STORED IMAGE-BASED MAP BUILDING AND NAVIGATION FOR PLANETARY ROVERS

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ABSTRACT

A novel method of image-based map building and navigation is proposed for future planetary rovers. The proposed map is not a usual height map, but consists of several images of landmarks connected by the required rover actions from the rover position and orientation from which one of the landmark image is obtained to the position and orientation where another landmark image is obtained. This is similar to the way we usually remember how to get to a certain place from another place, such as "going to the position where building A is seen like this, then turning right until we can see post B and then moving forward until we can find building C", etc. It provides a simple and effective map building especially in the case when a rover wants to make many roundtrips from the key station to experimental sites. The characteristics of this method is that the navigation based on it is robust to the errors in maps as well as in the estimation of current position and orientation of the rovers. Basic concept and algorithm are described, and the results of laboratory experiments are shown and discussed.

1. INTRODUCTION

When an autonomous rover lands on a certain planet, it will be frequently required that the rover must first make a map of the surrounding world for the later navigation purpose. This is because the maps made before the landing will be usually low resolution ones generated from the observations by the orbiters, and so cannot be used for precise navigation to reach certain points within small area. What types of map should be built by what kind of instruments is a hot research issue, for which many ideas have been proposed. This paper proposes one method of such map building, based on how human being constructs a map in his brain in order to remember the way to get to a certain place which he reached before.

The problems of using the most standard maps, namely "height maps", are that the navigation based on them will be highly sensitive to the accuracy of the maps and the current position estimation of the rover. For example, if a rover wants to go from point A to point B and then turn left and go forward to point C, where A,B and C are points on the height map, the rover must know the accurate distance from point A to point B as well as from point B to point C, and the angle between point A-B line and point B-C line, which should be estimated from the map. Moreover, during the actual moving phase, the rover should know its current position or how much it has already moved from point A, and by how much angle it has already turned. Maps made on planets and navigation system on the rover is predicted to be, however, not so accurate in many cases as to satisfy these requirements.

We, human beings, will do in completely different way to remember and use "a map" in our brain, if we don't have accurate maps or don't have any accurate methods to locate where we are now. We usually remember the way to go from one place to another in this way: "I must first go forward to the direction of that tall building A, and when I reach the post B, I must turn right until I can see the road C. I must go forward until I can see the building D like this size, then turn left to see the destination E. (Fig.1)" For this purpose, we have mental images of building A, post B, road C, building D (also with its size information), and destination E, and the required actions between them. During actually moving, we compare what we actually see now and these stored images to determine what action we should do next. This method is expected to be robust to the errors in maps as well as in the estimation of our current position and orientation.

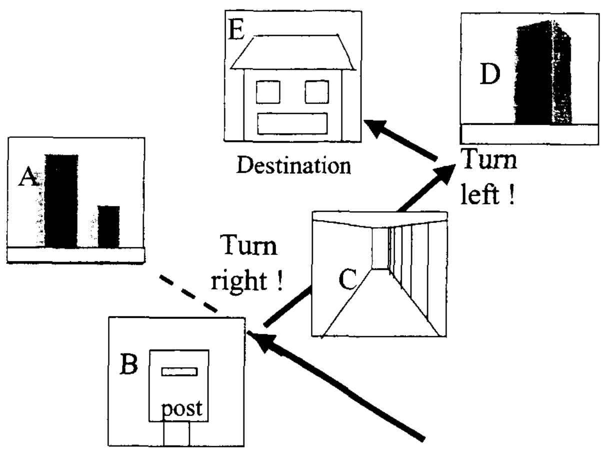

FIG.1 Our Everyday Navigation to Reach Known Place

The proposed map building and navigation method for planetary rovers is based on this simple navigation we usually do in the everyday life. This will provide very powerful and robust navigation especially when a rover

Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

wants to make many roundtrips from the key station to experimental sites.

In the next section, this concept is explored in more detail, and some key algorithms including image processing will be shown in section 3. We have performed some laboratory experiments to verify the feasibility of this concept and evaluate the performance, which will be explained and discussed in section 4. Conclusions and future plans are summarized in section 5.

2. CONCEPT OF IMAGE BASED MAP BUILDING AND NAVIGATION

As discussed in the previous section, the problem of using the usual height maps for planetary rovers lies in that this method is highly dependent on the accuracy of the maps and the estimation of the current position or orientation of the rover, which is in many cases difficult to achieve in simple systems.

