IMPLEMENTATION OF A LOW COST MOBILE MAPPING SYSTEM

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ABSTRACT:

This article describes a very low cost terrestrial Mobile Mapping System (MMS) that was developed at the University of Porto. It incorporates a direct geo-referencing system with a single frequency GPS receiver board and the remote sensors are two progressive CCD colour video cameras with 640x480 resolution. Alternatively the system was used with a direct geo-referencing system previously developed at Porto University based on the integration of data from a dual frequency GPS receiver and an Inertial Measurement Unit. The image acquisition system works independently so it can be used with any direct georeferencing system. The system allows for the association of a position and attitude to each digital frame captured by the video cameras. Furthermore, upon pixel location of objects appearing in the video frames, their absolute geographical coordinates can be extracted. Several calibration steps have to be overcome before the system is prepared to do the survey operations, namely camera calibration, relative orientation between cameras and determination of rotation and coordinate offset between vehicle and cameras reference frames. Procedures were developed in order to guarantee the perfect synchronization between direct geo-referencing data and image data. A software tool was created to allow for an easy object coordinate extraction either in auto mode, where the conjugate coordinates are obtained using image correlation techniques, or in manual mode. Tools for integration with previously existent databases and communication with other GIS platforms were developed as well. Several surveying experiments are described in the paper. The videogrammetry system implemented is a low cost system that can achieve an accuracy in relative positioning of a few decimetres. The overall accuracy depends mainly on the direct georeferencing system used.

1. INTRODUCTION

The main purpose in developing this terrestrial MMS was to use low cost equipment and to keep in an acceptable level the overall complexity in surveying procedures and system calibration. With those objectives in mind it was decided to use an up to date current consumer laptop, two CCD progressive colour video cameras with 640x480 resolution, a low cost direct geo-referencing system based on a single frequency DGPS receiver and car odometer and to implement simple, yet effective, system calibration procedures.

A very important subject when acquiring data from a geo-referencing system and image sensors is time synchronization. The implemented solution was to trigger the cameras with a frequency directly synchronized with the GPS pulse per second (PPS). This procedure allowed for simultaneously precise frame acquisition, freeing laptop from a dedicated system for precise time tagging.

The developed software is intended to be user friendly, automatically performing some usual tasks such as finding relative orientation parameters between cameras, getting coordinates or measuring object dimensions.

2. SYSTEM DESCRIPTION AND SURVEYING PROCEDURES

The work presented here explores the data acquired by a dead reckoning single frequency GPS receiver board as direct geo-referencing system. The unit contains a single frequency GPS receiver, a low cost gyroscope, connection for car odometer and for forward/reverse indication. The data from all sensors is constantly integrated by an internal enhanced Kalman filter (EKF) and the resulting WGS84 positions are stored, once per second, in a internal flash memory. The GPS receiver support DGPS and SBAS systems and operates with active antennas allowing for high sensitivity and multipath detection. The unit is also capable of generating a pulse per GPS second (PPS) and NMEA messages via RS232 cable.

The SBR-LS GPS receiver board is well suited for heavy urban environments allowing for continuous solutions in bad GPS conditions and with good performance in slow and stop and go traffic. The acquired positions allow for continuous smooth trajectories with 2 meter accuracy which is sufficient for medium scale mapping and for many kinds of road infrastructure surveys.

Figure 1: GPS CAM-SYNC box – inside and cover.

The GPS receiver board was enclosed in a box and a frequency multiplier was added to the pulse per second. The box was given the name GPS CAM-SYNC because one of its main tasks is to generate a GPS synchronized frequency, changeable with two buttons in the outside of the box (figure 1).

The data logged in the flash memory, once per second, is composed by WGS84 latitude and longitude, heigth, car velocity and time in UTC (Universal Time Coordinated) format. The instantaneous vehicle heading is derived from the GPS trajectory once its smoothness make feasible to consider the tangent to the trajectory in each instant as coincident with vehicle reference (figure 6).

The remote sensors are two AVT Marlin F046 CCD, with the following characteristics:

- Digital acquisition through a color CCD
- Resolution up to 780x580
- Progressive Scan
- Frame rate up to 30 Hz in color mode
- Transfer and control through Firewire Protocol
- External asynchronous trigger shutter

The cameras lens system are C mount, high resolution, 12mm focal length lenses, with fixation screw of focus and iris. Furthermore, the video or frame acquisition and real time storing in a hard disk of a normal up to date laptop, is feasible with no great deal with this cameras, through a firewire protocol port.

