A LOW COST MOBILE MAPPING SYSTEM

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ABSTRACT

In this work an alternative method, respect today's tipical road survey, is presented. Tipically, a road survey is carried out by a team composed by three operators at least, that moves with a vehicle on which an odometer is mounted on the rear in order to measure the effective travelled road. Given this operational procedure, a road survey requires, as a rule, a lot of time, resulting therefore very laborious and expensive regarding the employement of economic and human resources. Possible solutions to these problems could be represented by integration of Computer Vision technology with modern satellite positioning system, as GPS. Also in agreement with this idea, GeoVision, a digital photogrammetric software for road survey, has been developed at the University of Padua (Italy). The system consists of a van equipped with two digital cameras, Sony XC75CE recording in continous way the surveyed environment and a GPS receiver that provides post-processed differential positions. From a pair of correspondent digital images, the 3D position of a feature can be determined in a global reference system (namely WGS-84), by integration of photogrammetric triangulation techniques and computer vision algoritms. In following sections the tools regarding digital image processing subsystem of GeoVision will be described in detail.

1. INTRODUCTION

The use of a geographic information system (GIS) as decision tool for land and infrastructures management is even more increasing by public administrations so as private companies. This has resulted in a demand of a more precise GIS in planning and in an increasing demand for efficient data acquisition systems and up-date of existing databases. Therefore all these requirements make GIS information updating a permanent task. Traditionally, GIS data acquisition is a laborious process, requiring digitization of existing maps, manual data entry during the survey and other time consuming techniques and therefore have limited the applicability and uselfuness of GIS to potential users. From this point of view the automation and speed up of GIS data acquisition represent a very important issue in cases where field surveys have to be performed ([3] and [8]). In order to address the problems of update and reliability of GIS information, a low cost Mobile Mapping System, GeoVision, has been developed at the University of Padua (Italy). The system is based on a van equipped with two digital b/w cameras Sony XC75CE, with a basic format of 768x582 pixels, a GPS receiver an odometer and an analogue color videocamera. The CCD cameras, mounted on the front of the vehicle,

record in continous way the surveyed environment: on one hand they can provide more detailed information of objects on the earth in comparison to aerial photographs and remote sensing satellite images, on the other hand CCD images have to be georeferenced in order to supply 3D information about object position. To this aim the image acquisition stream is synchronized with GPS data collection via the PPS (Pulse Per Second) signal of the GPS receiver clock: in this way for each image pair it is possible to recover the geographic position of the cameras at the time of the shot. When signal blockages or poor GPS satellite geometry occur, the PPS signal is no more available until the minimum number of useful satellites is reacquired: in these cases the image acquisition is driven by the odometer, which data can be also used to interpolate the GPS positions. During the survey analogue images are also recorded by a color camera: these images are used in post-processing to extract all useful attributes, i.e. qualitative features, of selected objects of interest. All on board devices are controlled in real time via the GpsImage software, running on a PC Pentium III provided with a 13 GB Hard Disk. This high capacity allows up to 4 hours data recording, capturing two digital images, each of 450 KB, every second.

Although at the time only pseudorange measurements are collected, to improve the accuracy of GPS positioning these data are differentially corrected in post-processing together with the data recorded by a base station receiver of same type as the one on the van. The position of any object, visible on a pair of simultaneous images, can be determined firstly in the reference system of the two cameras, using digital photogrammetric techniques and computer vision algorithms, and after, merging this information with the GPS corrected data, it can be reported on any user selectable map.

As the main goal of our project was to realize a low cost mobile mapping system, GeoVision is not equipped with an Inertial Navigation System (INS). Therefore, as final step of the whole georeferencing process, our system doesn't provide 3D coordinates of object position, but rather its 2D coordinates on a map, as depicted in Fig. 3.

