Autonomous Locomotion : CNES Technological Program

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ABSTRACT

Autonomy seems necessary to improve the range of operation of a planetary rover : this paper presents the developments (hardware and software) accomplished in C.N.E.S. in this topic and the results of experimentation done using different vehicles on the G.E.R.O.M.S. test site.
C.N.E.S. works have been focused for several years on stereo devices and processing software including picture processing to build a 3D model, path planning and rover control.

1.INTRODUCTION

The interest of mobile platform for planetary exploration is no more to be demonstrated : a set of scientific experiments on board of a rover is able to process different kind of samples encountered on its way and to select the ones which look particularly interesting for the scientists who examine the pictures taken from the rover.
But to do this on another planet, we have to cope with the delays required by data transmission, and especially pictures, from the rover to the Earth where they will be processed. These delays include :

- radio propagation delay, which can reach 20 minutes for a single way transmission using a satellite as transmission relay, we have to wait for the visibility of the relay, which happens not more than a few times a day
- using direct rover-Earth transmission allows only very low rates (for instance 1 kbit/s.) even with a radiated power of 20 W and a large antenna
- availability of the Deep Space Network
- processing time.

- In any case the delay between a snapshot from the rover and reception of command from the Earth lasts at least several hours, that makes real time teleoperation unworkable.

Except the case where the rover is moving on a flat area without obstacles, it is unable to move beyond its perception range (i.e. in general several meters) between two command sessions if the path is defined from the Earth by an operator.
On this reason, a rover able to define its path and to move by itself on the soil of Mars will increase significantly its progression range.
For a lunar rover, the transmission delays are much less even if a relay satellite is necessary, however the time necessary to process the data, define and validate the path can remain noticeable and a ground support must be available as long as the rover moves ; autonomy in this case is not mandatory, but can decrease a lot the operational charges.

2.REQUIREMENTS FOR AUTONOMY

The degree of autonomy developed by C.N.E.S. corresponds to a one-day mission during which the operator selects a distant goal without necessary knowing if there is a path to this point : the rover finds its way to this point by itself.
For this, the functions necessary on-board are :

- perception
- terrain analysis
- path planning
- path execution

Perception : perception of the environment shall be fine enough to detect all the obstacles to the progression of the robot. The notion of obstacle is related to the crossing capabilities of the rover ; we take into account two criteria for discriminating navigable zones in every cell of the digital terrain model (DTM):

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- in an area of a size corresponding to the horizontal projection of a wheel, the difference of altitude between the lowest and the highest point shall not overpass a discontinuity threshold related to the crossing capability of the chassis ; this value must be chosen tc fit with the rover features
- the slope of the rover in any direction shall not overpass a threshold related to the stability of the chassis.

Taking into account the perception range requirement (larger than 5 m.) and the features of the chassis ("light" rover whose length is between 50 and 100 cm, weight between 50 and 100 kg and wheel size between 10 and 20 cm) we need to build a digital terrain model with an vertical accuracy better than a few centimeters.

Two devices can be used :

- laser range finder : a laser beam is swept in site and azimuth in the whole field of view and we measure the propagation time of the beam reflected by the soil : the accuracy can be good enough, but this devices is difficult to qualify in a stringent environment such as Mars or the moon due to the sweeping mechanisms. Furthermore, electrical consumption is high because of the mechanisms and wide-band electronics.
- stereovision : it consists of taking two pictures of the scene to analyze with two separate CCD cameras : in each camera, the pictures of a given object are at different places, according to the distance D between object and cameras. The difference of coordinates or parallax is proportional to 1/D : stereo hardware is not too complex ; the drawback of this device is to require a big amount of calculations ; but, on one hand, processors are becoming faster and faster, on the other one, algorithms have been optimized to reduce computation time and memory volume to quite reasonable values.

We have based our development on stereovision ; the main features of our device are the following :

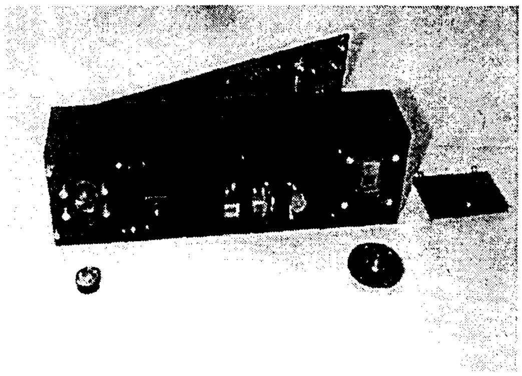
- stereo basis (distance between optical axes of the two cameras) : 200 mm
- CCD : 300x400 square pixels of 23 microns
- Focal length : 5.5 mm, giving as field of view +/- 40° in azimuth and +/-30° in site.

The grey levels of the pictures are digitized on 10 bits ; the pictures are sent to the processor through a serial line at a rate of 10 Mbit/s : the two pictures are transmitted in less than 1 s.