The system configuration and components when in a real surveying situation is represented in figure 2. The GPS CAM-SYNC box provides instantaneous positions of the moving vehicle and also generates a PPS synchronized frequency that simultaneously triggers the cameras at very precise GPS instants.

Figure 2: Surveying vehicle and system components.

The relative positions of the system components remains unchanged during surveying, and the corresponding parameters are settled accurately in a previous step. Of major importance is the determination of the camera orientations in the vehicle reference frame and the relative orientation between the cameras themselves, in the case that two are used.

3. SYSTEM CALIBRATION PROCEDURES

The correct term to apply to the calibration of an MMS is *system calibration* because it implies some calibration procedures that are interrelated. Camera lens calibration, relative orientation between cameras, relative orientation between platform and cameras and time synchronisation between the acquired data, are all aspects that take a roll in the quality of the achieved results.

Calibration procedures were thought following the principle, previously stated, of implementing a low cost and simple to use system. These procedures must be possible to do by a normal operator in the context of a normal system use.

3.1 Collinearity equations

For all the photogrammetric procedures the collinearity model is used (Wolf, 2000), however with a little modification in the photo coordinate system once the photo plane is considered a *(x,z)* plane and not *(x,y)* like usual. This modification turns the z photo axis of a terrestrial photo into a near vertical axis, so, in most situations, the angle rotations between camera and object reference systems, normally earth referenced, are mainly expressed by the heading (*k*) angle. The authors consider that this modification allows a more intuitive quantitative analysis of rotations between the two systems. In this situation the collinearity equations become:

$$\begin{cases} x - x_0 + \Delta x = f.\dfrac{r}{s} \\ \\ z - z_0 + \Delta z = \lambda.f.\dfrac{q}{s} \end{cases} \qquad (1)$$

where $r=m_{11}(X-X_0)+m_{12}(Y-Y_0)+m_{13}(Z-Z_0)$
$s=m_{21}(X-X_0)+m_{22}(Y-Y_0)+m_{23}(Z-Z_0)$
$q=m_{31}(X-X_0)+m_{32}(Y-Y_0)+m_{33}(Z-Z_0)$
f = focal length
λ = z coordinate scale factor
x, z = measured image coordinates
x_0, z_0 = image coordinates of the principal point
X_0, Y_0, Z_0 = coordinates of projection center
X, Y, Z = object coordinates in ground
m_{ij} = elements of cosines matrix rotation
$\Delta x, \Delta z$ = corrections due to lens distortions

3.2 Camera calibration

The characteristics and behaviour of the video sensors are vital for the overall system performance, especially the robustness of the lenses and the need to keep the inherent distortion factors at low levels. In one hand the lens system must offer the possibility of iris and focal length fixing in order to keep the internal characteristics practically unchanged, at least during a surveying session, and the internal characteristics itself must be determined by means of parameter estimation. To achieve this last requirement it is necessary to apply a self-calibration technique (Fraser, 1997) to determine the calibration parameters of the video camera lenses. These interior orientation parameters include the lens focal distance, principal point location and others used to model lens distortions. Several tests were carried out in order to determine what interior orientation parameters should be used. A distortion model of one of the cameras is shown in figure 3, with a scale factor of 30.

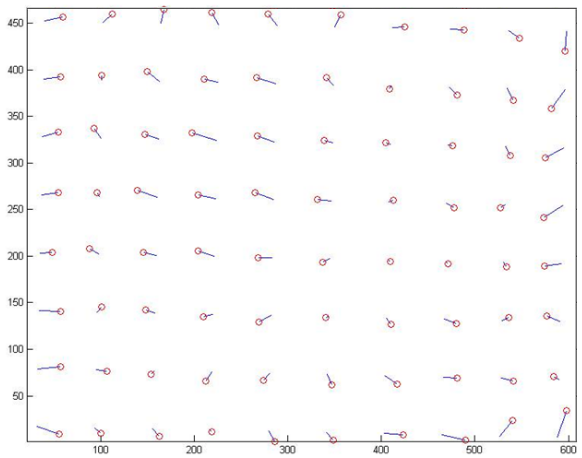

Figure 3: Distortion model of camera 1.