Given the absence of the INS, our major efforts were spent to implement a mobile system capable to carry out, anyway, rapid and enough accurate road surveys for all those public or private agencies that are interested in road data collec-tion for GIS applications. We have also in plan to employ such a system for teaching purposes in the Topographic field, in order to put in touch our students with GPS technology, digital photo-grammetry and related digital image processing techni-ques and GIS applications.
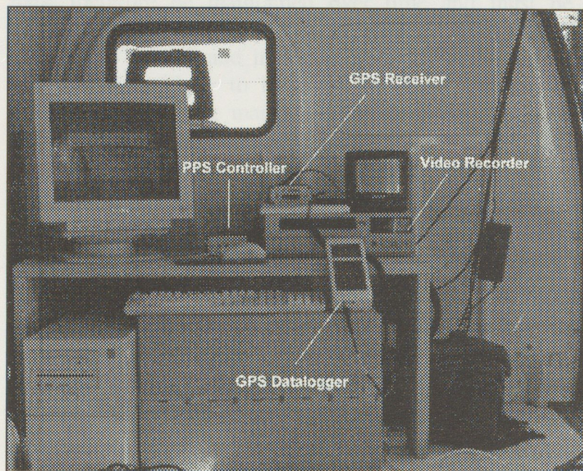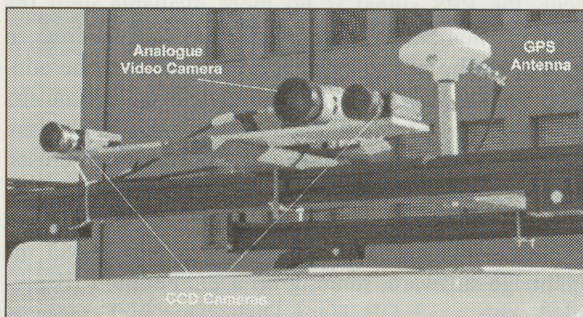

Fig.1 : Internal view of the van

Fig. 2: External view of the van

From software point of view, the GeoVision system was developed as four different, but not separated, modules, namely: *Caltool*, for the calibration of each CCD camera [6], *StereoCalib*, for the calibration of the whole stereoscopic system, *EpSearch* for the image matching and the triangulation step, i.e. the determination of 3D object coordinates in the stereoscopic reference system [2], and finally *NavPos*, the software module which integrates the corrected GPS data with the results of triangulation in order to determine the object position on a 2D map (Fig. 3).

In this paper we will focus the reader's attention mainly on this last module, pointing out the structure of the algorithm implemented in order to recover the van orientation on a mapping plane using only the GPS data and a Kalman filter.
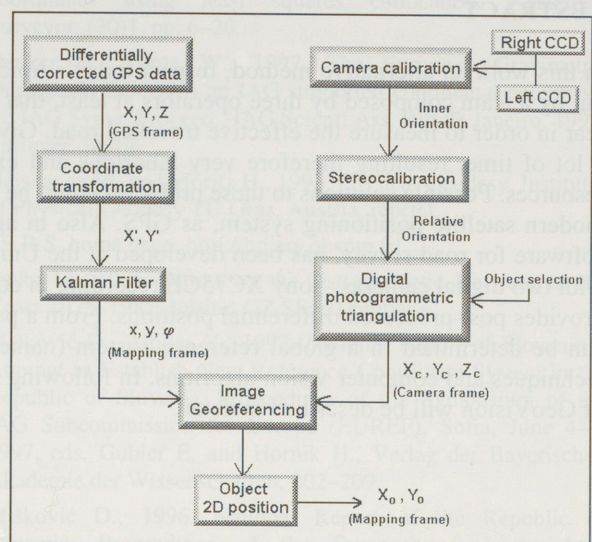

Fig. 3: The whole georeferencing process

2. THE GEOREFERENCING PROCESS

As exposed in [6], assuming that the origin of the stereopair is located on optical center of the left CCD camera, respect to the moving direction (Fig. 4), the 3D position of an object in the scene can be calculated as follows:

1) Compute the 3D object position in rover frame (Σ_r) by rototraslation from camera frame (Σ_c), as depicted in Fig. 5a and 5b,

$$\mathbf{r}_i^r(t) = \mathbf{r}_c^r + \mathbf{R}_c^r \cdot \mathbf{r}_c^r(t) \tag{1}$$

2) Compute the object position in the mapping frame (Σ_m) by rototraslation from rover frame (Σ_r), as depicted in Fig. 6,

$$\mathbf{r}_i^m(t) = \mathbf{r}_r^m(t) + \mathbf{R}_r^m(t) \cdot \mathbf{r}_i^r(t) \tag{2}$$

