer science data structures such as linked lists, sorting, searching and programming techniques.

The algorithm takes as input a reference elevation map that contains the height values of the lunar lander's path. When TRN is performed the active ranging sensor collects some range data and when sufficient data has been collected, the slope of the height values below the lander is calculated. This slope value is then searched within the DPAD. If there is only one match, the algorithm stops.

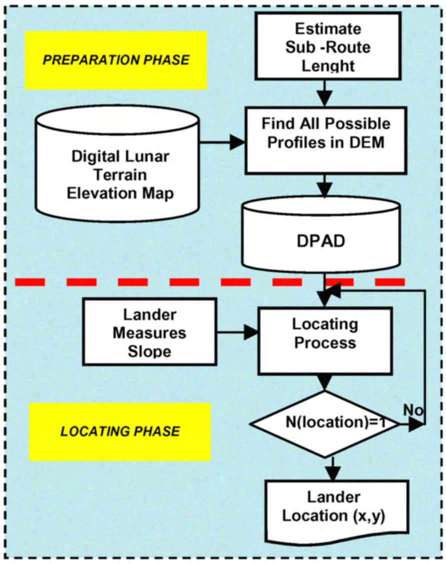

Figure 4 The block diagram of the proposed system

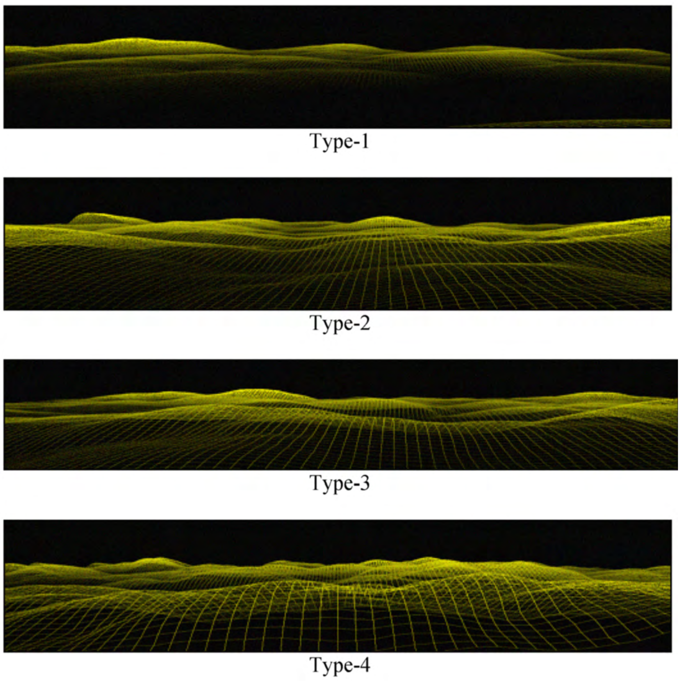

Figure 5. Examples of some terrain heightmaps. Type-1 is the smoothest, Type-4 is the roughest.

A. Preparation Phase:

In our system, terrain heightmap structure is used for defining the lunar terrains. The terrains are generated with the help of Hill Algorithm, Midpoint Displacement Algorithm, Fault Algorithm [10] and an algorithm that we have developed to simulate the lunar surface which is a mixture of Hill Algorithm and Midpoint Displacement Algorithm. Examples of height maps that we have worked on are shown on Fig. 5.

By these maps a lattitude-longtitute information can be achieved where the values of all (x,y) coordinates correspond to the actual height of the terrain. Digital terrain heightmaps are arranged as *x* and *y* coordinates horizontally and vertically. Every pixel values in the map are numbered with the help of (2) in order to achieve operation ease and less memory consumption. In this equation SIZE corresponds to the matrix's pixel dimension when the heightmap is a square,

$$P_n(x,y) = y.SIZE + x + 1 \qquad (2)$$

Also when given the pixel number, the row (x value) and column (y value) number can be estimated with the help of (3) and (4) consecutively.

$$Column(P_n) = (P_n \bmod (2.(SIZE-1)))/2 \qquad (3)$$

$$Row(P_n) = P_n / (2.(SIZE-1)) \qquad (4)$$

In this phase, the digital terrain heightmap is rearranged and the slopes of all the possible profiles are written to DPAD. When creating the values of DPAD, the slopes of all the routes are determined in order to differentiate a profile from the others. This file is used in the locating phase. Rearranging the map enables the system to locate very fast with less processor load.