After statistical and visual analysis of the results, it was concluded that the best parameters to use were the principal point coordinates, focal length and, additionally, a z coordinate scale factor (λ in equation 1, that accounts for not square pixels) 2 radial and 2 decentering deformation parameters. This leads to the following correction parameters in the collinearity model (1), with the inclusion of the radial distortion parameters, k_1 and k_2, and the decentering distortion parameters, p_1 and p_2:

$$\begin{cases} \Delta x = (x - x_0)\left(k_1 r^2 + k_2 r^4\right) + P_1\left(r^2 + 2x^2\right) + 2P_2 xz \\ \Delta z = (z - z_0)\left(k_1 r^2 + k_2 r^4\right) + 2P_1 xz + P_2\left(r^2 + 2z^2\right) \end{cases} \qquad (2)$$

where $r = \sqrt{(x - x_0)^2 + (z - z_0)^2}$

$\Delta x, \Delta z, x, z, x_0, z_0$ as defined in equation (1).

For each camera several images must be obtained of an object with well defined points measured in a true-size object reference system. These can lie in a plane like in the present case, (figure 4). The pattern used was obtained from a well known photogrammetric software, Photomodeler, but the software itself wasn't used.

Figure 4: Image acquisition to obtain calibration parameters of the video camera lenses.

Camera calibration is performed independently for each camera. The initial approximations for the exterior parameters, 3 rotations and 3 translations for each image, in the object reference frame, are obtained with a process that relies on the collinearity equation itself; otherwise there are no required initial approximations, except for the focal distance. The final calibration parameters are obtained from an iterative process using a bundle adjustment.

3.3 Relative orientation between cameras

Object coordinates are first calculated in the camera reference frame, whose axis coincides with left camera axis. This process relies on rigorous determination of position and attitude of the right camera relatively to the left. The relative orientation parameters are 3 rotation angles (ω, φ and κ) and 3 translation distances (Tx, Ty and Tz). Its determination is performed within the developed software. Due to small base vector between cameras (B=1.045 m) some instability was experimented mainly in the rotation angle between z axis, which defines the heading angle (κ), largely affecting the Y coordinate of calculated positions. To overcome this situation a control distance was introduced in the relative orientation process, which consists in measuring a distance between left camera origin and a point used in the relative orientation, including it as a constraint in the least squares adjustment. This procedure has showed itself quite effective, allowing for a much more correct determination of orientation parameters, with consequent benefit in correct coordinate calculation.

3.4 Relative orientation between vehicle and cameras reference frame

In order to obtain the relative orientation parameters between vehicle and cameras reference frames it is necessary first to define vehicle reference frame. It is a reference system whose origin coincides with phase centre of the GPS antenna and its orientation coincides with vehicle orientation: Y axis frontward and Z axis upward. The relative orientation between vehicle and cameras reference frames are 3 linear offsets, along the X, Y and Z axis of the vehicle reference frame and 3 rotations for each axis, called angular offsets. Figure 5 shows a top view of the cameras and vehicle reference frames.

The linear offsets of the cameras in the vehicle reference frame needs to be measured only once because the system components occupy predefined places in the vehicle. Therefore a very careful measurement of the components relative positions is made using standard tape. It is not necessary to use a high level precision measurement, such as a total station, because this error, expected at centimetre level, remains as a constant shift in calculated coordinates. This step will never be needed again, as far as the same vehicle is used.

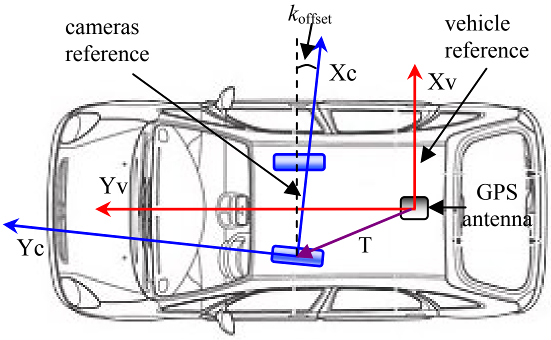

Figure 5: Cameras and vehicle reference frame.