The whole georeferencing process can be summarized by following relationship:

$$\mathbf{r}_i^m(t) = \mathbf{r}_r^m(t) + \mathbf{R}_r^m(t) \cdot \left[\mathbf{r}_c^r(t) + \mathbf{R}_c^r \cdot \mathbf{r}_i^c(t) \right] \qquad (3)$$
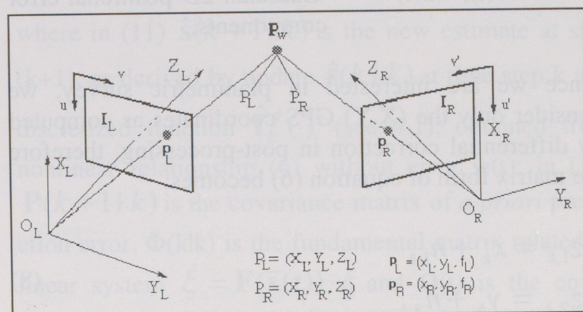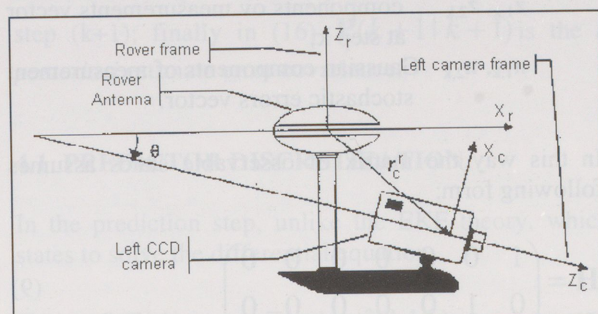

Fig. 4: The left and right camera frames

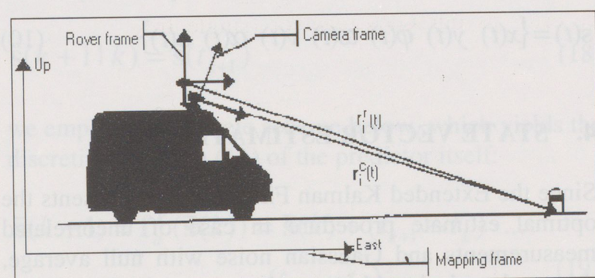Fig. 5a: Rototraslation btw. rover and camera frame

Fig. 5b: Another view of the relationship btw. rover and stereoscopic camera frame
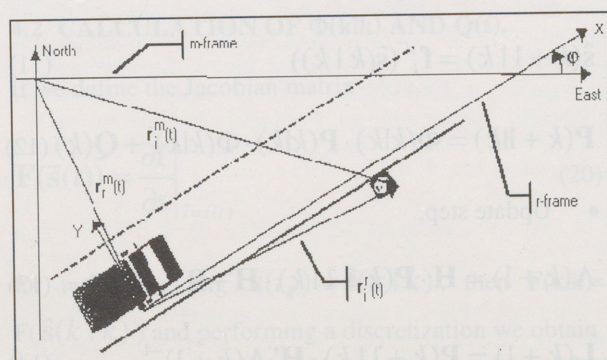

Fig. 6: Transformation btw. rover and mapping frame

While the first step is accomplished by the stereophoto-grammetric module using only digital image processing and photogrammetric techniques, in the second step we require not only the knowledge about the istantaneous position of the vehicle as derived by GPS receiver, but also the information regarding its direction, i.e. the bearing, respect to the mapping frame. This is needed to calculate the rotation matrix $R_r^m(t)$ between rover and mapping frame.

Given the absence of the INS, we have developed an algorithm to recover the bearing by GPS coordinates only. Certainly, the final accuracy will be lower than that achievable by MMS adopting the INS, but anyway we tried in our research to limit the error position to enough acceptable level for our mobile mapping purposes.