In order to compensate for these map and navigation inaccuracies, it is recommended that certain events (such as "beginning to see a certain terrain") should be utilized to trigger certain rover actions (such as "stopping moving forward" or "stopping turning right"). But if the rover only has height maps, such triggering events are difficult to define, or must be generated with much effort. Based on the observation of how we usually navigate ourselves in everyday life, we propose utilization of "images" for this triggering event; for example, the rover is programmed to stop moving forward when it sees a certain landmark in the way as stored in the memory. The size of the landmark, not only its shape, is also important if it is used for triggering, for example, the "moving closer to the landmark" action of the rover. As a result, the map consists of several images connected by the rover actions required to transit from the position and orientation where one image is seen to the other (Fig.2).

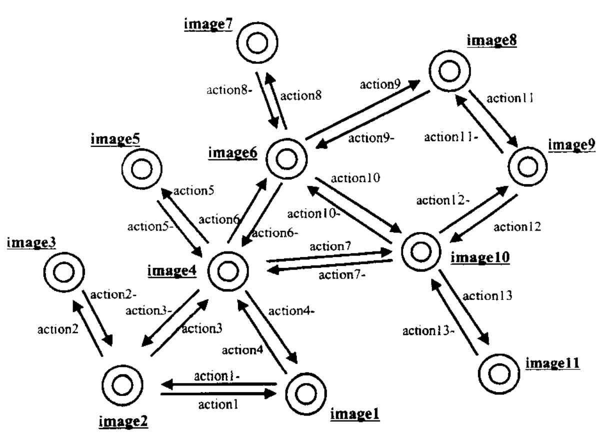

FIG. 2 Concept of Image-based Map

This navigation is highly dependent on the image matching capability of the current view with the stored images, which requires robust image processing system and algorithm. We employed a contour based matching algorithm, which is robust to the change in lighting condition and colors. The details will be given in section 3.

It would be too restrictive if the current view should perfectly match one of the stored images. The image matching subsystem has, therefore, some tolerance to such minute difference. However, if the difference between the current view and one of the stored image is small but cannot be neglected in planning of the next action (for example, "we are now a little too closer to post B to turn right to see road C"), then the system should make some adjusting actions to tune the current view to be matched with the stored one. We usually can do this kind of thing easily, because we know what kind of movement will modify the current view in the desired direction. For example, if the actual image is a little smaller than the stored image, we know that we should go nearer to the target to match the two images. This capability should also be implemented in the system.

The next question is the utility of this type of map and image based navigation. This map can be made only where the rover once visited. In other words, maps can never be made where the rover has never been to. So, is this map really useful for navigation purpose ? The answer is, yes for some objectives. Maps will sometimes be used for doing autonomously roundtrip several times from the key position (where a mother-ship is located, for example) to the sites where interesting scientific observations have been made. The proposed map and navigation way will be useful for such objective. Besides, if routes to several different interesting sites have been found and stored in this map form, then these routes can be connected by a certain key position (having a certain same landmark image, such as the position of the mother-ship), so that the rover can move from any points on the map to any other points on it.

3. BASIC ALGORITHM FOR MAP BUILDING AND NAVIGATION

The basic algorithm required for these operations will be as follows.

3.1 Image based map building

When a rover takes an action (during intentional search for a destination place or by chance during random movements, etc.), and this action has been found worth memorizing because, for example, it is found to be one leg on the route from the key station to the destination place, then the system stores the obtained image before and after the actions and actually performed action itself, in the form of the following triplet.

- image before action (called "Image-Before", or "IB")
- action ("A"),
- image after action ("IA")

FIG. 3 Images and Action Triplet

IB and IA are actually obtained images (such as rocks or terrain) which are considered to be candidates of "landmark images" useful for the later navigation purpose.

In order to do this, the rover should first tentatively store all these triplets during the movement into a kind of "short term memory", and when it finds the right way from a certain point (say, P) to the destination point (say, Q), then it stores only those triplets relevant to this way into the "long term memory." Fig.4 shows one example of a map built in this way. A0 through A5 show the triplets on the found sequence.

3.2 Image based navigation

Once it obtains this "one way triplet sequence," it can follow it to move from point P to point Q by taking the required actions written in the triplets in the sequence, using IA as the stopping condition of each action. To do this, the rover continually captures images and compares them with the stored images so that it can detect the current situation (the position and orientation of the rover) or detect the stopping condition of currently taken action. Efficient and not so time-consuming image matching algorithm is indispensable for this operation.

Besides, the rover can also move from point Q to point P by following the sequence backwardly and reversing the actions written in the triplets (for example, "move forward" is changed to "move backward.") , which is useful for making roundtrips.