The angular offsets of the cameras relative to the vehicle reference frame is a more delicate question. First, the errors made in its measurements largely affect the errors in coordinate calculation, growing its influence with distance, and secondly there isn't an explicit method for its determination. Furthermore they change each time the system components are mounted.
The simplest way to obtain the angular offsets is to link its determination to the relative orientation between cameras. Once the cameras are put in a line perpendicular to the Y axis of vehicle reference the searched angle offsets will come as a function of the base vector components between cameras:

$$\varphi_{offset} = \arcsin\frac{Tz}{B}, \varphi_{offset} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad (3)$$

$$k_{offset} = \arcsin\frac{Ty}{-\cos\varphi . B}, \kappa_{offset} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \quad (4)$$

where B is the length of the base vector between cameras.

Unfortunately it is not possible to find the ω_{offset} angle (rotation of X cameras axis) using this process. Once the cameras are put levelled over the vehicle it is considered that the most important offset angle to obtain is κ_{offset} (rotation of Z cameras axis) due to its influence in calculated object X,Y coordinates. The ω_{offset} angle mainly relates with height determination, which is not very important in the acquisition of coordinates for GIS data input. However, a good practice that we try to follow is to put the left camera as levelled as possible and to consider the referred offset angle as zero, so minimizing its influence in calculated coordinates.

3.5 Frame synchronisation with GPS time

The cameras are connected to the laptop through a firewire port and the images are stored in JPEG format using the software provided with the cameras. It is necessary to put a precise time tag to each acquired image, in order to precisely discriminate their position and attitude in the absolute reference system. It was decided to use the external trigger possibility offered by the cameras in conjunction with the frequency generated by the GPS CAM-SYNC which is, as described before, synchronized with the GPS PPS. In this way, the perfect simultaneity of the frames acquired by both cameras and its accurate synchronisation with GPS time is guaranteed. The time precision of the PPS is about 50 nanoseconds and the same is expected for the acquired frames.
However, to correctly time tagging the images, the system time of the logging computer itself must be synchronised with GPS time, although with not so great accuracy. The chosen procedure was to use the same receiver that is triggering the cameras to synchronise the laptop with NMEA time messages through a RS232 connection port, using current commercial software. This kind of laptop time synchronization typically leads to a 0.01 seconds of clock accuracy in the laptop.
To improve the correct time tagging of the acquired frames it was decided that the frequency generated by the GPS CAM-SYNC will miss the pulse corresponding to the integer second. In this way, when plotted the positions, bigger steps will be identifiable in the missed positions, which correspond to the integer seconds. During surveys the chosen frequency was, in most times, 5 frames per second (FPS) what leads to a separation time between frames of 0.2 seconds collected at 0.2, 0.4, 0.6 and 0.8 parts of each second. Figure 6 represents the architecture image acquisition.

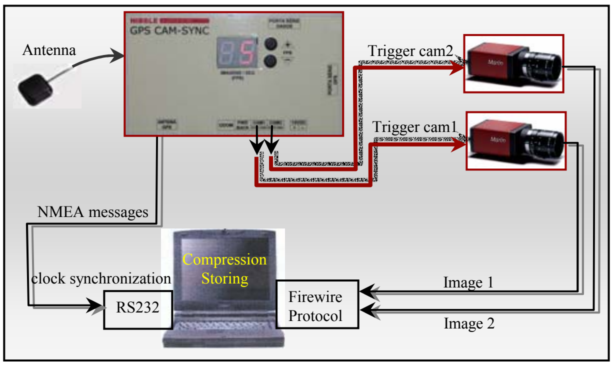

Figure 6: Image acquisition architecture.

It is important to notice that the image time stamping is not performed by the laptop. Its role is only to help the discrimination of which second belongs to the frames once the fractional part is already known. For this reason a laptop clock accuracy better than 0.5 seconds will suffice, even so the accuracy of clock used is far better than that. The time stamping work is performed in post-processing with a software module developed for that purpose.

4. MOBIL - SOFTWARE APPLICATION MODULE

A software application, named MOBIL, was developed in order to take full advantage of the data provided by the MMS system (see figure 7). It integrates the data coming from the videogrammetry system and from the direct geo-referencing system. The layout window allows for the full control of the cameras frame pairs in video mode. It is possible to perform with this application the calibration of the system and to obtain coordinates of conjugate points. This can be done in manual or auto mode, in which case the software uses stereo-correlation techniques to find conjugate points. The use of object measuring tools, either surface areas or linear lengths, is also possible, in which case no direct geo-referencing data is required. This can be of interest when the main goal is the extraction of geometrical information from the images.