Ideally the bearing can be obtained from vehicle trajectory, computing the curve that represents it, as result of GPS coordinates interpolation, and the tangent to the curve at the point of interest (Fig. 7).
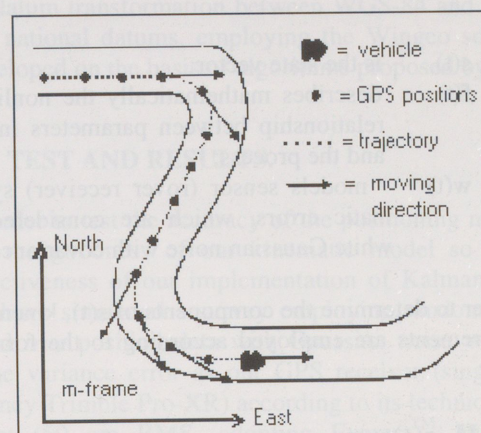

Fig. 7: Computation of vehicle's bearing

Although the GPS receiver provide us with 3 spatial coordinates, we are interested in positioning objects on 2D map, therefore we used in calculations only horizontal coordinates and only the angle φ between rover and mapping frame (Fig. 6) is computed through the algorithm described in next section. The estimates of that angle are performed in post-processing on the basis of all collected and double differentially corrected GPS measurements.

3. COMPUTING THE ROVER'S BEARING

In order to estimate the direction of the van for each collected GPS point we employed the prediction-update strategy of the well known *Kalman* filter [4].

The adopted kinematic model describes the vehicle trajectory in terms of state vectors represented by time dependent positional vectors, as derived from discrete-time measurements:

$$\begin{pmatrix} \dot{\mathbf{r}} \\ \dot{\mathbf{v}} \\ \dot{\mathbf{a}} \end{pmatrix} = \begin{pmatrix} \mathbf{v} \\ \mathbf{a} \\ 0 \end{pmatrix} \qquad \mathbf{r}(t) = \{x(t), y(t), z(t)\} \qquad (4)$$

This model can be applied in different operating modes, employing as state vectors whether pseudorange or carrier phase osservables, as collected by only one receiver or in differential mode. Note that (4) represents a costant acceleration model, in which vectors v and a incorporates the linear and angular components.

In order to take into account the error introduced by our unique positioning device (GPS) we use following formula:

$$\dot{\mathbf{s}}(t) = \mathbf{f}\{\mathbf{s}(t); t\} + \mathbf{w}(t) \qquad (5)$$

where

$\mathbf{s}(t)$ is the state vector;
$\mathbf{f}(t)$ describes mathematically the nonlinear relationship between parameters in $\mathbf{s}(t)$ and the process;
$\mathbf{w}(t)$ models sensor (rover receiver) systematic errors, which are considered as white Gaussian noise with covariance $\mathbf{Q}$.

In order to determine the components of $\mathbf{s}(t)$, kinematic measurements are employed according to the formula below:

$$\mathbf{z}_k = \mathbf{H} \cdot \mathbf{s}(t) + \mathbf{n}_k \qquad (6)$$

where

$\mathbf{z}_k$ measurements vector collected at discrete time t_k;
$\mathbf{H}$ matrix of measuring states;
$\mathbf{n}_k$ measurement Gaussian error with covariance $\mathbf{R}$.

In more detail our nonlinear kinematic model is composed by following 7 differential equations:

$$\begin{cases} \dot{x}(t) = v(t) \cdot \cos(\varphi) \\ \dot{y}(t) = v(t) \cdot \mathrm{sen}(\varphi) \\ \dot{\varphi}(t) = \omega(t) \\ \dot{\omega}(t) = \alpha(t) \\ \dot{v}(t) = a(t) \\ \dot{\alpha}(t) = 0 + w_1(t) \\ \dot{a}(t) = 0 + w_2(t) \end{cases} \qquad (7)$$

where

$x(t), y(t)$ 2D vehicle coordinates on mapping frame Σ_m;

$\varphi(t)$ angle of tangent to trajectory at time t;
$\omega(t)$ angular velocity of the van;
$v(t)$ linear velocity;
$a(t)$ linear acceleration;
w1(t), w2(t)   Gaussian 2D positional error components.

Since we are interested in planimetric survey, we consider only the (X,Y) GPS coordinates as computed by differential correction in post-processing, therefore the matrix form of equation (6) becomes:

$$\begin{cases} z_{1,k} = x_k + n_{1,k} \\ z_{2,k} = y_k + n_{2,k} \end{cases} \qquad (8)$$

where

$z_{1,k}, z_{2,k}$ components ov measurements vector at step k;
$n_{1,k}, n_{2,k}$ Gaussian components of measurement stochastic errors vector.