3.3 Image adjustment mechanism

As discussed in section 2, the rover sometimes requires adjustment actions to fine-tune the current view so that it coincides with the stored image before taking an appropriate action.

This adjustment can be made using the knowledge as to the relationships between the action (such as "move forward") and how the image changes in the camera frame by this action (such as "the image of the object in front gets larger"). Hopefully, this knowledge had better be obtained autonomously by generalizing experiential data of "action and resultant image changes." This kind of learning of actions and their consequences have been studied in various context [1]-[5], but little research has been performed concerning the relationships between actions and their effect on the image changes. Application of neural network-based

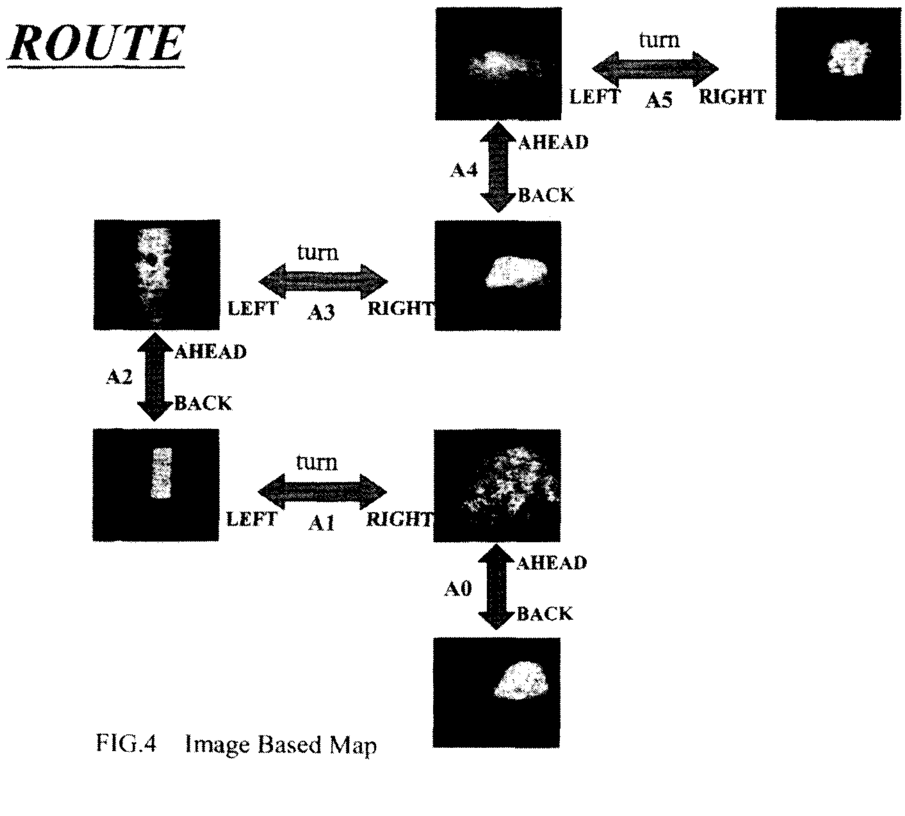

FIG.4 Image Based Map

learning mechanism is being studied in this line, with the objectives of realizing human-like capability of generalizing image changes; we human beings know from our everyday life how a certain object changes its outlook if we see it from the different angles, etc. Much research should be done for realizing it, and in our prototype system, these relationships are pre-coded in program level so that the system can decide which action to take to reduce the difference between the current and the stored images.

3.4 Connection of routes obtained differently

When the system accumulates this kind of "one way image sequences", it may happen that a certain image (say, X) of a sequence (say, P-Q) and a certain image (Y) in another sequence (R-S) almost coincides (such as in Fig.5). In such a case, the system tries to find what kind of motion(s) should be applied to reduce the difference between these two images X and Y, and stores the result in the form of the above mentioned triplet. By this process, the sequence P-Q and R-S get a linkage, and it becomes possible to move from P to R or S to Q. If the rover has some "key station" from which all the explorations start, then all the sequences get connected by way of this point.