It is assumed that the lunar lander starts its journey on a well known terrain. Although it is not necessary for a lunar lander to know its exact primary location, the DEM of the entrance area and the area where the flight will take place has to be known in advance. In this study, 256x256 and 128x128 sized entrance DEMs are used which cover nearly 5 km^2 and 2,5 km^2 surfaces respectively. All the possible routes that a lunar lander may follow is calculated with the Cartesian product of E(i,j)xF(I,j) where E(i,j) is the entrance area and F(i,j) is the final area. The routes are estimated with the help of **Digital Differential Analyzer** (DDA) algorithm [11]. According to Fig 6. there is 3x8 possible pixels that the lander may start its journey. So, the number of possible entrance pixels is 24, the final area has 3x8 pixels too. As a result there will be 3x8x3x8=576 possible routes that a lander may follow up.

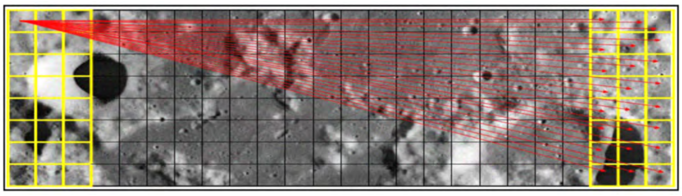

Figure 6. All the possible routes of a lunar lander are estimated in advance of a flight

After estimating all the routes, they are splitted to vertically equal lengths of sub-routes. These will be the sampling points of the lander. The ending pixels of the sub-routes would be the sampling points and the slopes of all the sub-routes will be calculated with *least square roots method* and the slope values are then written to disk on a DPAD. According to Fig. 6. all the profiles ($m_1\, P_1\, m_2\, P_2\, m_3\, P_3\, m_4\, P_4 \ldots$) have to be written to the disk. The number of the profiles depends on the DEM size, the size of the entrance and final areas, the sampling length and the map resolution.

For example, if there is 576 routes and every route has 100 pixel (vertical) length on a 25 m resolution map, then the length of a single route will be 100x25=2500 m long. If the sampling distance is chosen as 250 meters then there will be 10 sub-routes to be calculated. And this makes 576x10=5760 slopes calculations. Because the sub-routes are connected to each other, all the route information is recorded into a **linked list**, which is then loaded to the memory afterwards. By Using a linked list structure searching time decreases drastically. The sub-routing phase is shown on Fig. 7.

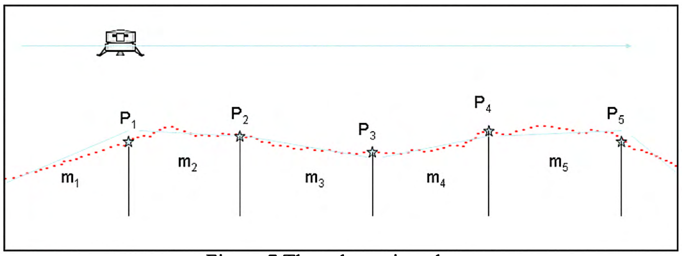

Figure 7 The sub-routing phase

The length of the sampling sub-routes is estimated in advance of the flight and the lidar frequency is tuned up according to the sampling length. For example on a 25 m resolution DEM, if the lander is flying at a velocity of 1000 m/sn over a reasonable altitude, the frequency of the lidar should be set to 40 Hz.

A distinct attribute of a profile is the slope angle of the profile that is estimated by the height values between the start pixel P_s and ending pixel P_e. The slope of the profile is calculated with the help of *least square roots method*. The result of least square roots is a line formula as shown in (5).

$$y=mx+n \qquad (5)$$

and the angle is calculated by (6)

$$\alpha = \mathrm{ArcTan}(m) \quad (6)$$

A negative α value means a descending hillside and a positive value corresponds an ascending terrain. The bigger the absolute value of α the more steep the terrain gets.

The entrance DEM and the corresponding DPAD are loaded to the landers memory in advance. The profile lenght L is also given as an input to the locator procedure. The terrain is sub-routed and the profile attributes (the slopes and the starting and ending pixel numbers) determined are written to a DPAD according to L, which will be the search space for the location phase. Instead of the DEM itself, the DPAD is loaded to memory before the flight.