To reduce processing time for parallax calculation, it is mandatory that the images of the same object point in the two cameras are situated on the same line of the matrix, that requires either very harsh optical and mechanical specifications or an accurate characterization of the focal plane ; we choose the latter solution : in the whole field of view, we measure the position in the focal planes of image points given by a beam whose direction is very accurately known : the gaps between real and theoretical coordinates are put into a map used to correct the pictures. The one requirement of optics and mechanics is to remain stable.

Two prototypes of these stereo devices have been constructed using conventional technology for electronics, optics and mechanics ; their main features are following :

- Stereo basis : 200 mm
- mass : 1 kg
- size : 250x66x55 mm
- electrical consumption : standby 5 W
snapshot 30 W



CNES-LAS stereo device

For space application (Rosetta project) flight models are under development by CSEM using a very compact 3D assembly technology and a larger 1024x1024 points matrix : the size of the camera, optics included is 35x30x20 mm. With this technology, a stereo device using a 1024x1024 matrix would present following features :

- Stereo basis : 120 mm
- mass : 350 g
- size : 130x35x30 mm
- electrical consumption : < 4 W.

The stereo device is equipped with a triaxial accelerometer which can give roll and pitch angles allowing to build a digital terrain model with a vertical z axis ; it is connected to the

processor through a serial link whose throughput is 10 Mbit/s. The input link (processor to stereo device) is used to command the snapshots and define their parameters (exposure time and analog/digital converter to optimize the grey level histogram), and to require pictures and accelerometers data ; the output link delivers the data to the processor.
The use of active pixel sensors (APS) instead of CCD would still reduce mass, volume and consumption.

Terrain analysis : the pictures are first rectified (i.e. corrected from geometrical aberrations such as distortions or mechanical biases...) using the results of the calibration previously achieved.
The rectified pictures correspond to two cameras with optical axes parallel and distant between them of the stereo basis B, lines and columns of the two matrices parallel ; for both pictures, snapshot parameters are identical : focal length f, size of pixels p. Each object point seen by the two cameras gives one image point in each camera (on the same line in both after rectification): the difference d between the positions of the two corresponding points, called disparity or parallax gives the distance D between the projection of the object point on the optical axis of the cameras and the optical center of the lenses by the relation : $D = f.B/d$.
This allows to define the 3 coordinates of the object point when we have got the parallax d.
To get the parallax, for each point of the left picture, we take a window centered on the point and we seek, in the same line of the right picture (in a range defined by maximal and minimal reconstruction limits) the position of the window giving a maximum of correlation between the textures of both windows according to our correlation criterion.
An interpolation gives a subpixellic value of the parallax to improve the reconstruction accuracy.
In return, taking the point found as maximum in the right picture, we look for its corresponding in the left picture : if we find the departure point, the correlation is validated ; if not, the point is labeled "unknown" : so, we eliminate most of the correlation errors.
When we have processed all the points, we have the parallax map from which a last filtering removes residual errors and we can build a cloud of 3D points used to build the digital terrain model.
Of course, this part of the algorithm requires a lot of processing time. This time has been reduced by different ways :

- simplification of the correlation criterion
- incremental calculation of the criterion by propagation along lines and columns
- calculation in two steps, the former one with reduced resolution to reduce the parallax interval.

This algorithm which represents the main part of the whole processing time requires less than 480 ms. on Ultrasparc II at 248 MHz and less than 850 ms. on PowerPC604 at 150 MHz for pictures of 384x280 pixels, with a parallax interval of [4..60] and a base of 200 mm.
The digital terrain model is not complete : the correlation does not work on areas which are not seen by both cameras, and on very uniform places. These places are labeled "unknown" The other ones are labeled "navigable" or "not navigable" according to the criteria defined here above.

Path planning : we suppose that the goal of the robot is either a given point or a given direction. With a navigation map labeled as "navigable", "not navigable" or "unknown", it is possible or not to define a path leading to the goal through only navigable areas. If no path is available, the solution is to turn the cameras toward another direction to find a path.
This method called "step by step planning" gives good results, but is not optimal for two reasons :

- if an accurate localization is not available, to take into account the uncertainty of the path execution it is necessary to enlarge the obstacles of a value equal to the maximum drift of the rover (proportional to the distance crossed by the rover), so that the planner would not pass between two obstacles separated by a gap wider than the rover if they are far from it.
- some navigable areas are labeled "unknown" when they are far from the rover because the density of 3D points decreases with the distance to the rover

To overcome these drawbacks, another method called "continuous planning" has been developed [7] which consists of :

- merging the successive navigation maps to get larger planning areas : merging navigation maps whose content is the local slope and maximum discontinuity inside a cell solves the problem of elevation discontinuities due to localization and attitude uncertainty which occurs when we merge digital terrain models.
- The planning area around the rover is divided into two parts : one surrounding the rover can be crossed before a new perception and thus uses the same