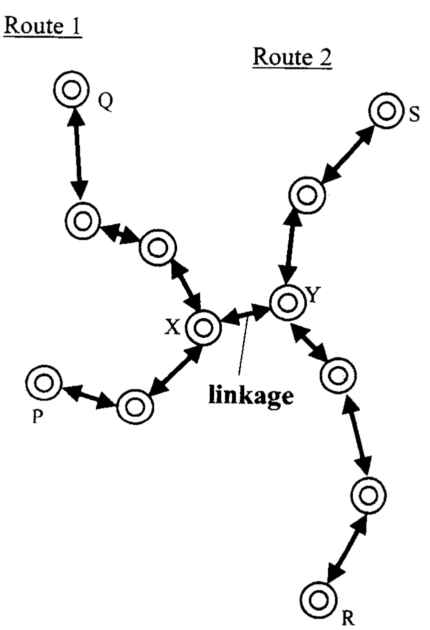

FIG.5 Connection of Differently Generated Sequences

3.5 Image matching algorithm

Image processing for matching the captured image with the stored image is the key ingredient in the overall algorithm. In our system, the following very simple yet efficient algorithm is utilized.

1) An object is extracted as a cluster of pixels from the background using the following clustering algorithm:

1-1) 4 by 4 pixels are considered as one "cell," whose brightness in RGB is calculated as the average of the 16 pixels
1-2) Cells whose brightness (sum of RGB brightness) is below a certain threshold are considered as background.
1-3) Horizontally neighboring cells whose brightness are above a certain threshold are integrated into one cluster
1-4) Vertically neighboring clusters are integrated into one cluster

2) The x-y coordinates of the contour of the cluster are calculated, with the origin of the coordinate being the C.G. of the cluster and the length being normalized using the distance from C.G. to the topmost contour point. The number of coordinate points used for matching is fixed at 50 and they are distributed on the contour at almost equal interval.

3) These 50 coordinate points of the captured image is compared with the coordinate points extracted in the same way from the stored image (Fig.6). The Euclidian distance between the corresponding contour points in two images are used to judge the similarity between these two points. Then the number of "similar" point pairs is used to judge the similarity of the two images; if this number is above a certain threshold, the two images are considered to be matched.

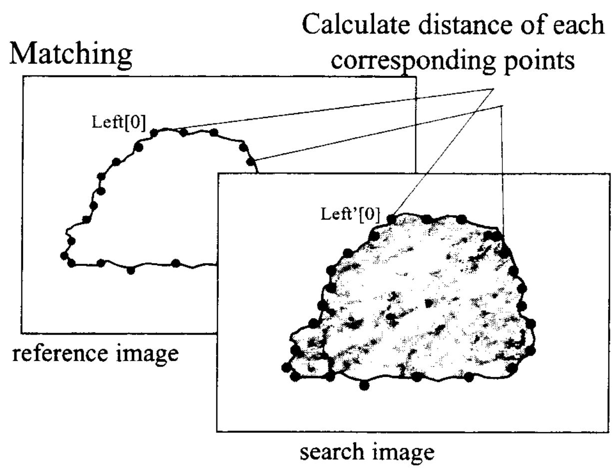

FIG.6 Image Matching Algorithm Based on Contour

4. LABORATORY EXPERIMENT

4.1 Experiment setups

In order to verify this concept, we have developed laboratory experiment system (Fig.7), in which a rover (Fig.8) with an on-board camera and a computer system is used to experiment the above mentioned map building and navigation on the laboratory floors where many types of actual rocks are placed. (Fig.9)