In this way the matrix of osservable states assumes following form:

$$\mathbf{H} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \qquad (9)$$

being the state vector

$$\mathbf{s}(t) = \{x(t) \ y(t) \ \varphi(t) \ \omega(t) \ v(t) \ \alpha(t) \ a(t)\} \qquad (10)$$

4. STATE VECTOR ESTIMATE.

Since the Extended Kalman Filter (EKF) represents the optimal estimate procedure in case of uncorrelated measurements and Gaussian noise with null average, the employed algorithm can be summarized by following formulas:

- Prediction step,

$$\hat{\mathbf{s}}(k+1 \mid k) = \mathbf{f}_k^d(\hat{\mathbf{s}}(k \mid k)) \qquad (11)$$

$$\mathbf{P}(k+1 \mid k) = \Phi(k \mid k) \cdot \mathbf{P}(k \mid k) \cdot \Phi(k \mid k)' + \mathbf{Q}(k) \qquad (12)$$

- Update step,

$$\Lambda(k+1) = \mathbf{H} \cdot \mathbf{P}(k+1 \mid k) \cdot \mathbf{H}' + \mathbf{R} \qquad (13)$$

$$\mathbf{L}(k+1) = \mathbf{P}(k+1 \mid k) \cdot \mathbf{H}' \cdot \Lambda(k+1)^{-1} \qquad (14)$$

$$\hat{\mathbf{s}}(k+1 \mid k+1) = \hat{\mathbf{s}}(k+1 \mid k) + \mathbf{L}(k+1) \cdot \dots \\ \cdot [\mathbf{z}(k+1) - \mathbf{H} \cdot \hat{\mathbf{s}}(k+1 \mid k)] \qquad (15)$$

$$\mathbf{P}(k+1|k+1) = [\mathbf{I} - \mathbf{L}(k+1) \cdot \mathbf{H}] \cdot \mathbf{P}(k+1|k) \cdots$$
$$\cdot [\mathbf{I} - \mathbf{L}(k+1) \cdot \mathbf{H}]' + \mathbf{L}(k+1) \cdot \mathbf{R} \cdot \mathbf{L}(k+1)' \tag{16}$$

where in (11) $\hat{\mathbf{s}}(k+1|k)$ is the new estimate at step (k+1), as derived by update $\hat{\mathbf{s}}(k|k)$ at time step k and discretized function $\hat{\mathbf{f}}_k^d(\cdot)$ (see 4.1), obtained from nonlinear relationship (6) without error $\mathbf{w}(t)$; in (12) $\mathbf{P}(k+1|k)$ is the covariance matrix of *a priori* prediction error, $\Phi(k|k)$ is the fundamental matrix related to linear system $\dot{\xi} = \mathbf{F}(\overline{\mathbf{s}}(t)) \cdot \xi$ and $\mathbf{Q}(t)$ is the covariance matrix of discretized error $\mathbf{w}(t)$, both reported in subsection 4.2; in (14) $\mathbf{L}(k+1)$ is the gain matrix of the filter; in (15) $\hat{\mathbf{s}}(k+1|k+1)$ is the new update at time step (k+1); finally in (16) $\mathbf{P}(k+1|k+1)$ is the *a posteriori* estimate error covariance.

4.1 PREDICTOR DISCRETIZATION.

In the prediction step, unlike the EKF theory, which states to solve the differential equation

$$\dot{\overline{\mathbf{s}}}(t) = \mathbf{f}(\overline{\mathbf{s}}(t)) \qquad \overline{\mathbf{s}}(t_k) = \hat{\mathbf{s}}(k|k) \tag{17}$$

to compute the predictor

$$\hat{\mathbf{s}}(k+1|k) = \hat{\mathbf{s}}(t_{k+1}) \tag{18}$$

we employ the discrete scheme below, which yields the discretized form in (11) of the predictor itself:

$$\overline{\mathbf{s}}(k+1) = \mathbf{f}_d^k(\overline{\mathbf{s}}(k)) = \overline{\mathbf{s}}(k) + (t_{k+1} - t_k) \cdots$$
$$\cdot \mathbf{f}(\overline{\mathbf{s}}(k)) + \frac{(t_{k+1} - t_k)^2}{2} \cdot \dot{\mathbf{f}}(\overline{\mathbf{s}}(k)) \tag{19}$$

