Landmark recognition for localisation and navigation of aerial vehicles.

Andy Shaw, Dave Barnes and Phil Summers
Department of Computer Science,
University of Wales, Aberystwyth,
Wales, UK, SY23 3DB.
email:ajs@aber.ac.uk, dpb@aber.ac.uk, prs94@aber.ac.uk

Abstract

Work has been undertaken at the University of Wales, Aberystwyth in the area of localisation and navigation for aerial vehicles (aerobots) for large unstructured environments (i.e. natural outdoors). A pre-requisite for this navigation method is that a low resolution topographical map of the environment is required. Also the aerobot requires an on board capability for generating high resolution topographical data.

The localisation and navigation method presented in this paper was developed for planetary exploration with an emphasis on Mars. This planet meets the criteria specified above because it has an atmosphere allowing the use of aerobots, and the Mars Orbital Laser Altimeter (MOLA) [1][2] has provided the low resolution topographical map.

This MOLA data [3] then provides the scenery for FlightGear [4] an open source flight simulator, which provides the base within which all the localisation and navigation experiments have been conducted.

Localisation and navigation is achieved by extracting naturally occurring surface features (Landmarks i.e. peaks, ridges, planes, passes, channels and pits) from the topographical maps. The result is then compared to known features to provide a surface which has been categorised by features. This method has proven very robust as features are still found even when other feature generation extraction methods fail [6].

Localisation is achieved by matching the topographical features in a high resolution topographical map, generated by an aerobot mounted (e.g. a laser altimeter) scanning device, with the same topographical features in the low resolution global map (MOLA data). This matching procedure provides an estimation of the position and orientation with respect to the environment. Ease of the localisation depends on the richness of feature in the target environment.

Once the aerobot has localised, navigation to desired locations is achievable by using surface features as way-points. This feature path is generated by the user (scientist) who can determine points of scientific interest. Then using a combination of the feature path (feature navigation) and inertial navigation methods, the desired location can be reached.

This paper presents the results obtained from the localisation and navigation phases, from the point at which an aerobot obtains topographical maps of the surface, analyses them for features, estimates its position and orientation, to the point of navigating to the desired sites of scientific interest.

Keywords

Aerobot, localisation, navigation, autonomous, planetary exploration.

I. Introduction

The area of space exploration generates many challenging problems, across numerous disciplines. Autonomous operation of exploratory vehicles is essential due to the large time delays in interplanetary communications, Mars for example, can take up to 35 minutes round trip communication time. These time delays mean that tele-operation although very useful for rovers and landers, would not be suitable for aerobots because of the uncertainty in the aerobots position between communications.

This means that any aerobot would need to be fully autonomous, accepting high level commands to go to a given location and conduct these sets of experiments [5]. As an aerobot can move freely in 3D Cartesian space the solutions to navigation and control become more complex, also the system requires sufficient sensors to allow the system to meet its desired goals.

Such a sensor array would have to be able to acquire data on the horizontal and vertical wind velocities, as well as the atmospheric temperature, density and pressure, so an aerobot could calculate the most efficient method of point to point motion. This paper discusses a single aspect of these required systems, namely localisation and navigation with in the aerobots environment.

II. Navigation methods

Terrestrial aerobots have several methods of navigation available to them, namely:

- Global Positioning System (GPS) [7] requires line of site of at least four satellites to acquire a position from a code-phase signal sent from each satellite, but as there are no plans to launch such systems to other planets, this form of navigation at the moment is not applicable.
- Celestial navigation [8] requires very accurate star charts and an accurate time piece, such a system is very reliable and has been around for centuries, the major problem is that during the day light hours an aerobot would become lost using this navigation method.
- Vision navigation [9][10][11] can have multiple uses, namely generating images of the terrain while traversing it, which can be used for publicity, surface characterisation etc. or navigation. By using two cameras it is possible to triangulate

the distance and position of objects, with in the view port. A problem arises with surface illumination during the night where either the system is shut off (aerobot looses position) or lighting is used which becomes very power intensive, unless night vision cameras could generate adequate images.