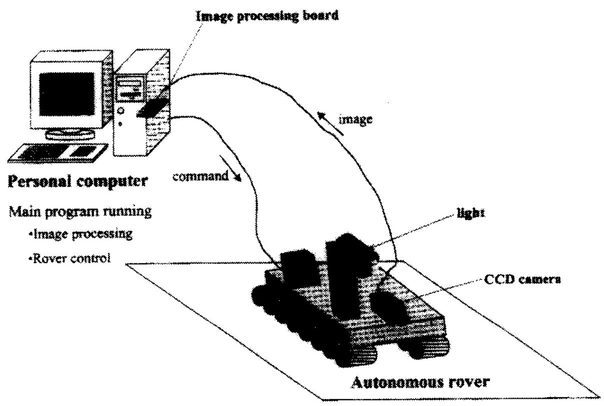

FIG.7 Experimental System Overview

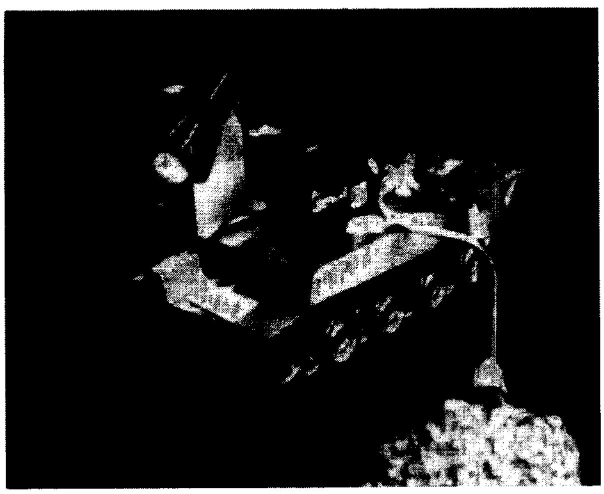

FIG.8 Photo of the Used Rover

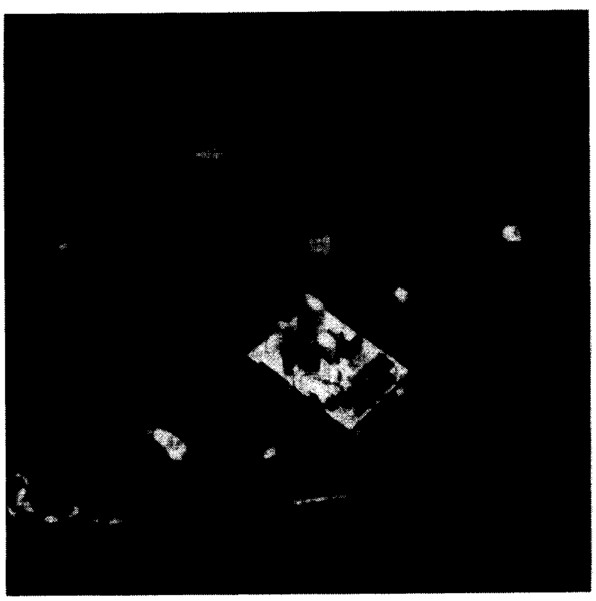

FIG.9 Experiment Setup with Rover and Rocks on Floor

The experiment is performed in the following way:

1) We control the rover manually from a certain point P to another point Q, during which the rover system gathers triplets. At this point, the map described in Fig.4 is obtained.
2) The rover is placed at point P and then it is ordered to follow the same route to reach point Q using the obtained map.
3) Then the rover is ordered to move backwardly from point Q to point P, also using the map.

Connection of differently obtained sequences (such as in Fig.5) has not been experimented yet.

4.2 Results of laboratory experiments

The results obtained up to now can be summarized as follows:

(1) Once a rover finds a way from P to Q, then it can move backward from Q to P and forward from P to Q almost without failure.
(2) The image adjustment mechanism, which are coded now in the program level, works effectively when the difference of images are rather small, but works poorly when it is large.
(3) The employed image matching algorithm works rather well, but sometimes makes mismatch in the case that the lighting condition is severely changed from when the map is made to when the actually navigation is performed. The shadows on the rocks often become the cause for such mismatching.

We are now trying to enhance the matching algorithm, especially in terms of compensation for the change of lighting condition. More consideration is now being made as to the utilization of many, not one, objects in the image for matching, in order to make the matching algorithm more reliable. Experiment on connection of differently obtained sequences is planned to be performed shortly.

4.3 Discussions

The drawbacks of this system are (1) the system cannot accumulate information as to the region where the rover has never visited and (2) the system requires high volume of memory to store large number of images. For (1), we think that one of the important objectives of making detailed local maps will be to remember how to get to the places which have been found interesting by exploration. The image adjustment mechanism is considered important for "interpolating" between the images in the map, which will reduce the number of required images per area. We are now studying the application of neural network based learning algorithm for this objective.

The second problem will be solved to some extent by the currently very fast development of larger volume on-board memory. Effective data compression method such as JPEG/MPEG will further reduce the required memory size. In the algorithmic field, we are now also studying about storing the images not in the "image" form, but in already pre-processed form such as the list of contour points. This will reduce the flexibility about how to use the stored image, but tremendously reduce the required memory size. Trading-off between these two factors is now being made to find an appropriate coding method of the stored images.

5. CONCLUSIONS

A new map building and navigation method fully based on obtained images have been proposed, referring to how we human beings remember the way to a certain place in the everyday life using images memorized in our brain. The proposed method is expected to provide very simple and robust navigation method especially for such rovers that make roundtrip from the key station to the experimental sites many times. Laboratory experiments have shown the feasibility of the concept.

The important future works will include the enhancement of the image processing and matching algorithm, efficient and flexible coding of the stored images and application of machine learning to enhance the image adjustment functions. We are continually studying in these lines.

ACKNOWLEDGEMENT

This research is funded by "System Theory of Bio-Informatics and Its Extension towards Engineering Design Theory," which is one project of "Research for the Future of Japan Society for the Promotion of Science."

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