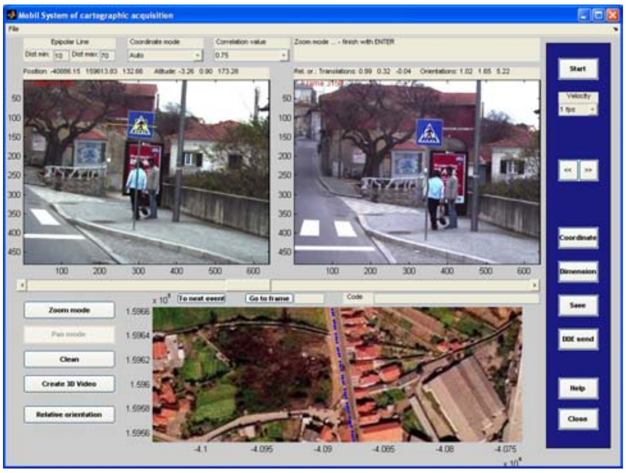
Epipolar Line: Dist min: 10 Dist max: 70
Coordinate mode: Auto
Correlation value: 0.75
Zoom mode ... - finish with ENTER
Position: -40886.15 159613.83 132.66 Altitude: -3.26 0.90 173.28
Rel. or.: Translations: 0.99 0.32 -0.04 Orientations: 1.02 1.65 5.22
Velocity: 1 fps

Figure 7: A layout window of Mobil program.

Some useful tasks were added to the software in order to make the video survey as effective and comfortable as possible.

- The Mobil program is able to detect if an object was previously surveyed, giving a warning message.

- An events file can be fulfilled during data acquisition and, if required, the program will jump between the events.
- A geo-referenced image or vector GIS data can be drawn below the plotted trajectory and measured points in order to perform quality control.
- Measured data can be directly sent to cartography in dwg format.

5. TESTS AND RESULTS

5.1 Results in camera calibration

For each camera, 10 images of a panel with object points coordinates measured at the millimetre level, were obtained from different angles and positions (see figure 8). In the actual case 80 object points in a regular grid distribution were used. The results for camera 1 are presented below. Coordinates and focal distance are expressed in pixel units.

x0 = 426.23
z0 = 240.81
f = 1525.96
λ = 0.9969
k1 = 3.6543E-08
k2 = 2.3582E-14
p1 = -9.8372E-06
p2 = 1.1266E-06

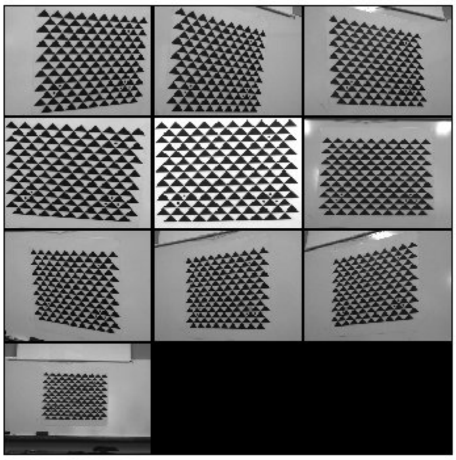

Figure 8: Set of images obtained with camera 1 for camera calibration purposes.

For quality control, the object point coordinates are re-projected to images according to the calculated image space geometry and the pixel differences (residuals) for the original image coordinates are statistically analysed. The residuals found have mean zero and standard deviations of 0.5 pixels. In figure 9 the re-projection error graph for the entire object points in all the images are shown.

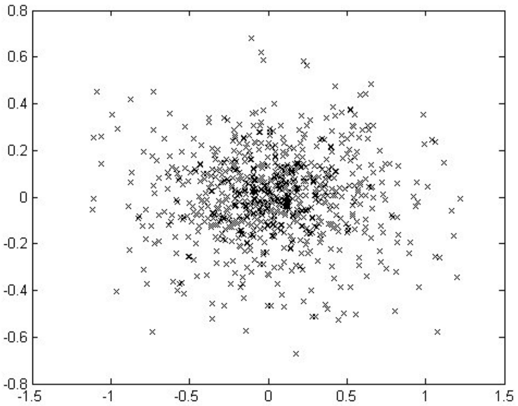

Figure 9: Pixel re-projection error of all object points in all images (coordinates in pixel units)

5.2 Test with measured distances

In order to assess the capability of the system in measuring distances to observed objects, the system was mounted on a stopped vehicle in front of a building façade (figure 10). Points on this façade were surveyed with a total station, as well as the camera positions. The process was done from three locations of the vehicle.