- Magnetic navigation [12] i.e. using a compass to align the aerobot to "Magnetic North" (calculation of the heading) but not position. Planets such as Mars only have localised fields which are hard to map with sufficient reliability.
- Geomorphometric navigation uses naturally occurring geological features of a terrain to localise and navigate from (orienteering), with which any method of surface topography generation can be used, i.e. laser / radar scanning systems.

III. GLOBAL MAP GENERATION

If the geomorphometric navigation system has a method of generating the surface topography, then the system could operate continuously, for this radar or laser scanning methods can be used.

Time-of-flight laser rangefinder scanning mechanism; This is a proven method of topography map generation as the MOLA instrument [1][13] was in operation from late 1998 to July 2001 and made over 640 million range measurements (total mission time of 1696 days). From these measurements a topographical map of the entire surface of Mars has been generated to a resolution of 300 meters with a vertical resolution of approximately one meter.

Imaging Radar Scanning; Again an already successful mission took place in early 2000, where radar instrumentation on board the space shuttle [14], scanned the surface of the Earth generating 12 Terrabytes of information. The analysed data finished in mid 2002 produced 1 and 3 arc-second topographical maps of the surface, with a horizontal resolution of 30 meters (1 arc-second).

As the MOLA instrument has generated a topographical map of the entire surface of Mars with a profiling resolution of approximately 300m (18 arc-seconds) and a height resolution of approximately 1m it was decided that a laser scanning system would be used in the geomorphometric navigation.

IV. SIMULATOR ENVIRONMENT

A complete overview of the simulation enviroment can be seen in Fig.1 the core of which is an open source flight simulator FlightGear [4], which comes with accurate flight dynamic models was customised to match the Martian environment Fig.2. This included the changing of the atmospheric properties, removing the Earth based scenery and replacing it with scenery generated from the MOLA data. This simulator also has accurate star maps and could have weather information in-ported, should research require this capability.

The MOLA data (14 Gigabytes) was first sorted, filtered and then converted into 30 arc second digital elevation maps (DEM's), giving a horizontal resolution of approximately 490 meters. The surface then had a desert image draped over the scenery to give a Martian look.

This simulator has provided the base from which all experiments have been conducted. The FlightGear project has numerous other projects working along side, one of which called Atlas [17] which is a map projection program. This software takes positional information from FlightGear and plots an aircrafts track over the surface Fig.6. This program has proven very useful for positional and orientation verification of the aerobot within the environment.

V. LOCAL MAP GENERATION

Local map generation was accomplished by a laser scanning module which was added to the open source simulator along with a PID autopilot. The laser scanning module was modelled on commercially available laser rangefinders