B. Location Phase

Location phase is where the position of a lander is determined. As stated earlier it is assumed that the lunar lander starts its journey on a well known terrain. For example, when a 256x1024 sized map is used, 64 pixels of profile length is chosen and the entrance and exit area size are 256x10 pixels, there would be totally 256x10x256x10=6.553.600 route profiles to be searched exhaustively. Every route is then splitted into small sub-routes. For this example the vertical route length is 1024 pixels, and there will be 1024/64=16 sub-routes for every route. Totally there would be 6.553.600 x 16 = 104.857.600 slope values all over the DEM. In order to optimize the search within DPAD, the DPAD is sorted and a hashed index is made which holds the starting line number of distinct slope values in the file. The searching first starts to check the index to reduce the search space.

When the total number of routes (search space) is large, the process concludes in slower locating processes. In order to lessen the search space, the probable locations (pixel numbers) that are found after the very first search are written to a linked list array. These list values are the coordinates of the probable ending pixel values. Unless there is only one location solution, the algorithm loops. For the next step, the array values will be the probable starting pixel positions of the next profile. This scheme decreases the search space dramatically. The flow chart of the locating phase is shown on Fig.8.

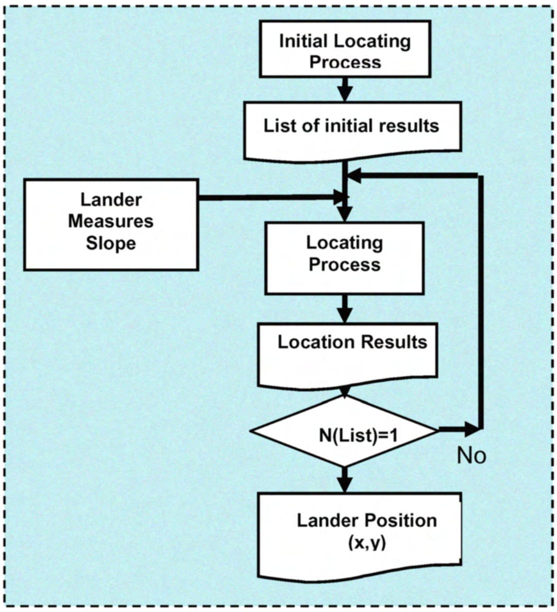

Figure 8 The flow chart of the locating process

IV. CONCLUSION

Traditional lunar landing approaches based on inertial sensing do not have the navigational precision requirement to autonomously land within 100 m of a predetermined location on lunar surface. The aim of Terrain Relative Navigation systems (TRN) is to augment inertial navigation by providing position estimates relative to known lunar surfaces.

In this proposed work, a novel TRN system is developed which mainly focuses on pre-processing and reorginizing the DEM data into a Digital Profile Attributes Database (DPAD) with the help of computer graphics algorithms. By utilizing computer sceince data structure techniques, searching within all the possible route values becames very fast.

When a lunar lander makes journey over a known terrain and collects height values, a profile is formed and this profile's slope is searched in a file called DPAD. Generating the DPAD values is a key feature of this study that is formed in advance of flight which is named *the preparation phase*. While flying, a *locating algorithm* runs and if only one location solution is found, the program stops.

Unlike other TRN systems, our system doesn't include complex mathematical calculations. There is less process load but the system needs some amount of memory to hold the DPAD.

In Table 1, the number of location solutions on 4 types of 256x256 terrains is shown. The resolution of the terrains is 20 m. according to Table 1. on a very rough terrain (type-4 terrain), the lander finds its location in 5 steps (distance traveled would be 1,2 km). If the terrain is very smooth (type-

1 terrain) the lander finds its location in 10 steps, after travelling a distance of nearly 2,1 km.

TABLE 1. Number of location solutions on a 256x256 heightmap (map resolution is 20 m)

STEP	Type-1	Type-2	Type-3	Type-4
1	44339	34751	32545	27782
2	2284	2126	2708	424
3	315	238	189	47
4	67	34	30	15
5	29	25	16	1
6	28	11	1	-
7	16	1	-	-
8	15	-	-	-
9	11	-	-	-
10	1	-	-	-

For future work we are planning to establish probabilistic TRN systems instead of deterministic ones.

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