Figure 10: Total station survey for tests in relative coordinates and distances.

The relative orientation parameters between cameras were obtained with one of the videogrametric pairs. The first test was to assess how accurate the distance to object given by the system is. This parameter is crucial once it is necessary in coordinate transport and greatly relates with relative orientation angle κ. Besides, this test allows analysing the effect of errors in camera calibration parameters, in relative orientation parameters and in conjugate point determination in the images. The results in distance measurements to 21 points are presented in figure 11. The mean of the errors is -0.13 m which may indicate some systematic error that couldn't be identified. The root mean square (RMS) error was 0.33 meters.

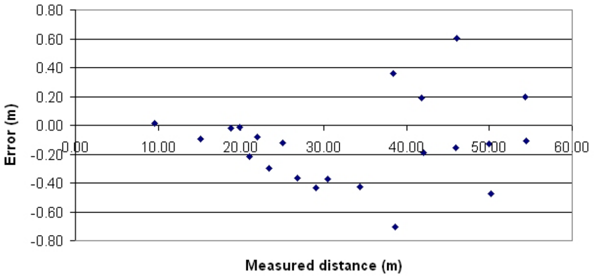

Figure 11: Errors in measured distances to objects.

5.3 Test with total station coordinates

The next test relied on measurement of coordinates of the building and its surroundings in the reference frame defined by the total station survey. The results of this test will also be affected by the errors in angle offsets determination of the cameras reference frame related to the vehicle reference frame. It is considered that camera positions are very accurately obtained by topographic methods, using the total station. Offset angles were obtained using equation (3) and (4).

To carry out this test 32 points of known coordinates in the building and its environment were measured with the system in all of its positions. Differences to the known coordinates were calculated and are presented in figure 12. The statistical analysis (mean and RMS error) are presented in table 1. A division was made between distances less and above 30 meters. At this point it was observed that the errors introduced by the calibration processes and by the image point conjugate determination are very well self contained, leading to errors in measured coordinates, in general smaller than 30 cm at distances of about 30 meters or inferior. For distances between 30 and 50 meters the errors increase but are in general less than one meter.

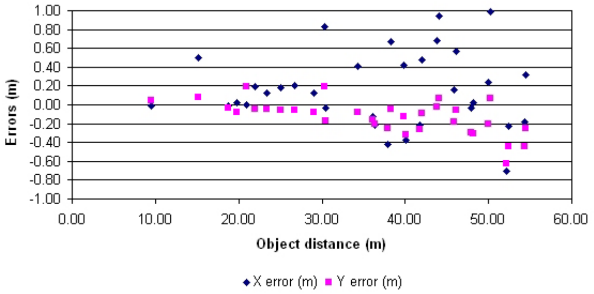

Figure 12: Errors in measured total station coordinates with distances to objects in meters.

	Distances < 30 m		Distances > 30 m	
	X error	Y error	X error	Y error
Mean	0.13 m	-0.01 m	0.18 m	-0.18 m
RMS	0.20 m	0.08 m	0.49 m	0.26 m

Table 1. – Mean and RMS error in object coordinates of the 32 points measured with total station

5.4 Test with absolute coordinates

In the previous tests the errors introduced by the direct geo-referencing system weren't present. This third test will account for those errors. Twenty traffic signs distributed in urban and near urban areas, were surveyed with GPS differential static methods (example of a surveyed sign is shown in figure 7). The accuracy of these measurements is expected at centimetre level. With the developed MMS system mounted on a vehicle this traffic signs were surveyed, in motion along the roads. Differences to the GPS coordinates were calculated and are presented in table 2, together with mean, standard deviation and RMSE.