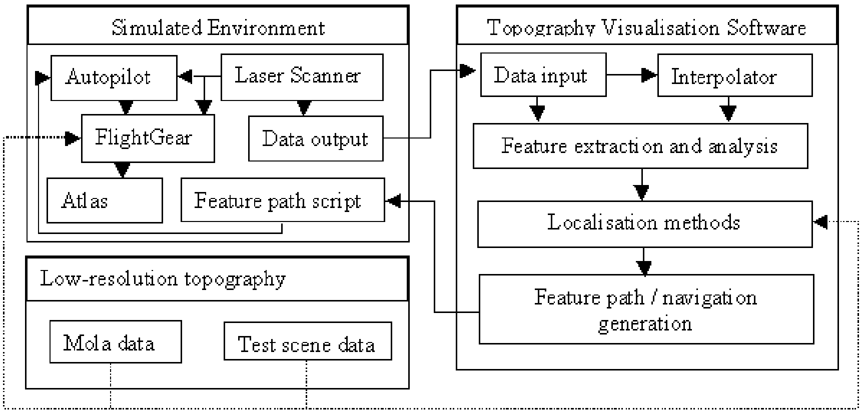

Fig. 1. An overview of the simulator software used

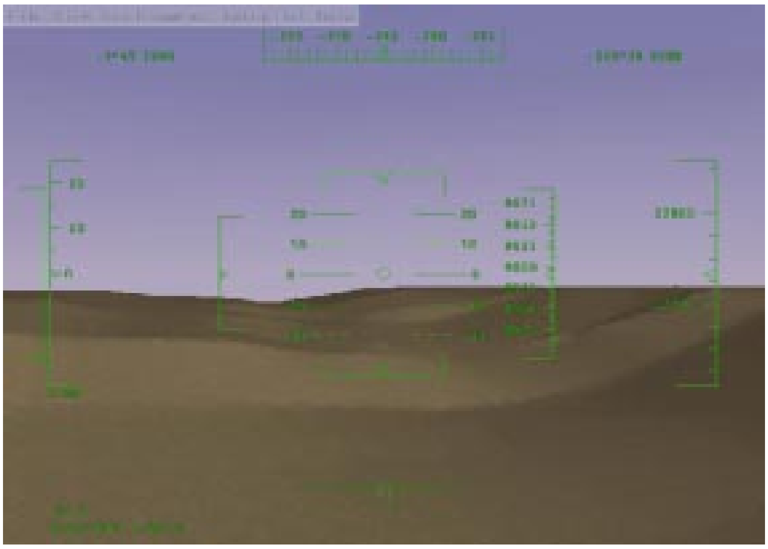

Fig. 2. The FlightGear simulator

[15][16] each having varying characteristics depending on the desired application (range and frequency of measurement). It was decided that the range finder should operate at a varying frequency (dependant of forward speed measured by inertial sensors) to produce gridded data with spacial resolution of approximately 10m. From the investigated systems it was decided that the model would have a maximum range of approximately 1.5km and a resolution of ± 15cm and an operating frequency between 0 - 2kHz.

With these values it is possible to travel at speeds of 20ms^{-1} collecting data with approximately 10m horizontal resolution or 2ms^{-1} with data at 1m resolution. From the operating range of the modelled scanner the ideal altitude above ground was set at approximately 870m as this allowed a scan footprint of a 1km over the surface (using a scanned angle of 60 degrees) perpendicular to the direction of motion.

VI. Feature Extraction algorithms

The feature extraction algorithms used in the Geomorphometric Navigation software are based on the radius of curvature of a point on the surface and are characterised by six main features Fig.3. Fig.4 shows the test scenery (which is a section of the grand canyon) as shown as a false colour height image and with the various features extracted for a given threshold set. The features are colour coded for ease of analysis (Red = Peak, Magenta = Ridge, Green = Pass, Yellow = Plane, Blue = Channel and Black = Pit). In the feature extracted image Fig.5 all the various features can be seen with the exception of pits. Due to the values used for the curvature and slope threshold variables, the clearest feature to see is the plane, as the river and the top of the mountainous region for all intensive purposes appear flat. It is also easy to see the ridges that follow the the river tracks.

The percentage of extracted features from a scene can be varied by adjusting the slope, minimum curvature and resolution thresholds. The slope threshold determines an angle, above which the terrain is said to be sloping and below it is said to be horizontal. The minimum curvature is an angle above which the terrain is said to be curved and the resolution threshold determines the number of surrounding data points used in the calculations.

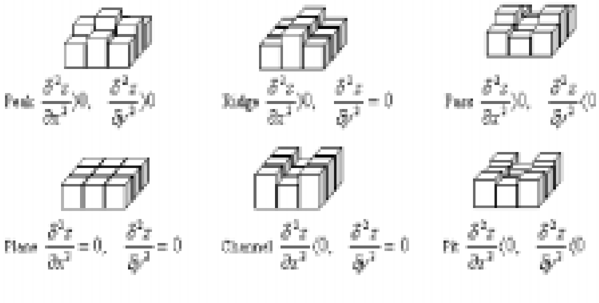

Fig. 3. The six feature classifications

Another method for surface point analysis is using the differential and the double differential of the point. This method was initially used but the results obtained were found to be unsatisfactory when compared to the radius of curvature method. The differential results produced less feature points often missing major features making the surface analysis very difficult, especially during the localisation phase.

VII. LOCALISATION

Localisation in an environment such as Fig.4 can be quite hard because of the shear volume of feature data. By adjusting the slope, curvature and resolution threshold values and by varying the desired feature it is possible to reduce the number of possible locations the scanned region can be related to. Using the topography visualisation software written by the author, of which the display window can be seen in Fig.4, allows the user to interact with the scenery in 3D and configure the afore mentioned parameters. It also allows the user to select the type of localisation method either manual or automatic.