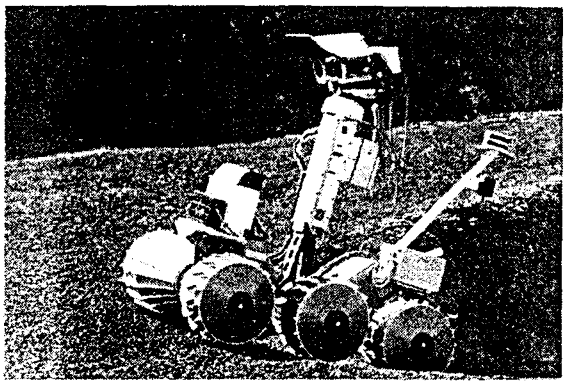
algorithm than step by step planning ; but beyond, in the peripheral area, a new perception will be done before crossing it, and it is not necessary there to enlarge the obstacle or to forbid unknown areas which can become navigable by the next perception.

Path execution : the major problem in path execution is to get a good estimate of the motion ; on smooth soils, dead reckoning gives good results, but as far as soil becomes rocky or loose, the results become very poor. Inertial sensors can be used, but their mass and consumption are still very important.
Motion estimation by vision has not these drawbacks and two different algorithms are presently under evaluation : accuracy of a few percent seems to be feasible.

3 Results of experimentation

GEROMS test site

A first experimentation of these methods has been tested in CNES on the GEROMS site [1] using EVE vehicle adapted from a Marsokhod chassis [2]. In absence of gyros allowing measurement of instantaneous attitudes, image acquisitions are preferably performed with the chassis at stop. The experimentation validity is however satisfied since this mode could correspond to a non-nominal situation that would undervalue the method potentiality. Trajectories have been also adapted to the locomotion capabilities that can only execute linear movements and rotations on place. Localization errors up to 10% of the distance traversed and 2% in attitude have been considered for path planning. This method has already demonstrated its efficiency to drive the robot out of quite constrained rocky zones where the previous techniques [2], [7] met their limitations.



EVE vehicle

4. Conclusions

The major contribution of this method is the capability to improve the autonomy of a planetary rover by widening its knowledge of the environment already traversed. The robot can thus generate itself even better trajectories than what could be determined by an operator on the ground.
An interesting property of the navigation maps that we have proposed is the absence of hypothesis on the sensor type that produced the elevation data. This type of method will easily take into account data coming from other sensor devices (proximeters, radars for soft soil detection). Another advantage is the possibility to rely on localization sensors (position and attitude) with poor accuracy. This is particularly a critical issue for missions involving light vehicles (mass and power consumption). Finally the method is generic enough to be applied to small rovers (small CPU power and low memory). Perception data can be acquired either in motion or at stop. There is also no particular hypothesis made on the type of vehicle being used and the kind of trajectories executable by the locomotion system (gyrations, rotations on place, linear displacements...).

5. References

[1] M. Delail. First campaigns on the GEROMS mobile robot test site. IARP., Montreal, June 1994.

[2] M. Lamboley, C. Proy, L. Rastel, Marsokhod : Autonomous Navigation Tests on a Mars-Like Terrain, Autonomous Robots, 2, 1995.

[3] J. Matijevic, D. Shirley, the mission and operation of the Mars Pathfinder microrover. IFAC 13th Triennal World Congress. San Francisco, USA, 1996.

[4] R. Volpe, J. Balaram, T. Ohm, R. Ivlev, The Rocky 7 Mars Rover Prototype. 1996 IEEE Robotics and Automation Conference, Minneapolis April 22-28, 1996.

[5] V. Michkiniouk, S. Medvedev, G. Koslov, Chassis of IARES-L planet rover demonstrator with a broad range of functional opportunities. i-SAIRAS'97, Tokyo, July 97.

[6] L. H. Matthies, C. F. Olson, G. Tharp, S. Laubach, Visual Localization Methods for Mars Rovers using Lander, Rover, and descent Imagery. i-SAIRAS'97, Tokyo, July 97.

[7] M. Delpech, C. Proy, L. Rastel, High Rate Autonomous Navigation For A Non Stop Traversing Rover. i-SAIRAS'97, Tokyo, July 97.

[8] R. Volpe, Rocky 7 Lavic Lake Field Tests, IROS97 Rover Workshop, Grenoble, France, September 1997.

[9] L. Rastel, M. Delpech, Rover Continuous Path Planning Using Merged Perceptions 1998 IEEE Robotics and Automation Conference.

[10] M. Delpech, L. Rastel, M. Lamboley, Enhanced Path Planning and Localization Techniques for Autonomous Planetary Rovers ASTRA98 Advanced Space Technologies for Robotics and Automation ESTEC, Noordwijk December 98.