Traffic sign	X error (m)	Y error (m)	Linear error (m)	Object distance (m)
1	0.27	0.56	0.62	10.27
2	0.53	-0.87	1.02	37.47
3	-0.74	-1.23	1.44	13.87
4	1.68	-0.70	1.82	10.84
5	-1.95	-1.26	2.32	10.57
6	-1.21	-1.69	2.08	9.77
7	-1.29	-3.44	3.67	5.42
8	0.10	-3.02	3.02	9.51
9	-0.05	-2.58	2.58	9.47
10	-1.68	-3.01	3.45	16.87
11	0.70	0.70	0.99	10.95
12	1.26	-0.13	1.27	43.80
13	2.03	-1.92	2.79	25.69
14	-0.71	0.69	0.99	12.71
15	1.06	-1.14	1.56	15.09
16	-1.74	-1.37	2.21	14.32
17	0.52	-4.03	4.07	33.17
18	-3.38	-1.85	3.85	16.57
19	1.13	-1.29	1.71	32.46
20	-0.13	-1.92	1.92	34.03
Mean	-0.18	-1.48	2.17	
StDev	1.39	1.33		
RMS	1.37	1.96	2.39	

Table 2. Errors obtained in absolute coordinates of traffic signs.

The positioning method of the direct georeferencing system used only pseudo-ranges and EGNOS corrections. The expected accuracy agrees with the results obtained, i.e., RMS errors smaller than 2 metres. The errors introduced by the videogrametry system, as shown before, are of smaller magnitude. The graph of figure 13 shows the X, Y and linear errors against the distance to the coordinated point. It can be observed that there isn't an evident connection between errors and distances to the coordinated objects. It is clear to the authors that the errors introduced by the direct geo-referencing system, actually the data from the GPS CAM-SYNC box, are contributing with the larger portion of the final errors in coordinates and masking the smaller errors introduced by the cameras system, which increases with the distance.

The mean of the Y error is high, appearing to indicate some systematic error that couldn't be identified once the survey trajectories, when measuring object coordinates to this experiment, occurred practically in all directions. So it can't be a shift in the measured distance or in κ attitude angle.

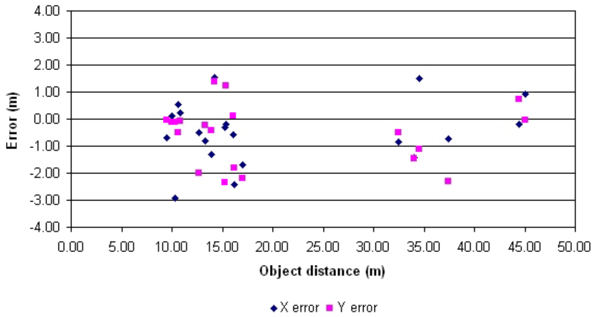

Figure 13: Errors in measured absolute coordinates with distances to objects in meters.

6. CONCLUSIONS

Building a simple, low cost and efficient Mobile Mapping System is not, definitely, an easy task. In fact, there are a set of inter-depending aspects that must be resolved in order to achieve a final acceptable stage according to the goals previously defined. Our main goal was to keep in simple level the technical and equipment demands, while being rigorous and trying to achieve good quality standards in the final results.

A mathematic model was developed, relying on the collinearity condition, and applied to all subsequent issues related with the data acquired with the video cameras.

The presented method for relative orientation between vehicle and cameras reference frame tries to avoid complicated schemes for each survey, linking it to the process of relative orientation between the cameras. Mathematically the method is sustainable but questions may be put relatively to the high dependency of offset angles with the linear translations computed during the relative orientation. However no systematic angular shift could be detected in the several tests that could be attributed to bad angle offsets determination.

The authors consider that the camera frames synchronisation problem was satisfactorily resolved once the captured frames are directly ordered by a GPS receiver using an external trigger. In this way two important issues in MMS surveys could be overcome. First the simultaneity of acquired frames by both cameras, and secondly the correct discrimination of the GPS acquisition time with an accuracy better than milliseconds. So, the synchronisation of acquired frames with GPS time is almost perfectly achieved.

The videogrammetry system contributes to the positional accuracy with an error below 30 cm at distances less than 30 meters and below 1 meter at distances less than 50 meters. The direct geo-referencing accuracy is the main bottleneck in the overall accuracy.

Future developments of the current system, keeping the low cost and simplicity standards, include the connection to the car odometer and the incorporation of gyroscope measurements of U-blox GPS unit.

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