The manual method is where both the global data map and the scanned data map are loaded into the same work space, where they can be rotated, moved and scaled in 3 dimensions. With the manual method it was found that the probibility of a match was dependant on the amount of scanned data, the less data the harder it became to match the surfaces, this is why the automatic methods were implimented.

The first automatic method analysed the gradients between four selected points, usually the extremes of the data. The points are numbered clockwise and the gradient between points 1-2, 1-3 and 1-4 are calculated. The global data is then searched (all orientations about each point) for regions of corresponding gradients, each gradient is also allowed an error threshold, if any regions are matched they are highlighted in white.

The second automatic method extracts the various features at selected threshold values, between either the same four points as selected in the gradient or another four. This then generates a histogram of the various features, again the global data set is searched for regions that contain similar feature ratios, if a match is found then the region is coloured orange.

As these localisation processes can produce several regions that are candidates for the aerobot position, the results are ANDed together, providing regions which match the scanned regions data. Each of these regions will then provide an aerobot position and orientation with respect to the global data, this can then be used to narrow the number of locations down because if the aerobot moved off in a set direction one can predict the scanned data values.

As the proposed environment Mars is covered with craters, an analysis of these was performed, by matching of an elliptical equation to the ridges of the craters. The results showed that by using the ratio between the major and minor axes and a depth measurement (altitude difference between the center of the crater and the highest point on the crater ridge) that nearly all differed significantly, therefore providing another very useful method for localisation on Mars.

Again by implementing a data base search of the global regions crater values against the scanned crater values. Calculating the orientation and the postion of the aerobot was achieved using the major and minor axes of the crater, because knowing the orientation of the crater in the environment and the aerobots position on the crater ridge a heading and position could be calculated.

VIII. FEATURE PATH GENERATION

Once the aerobot has been localised with in its environment, it is possible to generated a feature path from the global map to a desired location. These paths can be generated either by the user (scientist) or automatically (shortest distance between two points), if the user generates the path they can pick each of the points the aerobot will traverse over / visit

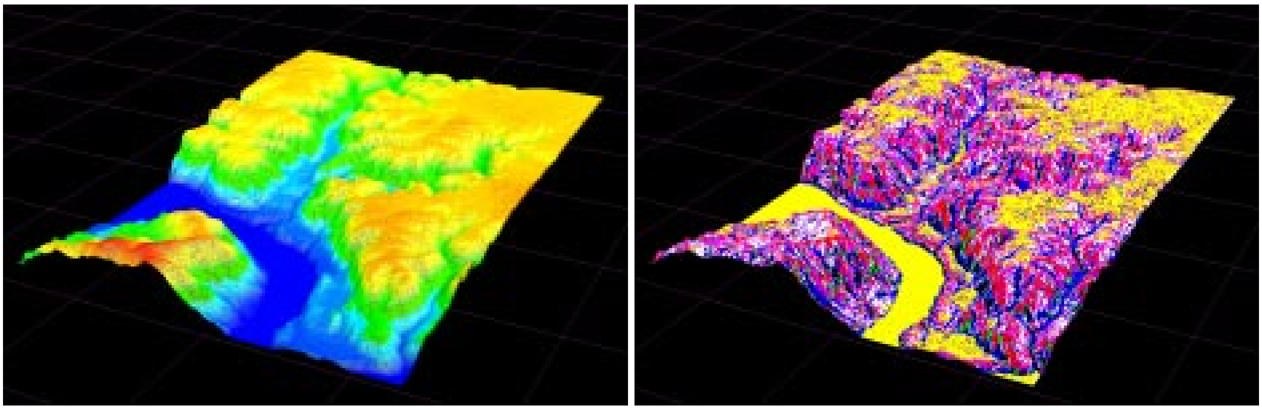

Fig. 4. Test scenery shown as a false colour height on the left and with the various features extracted on the right

on its way to the desired location. This route will not necessarily be the most efficient but would probably be the most scientifically interesting because these feature 'way-points' could be used for setting positions for conducting various experiments.