4.2 CALCULATION OF $\Phi(k|k)$ AND $\mathbf{Q}(t)$.

If we define the Jacobian matrix

$$\mathbf{F}(\overline{\mathbf{s}}(t)) = \frac{\partial \mathbf{f}}{\partial \mathbf{s}}\bigg|_{\overline{s}=s(t)} \tag{20}$$

for t=tk, assuming $\overline{\mathbf{s}}(t_k) = \hat{\mathbf{s}}(k|k)$, then $\mathbf{F}(k|k) = \mathbf{F}(\hat{\mathbf{s}}(k|k))$ and performing a discretization we obtain

$$\Phi(k|k) = \exp\{(t_{k+1} - t_k) \cdot \mathbf{F}(k|k)\} \tag{21}$$

As regards $\mathbf{Q}(t)$, the covariance matrix of error $\mathbf{w}(t)$ assumes following form:

$$\mathbf{Q}(k) = (t_{k+1} - t_k) \cdot \Phi(k|k) \cdot \mathbf{Q} \cdot \Phi(k|k)' \tag{22}$$

5. COORDINATES TRANSFORMATION.

Our main purpose for realizing such a mobile mapping system consists to carry out tipically road surveys on behalf of various italian public administrations or private agencies which are interested in road data collection for GIS applications. To this aim in most cases we will have to deal with cadastral maps that in Italy involve two different cartographic projections: Gauss-Boaga and Cassini-Soldner. The first is based on Hayford ellypsoid, oriented in Roma-Monte Mario, while the second refers to Bessel ellypsoid oriented in Genova: these are the two national geodetic datums, commonly used for mapping applications. Therefore prior to use the corrected GPS positions, as measurements input for the Kalman filter, we perform a geodetic datum transformation between WGS-84 and one of our national datums, employing the Wingeo software developed on the basis of algorithms proposed by [1].

6. TEST AND RESULTS.

In order to test the accuracy of the positioning module, i.e. the goodness of our kinematic model so as the effectiveness of our implementation of Kalman filter, we have simulated a survey employing random generated *true* position data with Gaussian noise with the same variance error as our GPS receiver (single frequency Trimble Pro-XR) according to its technical data sheet (50 cm RMS, adopting Everest™ multipath rejection technology).
Comparing these true positions with that computed by the filter, 86% of angle estimates move less than 2 degree away from true value, while 50% present a discrepancy limited to 1 degree (Fig. 8).
On the basis of these results and positioning accuracy of our receivers, as guaranteed by Trimble, we could conclude that our NavPos software module provides a positional error about 30-35 cm for object at distance of 10 m from the vehicle.
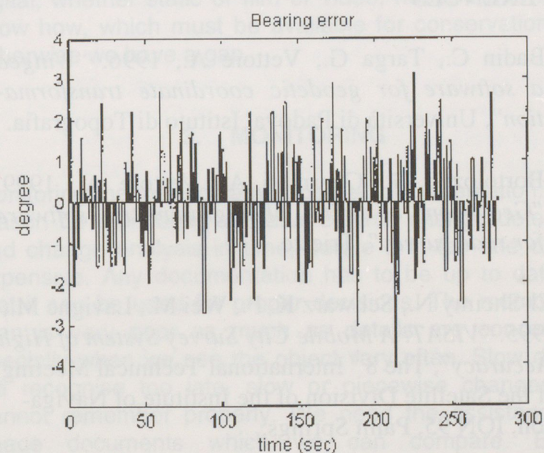

Fig. 8: Simulation results on bearing error

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7. CONCLUSIONS.

We have presented the current state of our research in order to develope a low cost mobile mapping system, providing sufficient accuracy to perform road surveys for GIS applications. The lack of the INS has lead us to implement a georeferencing algorithm by which the istantaneous position and orientation of the van can be recovered by the differentially corrected GPS data only. For the same reason above, we can't get the 3D coordinates of any object selected on corresponding images, but rather its 2D coordinates on a projection map, therefore the object elevation cannot be restituted. Anyway, the capability to locate on a map any feature of interest through rapid road survey has represented our primary goal in developing such a MMS.

At the present we have carried out only separated tests for the various modules which make up GeoVision, but we have in plan to assess the performances of the whole surveying system in real environment, testing it capabilities for real time data acquisition and the final accuracy for object position as derived by post-processing step.

Through the contribution provided us by the VRG (Virtual Reality Group) of NRC Canada, this mobile mapping system can be integrated with the BIRIS sensor, in order to detect the road surface deformations.

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