An automatic route generation process creates the most efficient path that uses the minimum number of feature points. Also no extra stopping points can be selected therefore giving the quickest, direct route.

IX. Feature navigation

After the aerobot has localised and a feature path has been generated the aerobot navigates by using a combination of both, dead reckoning and feature navigation. The dead reckoning is used to point the aerobot in the right direction an move for a certain distance, which is calculated using inertial sensors. The system then switches to the feature navigation, using the scanned data to position the aerobot over the center of the desired feature. This method is then repeated from one way-point to the next, landing if required to conduct any experiments until the aerobot reaches the final location where it lands and waits for the next feature path.

Features can be extracted from the line scan data because previous scan data is stored. Feature extraction software can extract the different features during the traverse through the environment and relate these features to the global map.

X. Experimental results

During the testing / validation period of the experimentation a 2 x 2 degree test scene Fig.5 was generated which contained all the six features Fig.3. Also in this test scenery craters were added, which often are a peak surrounded by a channels which is in turn surrounded by a ridge. From the three craters added two were elliptical with the very similar major and minor axes but with 90 degree changes in orientation.

When the aerobot was 'dropped' in to the environment, it started the localisation process. Initially the aerobot snaked across the surface until the start of a feature, i.e. a slope. The aerobot was programmed to head towards the highest point, a peak, or towards the lowest point, a pit, the aerobot decides which to head for depending on which way it is facing on the slope. Two examples of the aerobots localisation phase can be seen in Fig.6, here the left image shows the aerobot navigating along a channel to its lowest point, the pit, and stopping. The right image shows the aerobot navigating up the side of the ridge, along it and stopping on the peak.

The aerobot is programmed this way because it is easier to find a peak or a pit, than it is to determine where on a ridge or channel the aerobot has stopped, unless there are any other distinguishable features which could be used to narrow down the location.

Once the aerobot has found either a peak or a pit, it could land and send the scanned data back to the the control center, here the data could be analysed, using the Geomorphometric navigation software. This software would allow both the global and scanned data to be view in 3D at the same time, either as a false colour height image or as feature extracted image. The type of localisation process can also be chosen. In Fig.7 the scanned data from Fig.6 can be seen matched manually to the global terrain. The data is quite easily matched because of the distance travelled by the aerobot is quite large, therefore a lot of data points have been ggenerated

When the scanned data is loaded in to the viewer, it can either be loaded as the raw point data or loaded as an interpolated area at 3 or 30 arcsecond.

To further narrow down the position and orientation of the aerobot within its environment the automatic matching methods can be used. Here the scanned data is loaded into the viewer and the data extremes are marked because of

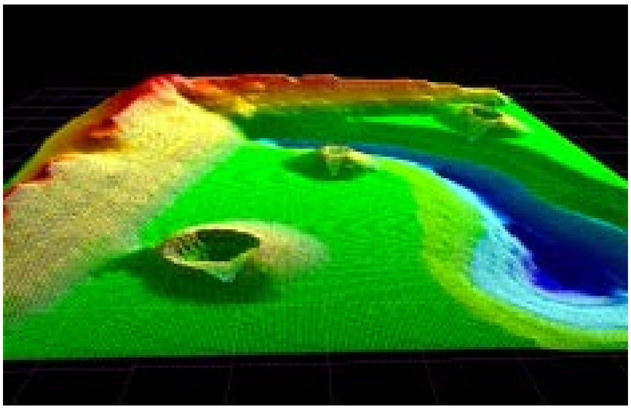

Fig. 5. The 2x2 degrees test scene containing the six terrain features

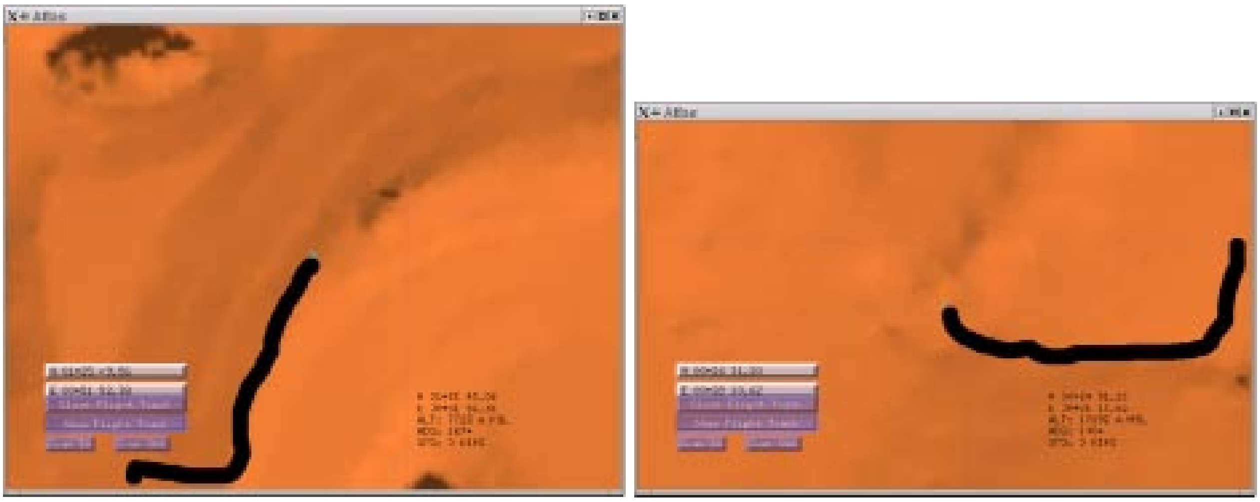

Fig. 6. Results from the localisation on a peak and pit using the Atlas display software

the view port scaling, then four points of the scanned data are selected. The first auto-method calculates the gradient between the selected points while the second method, calculates the number of different features with in the area enclosed by the four points.

The results of the auto-gradient search for the in data Fig.6 can be seen in the left hand image of Fig.8. In this image the areas that match the calculated gradient with in a 10 percentage error difference can be seen highlighted in white. The search method used visits each point in the data and inspects it in all orientations for a match. The region selected on the scanned data was the initial traverse down the hill side to the valley bottom. As there are multiple regions in the image on the left hand of Fig.8 which match the scanner gradient, the actual position was marked with an arrow.

The feature method matching results can be seen in the right hand image Fig.8, for this the channel section of the scan was used as the slope region contain no features. The areas highlighted in orange contains similar numbers of each feature as that region selected from the scanned data.

The results from the second auto-gradient localisation process can be seen in left hand image of Fig.9 here again the initial section of the scan was used, the ascending slope. In this scan numerous matching regions can be seen and again the actual region is marked with an arrow. The right hand image of Fig.9 shows the auto feature matching results, the areas shaded orange have the same number ratios of each feature as the original selected area, which was the end of the scan, the peak, again marked with an arrow.

Once the aerobot has localised it is possible to generate a feature path, again this is done in the topography visualisation software on a point and click basis. During this process the controller can decide if the aerobot should land at any of the way-points, if not the aerobot will continue until the final destination has been reached where it will land and wait for another flight path. This feature path can also be generated automatically by selecting the end point, then features are selected along the minimum trajectory. This feature path is then up loaded to the aerobot.

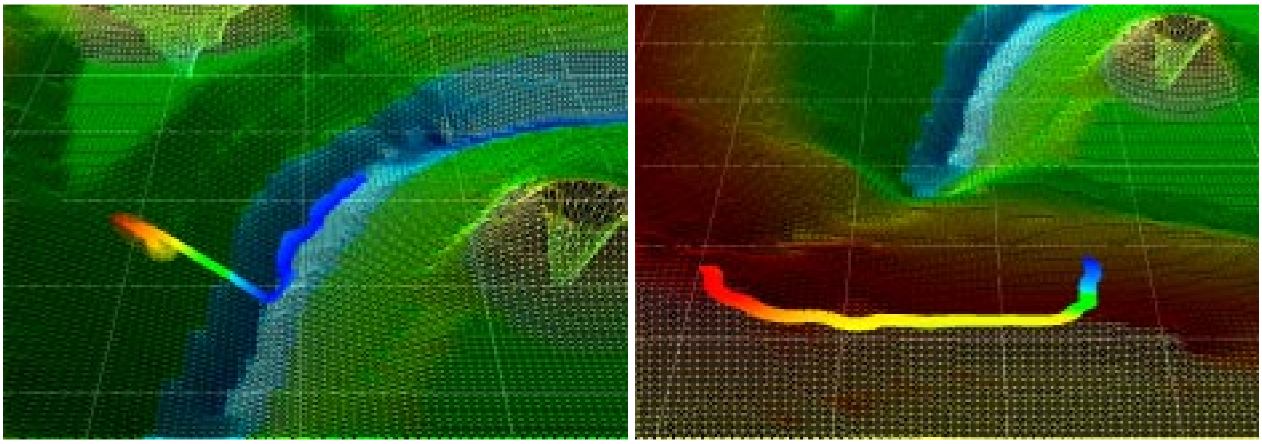

Fig. 7. Result of a manual matching process of the scanned data from Fig.6

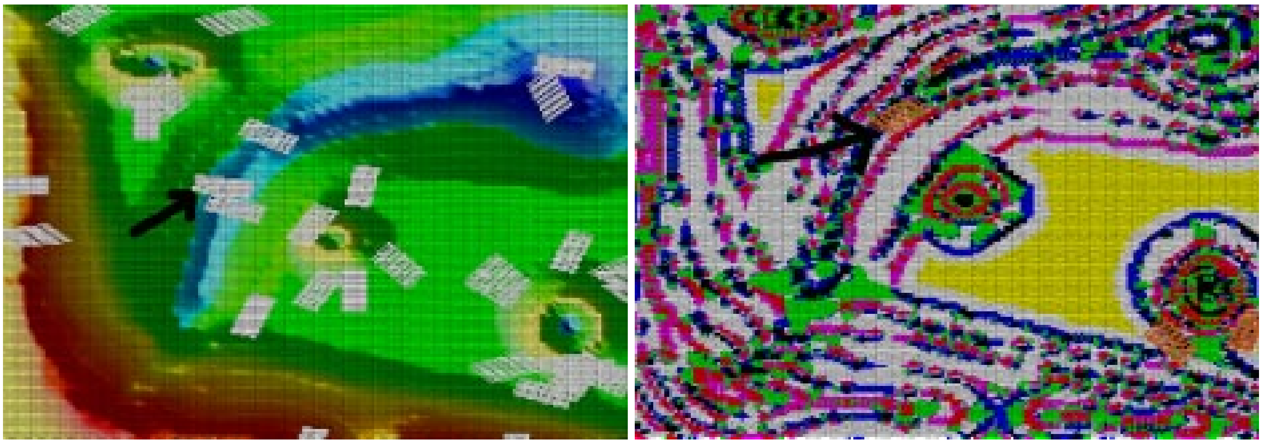

Fig. 8. Results of the automatic matching processes of the channel scanned data from Fig.6

XI. Discussion and Conclusion

This method of using geological features for localisation and navigation has proven to be quite robust, as during all the initial experiments the aerobot has localised on either a peak or pit, each time starting from various altitudes, orientations and locations within the region.

The experiments conducted to date have been in feature rich environments, future work includes conducting similar experiments with varying degrees of feature richness. Then all experiments will be repeated with varying degrees of sensor noise. The results of these experiments will be used to determine the types of terrains this navigation system can function in and the robustness of the feature following algorithms.

Obvious examples of the limitations of such a system are when the terrain contains very few features such as a plains or many features of the same kind with few of no distinguishable differences. This means that on Mars the system could operate in the Southern hemisphere but may have difficulty operating in the Northern hemisphere, due to the lack of surface features.

XII. Acknowledgments

This work is being funded by the Department of Computer Science, UWA, U.K.

References

[1] Dr. David E. Smith, *The Mars Orbiter Laser Altimeter (MOLA) Instrument and Science Investigation*, NASA GSFC, 2000.
[2] Robert S. Afzal, The Mars Observer Laser Altimeter: Laser Transmitter Applied Optics, 33, 3184-3188, 1994.
[3] Planetary Data System, *MOLA Data Product Archives*, http://wufs.wustl.edu/missions/mgs/mola/index.html, 2002.
[4] Curtis L.Olson, *FlightGear*, http://www.flightgear.org, 2002.
[5] Shaw A., Summers P., Geneste E, and Barnes D., *ALTAIR-1: A laboratory based aerobot for planerary exploration experiments*, Proceedings of European Advanced Robotics Systems Masterclass and Conference, 2000.
[6] J. D. Wood, *Virtual Field Course: Landserf*, http://www.geog.le.ac.uk/vfc/software/landserf/index.html, 1999.

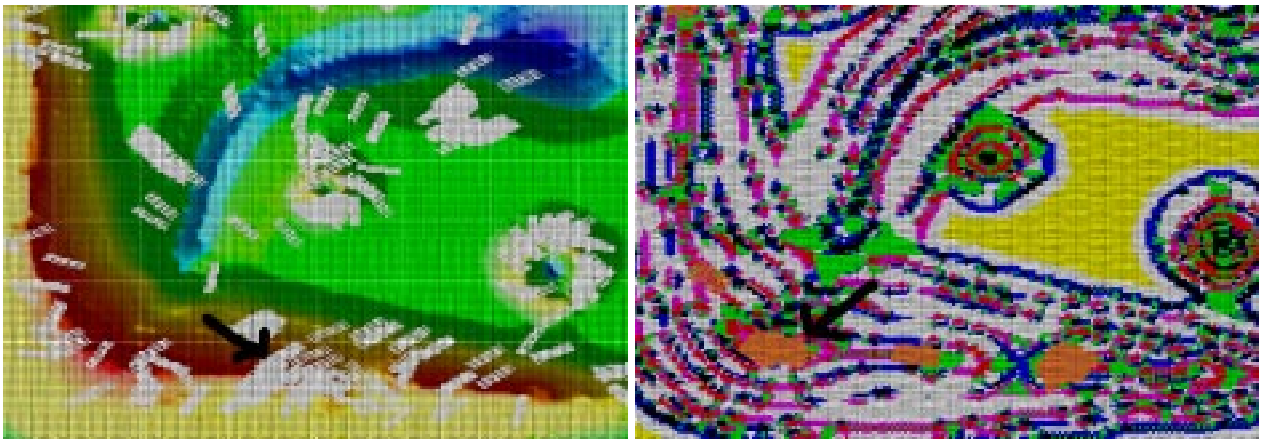

Fig. 9. Results of the automatic matching processes of the ridge scanned data from Fig.6

[7] Peter Dana, *Global Positioning System Overview*, http://www.utexas.edu/depts/grg/gcrafts/notes/gps/gps.html, 1999.

[8] Bill Myers, *Celestial Navigation*, http://www.nav.org/cel/introduction.html, 2000.

[9] Stephen D. Fleischer and Stephen M. Rock and Richard Burton, *Global Position Determination and Vehicle Path Estimation from a Vision Sensor for Real-Time Video Mosaicking and Navigation*, Proceedings of the OCEANS 97 Conference, 1997.

[10] Stephen D. Fleischer and Stephen M. Rock, *Experimental Validation of a Real-Time Vision Sensor and Navigation System for Intelligent Underwater Vehicles*, IEEE Conference on Intelligent Vehicles, 1998.

[11] Kortney N. Leabourne and Stephen M. Rock and Stephen D. Fleischer and Richard Burton, *Station Keeping of an ROV Using Vision Technology*, Proceedings of the OCEANS 97 Conference, 1997.

[12] Natural Science 412, *Discovering Magnetism/Compasses/Navigation* http://earthview.sdsu.edu/trees/mag.html, 2000.

[13] Ryan Simmons, *Mechanical analysis MOLA-2 CDR*, NASA GSFC, March, 1995.

[14] Shuttle press kit, *Shuttle Radar Topography Mission*, January, 2000.

[15] Riegl Instruments, *Applications*, http://www.riegl.co.at/applicat.htm, 2000.

[16] Coner D., *A Basic Time of Flight Pulsed Ranging System*, E-O Devices, 2000.

[17] Per Liedman, *Atlas*, http://atlas.sourceforge.net/, 2002.