APPLICATION OF A LOW COST MOBILE MAPPING SYSTEM TO COASTAL MONITORING

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ABSTRACT:

This paper describes the application of a Mobile Mapping System (MMS) to coastal monitoring. The MMS uses as remote sensors two progressive CCD colour video cameras. The image acquisition system works independently so it can be used with any direct georeferencing system. A user friendly software tool was created to allow for an easy object coordinate extraction, efficient integration with previously existent databases and communication with GIS platforms.

The system has proven its efficiency for road inventory and other applications involving the collection of GIS data. The challenge here is the adaptation of the system to surveys in a quite different environment such as sandy beaches and dune areas. The main goal is to obtain a continuous image inventory of beaches and associated sand dunes, from which accurate 3D positions can be obtained. This procedure will be repeated in order to track changes in coastal geomorphology. The information gathered will allow for the automatic extraction of major geomorphological features of beaches and its incorporation in a GIS. The system will also allow the automatic or manual measurement of lengths and areas from the obtained images what makes possible the tracing of coastal changes. This information will be analysed in conjunction with the information extracted from aerial photography. All imagery will be fully searchable using continuous drag, specific coordinates, locality, and geomorphological occurrence.

The possibility to do periodic re-observation of the same beach sectors, and, also the ability to survey specific areas after storms, is fundamental for an efficient monitoring of the morphodynamical changes occurring in the coastal zone, and for the identification of the more prone sectors to coastal erosion. At the Faculty of Science, innovative methodologies, based on the use of a dedicated DGPS system for coastal monitoring, were developed and are in use after several years. This work presents an evolution of this approach by exploiting a MMS. The paper describes the strategies used to adapt the system to this particular environment and, an accuracy assessment, especially in the height measurements.

1. INTRODUCTION

The Portuguese coast, especially in the western part, suffers significant degradation due to the action of the ocean (Ferreira, et al., 1995). This is increased by the fact that coastal areas are subject to a strong pressure of antropic origin, associated with human settlements and construction which have as consequence the destruction of dunes and other natural protections. Significant topographic changes occur in short periods of time that need to be monitored. In order to detect and quantify change in coastal areas, both for safety and economic reasons, very frequent surveys are required.

Although elevation changes in beach landforms, due to natural origin or human activity, can be of several meters even in short periods, survey systems should meet accuracy requirements at the decimetre level in order to be useful. Both traditional field surveying and airborne systems can meet these accuracy requirements.

Airborne laser scanning is widely used for detailed three-dimensional mapping, having important applications in coastal areas. Although relatively expensive, it is a very efficient technology mainly due to its high degree of automation (Baltavias, 1999). It can also easily reach the decimetre accuracy or better.

Aerial photography, especially with high resolution digital cameras, is an alternative for relief data collection in coastal areas. Using large resolution, for example a ground sampling distance of 5 to 10 cm, the vertical accuracy of 1 or 2 dm can be easily obtained. Although having a smaller degree of automation (need for aerial triangulation and Digital Terrain Model - DTM - extraction from stereo pairs) it also provides the image base which is very helpful in the monitoring of coastal change processes.

Furthermore, costs of airborne based surveying systems are relatively high, especially if the study area is small. Response times may also not be appropriate, for example when there is a severe storm and a survey is required in a very short period. When there is a need of establishing regular observation programs of coastal monitoring, especially in small but sensitive areas, field survey techniques must be considered (Baptista et al., 2008). Traditional land survey methods using total stations are very accurate but time consuming and not cost effective. Kinematic GPS is more efficient and also very accurate, since, due to the absence of obstacles in beaches, phase processing becomes a simple task. Anyway both field survey techniques are invasive, requiring the operators to physically occupy the observed points, which is not convenient, for example with sensible vegetation over sand dunes. The combination of GPS positioning with image acquisition sensors, such as video cameras, is a methodology that can be very productive, allowing for fast and accurate surveys.

This paper describes the application of a Mobile Mapping System (MMS), initially developed to operate in urban environments, which is composed by two video cameras combined with a direct georeferencing system. The later must be composed by a dual-frequency GPS receiver and may...
incorporate other sensors for attitude determination, such as Inertial Navigation Systems (INS) or a set of GPS antennas. Although the system is fully prepared to incorporate INS, or more GPS antennas, it was presently assessed using only one GPS receiver. The particular conditions of acting in beaches and sand dunes, where analyzed.

2. SYSTEM DESCRIPTION

2.1 System components

The imaging sensors of this MMT are two video cameras, with the following characteristics:
- Resolution of 640x480
- Pixel size 5.6 μm
- 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, 2.2 mm focal length, with fixation screw of focus and iris. The cameras are kept in protecting boxes which are mounted on an aluminium structure, with a separation of 1 meter. Figure 1 shows the structure, with the two cameras and a GPS antenna, mounted on a moto-quad vehicle for use in beach environment.

The image storage can be made in real time on the hard disk of a standard laptop, through firewire ports. Time synchronisation is done by a component designated as GPS CAM-SYNC, which is composed by a low cost GPS navigation 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 an internal flash memory. The GPS receiver supports 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 second (PPS) and NMEA messages via RS232 GPS port. The GPS receiver board was enclosed in a box and a frequency multiplier was added to the pulse per second (Madeira et al., 2007) 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 (represented in figure 2).

The data logged in the flash memory, once per second, is composed by WGS84 latitude, longitude and height, car velocity and time in UTC (Universal Time Coordinated).

Although a standard laptop PC could be used, which makes the system very simple and cheap, the present system has a dedicated data-logger, which incorporates the CAM-SYNC, and is more robust for operation in the beach environment, and has a large capacity storage disk.

The CAM-SYNC GPS receiver board is well suited for heavy urban environments allowing for continuous solutions even 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. However, for the present case where the required positional accuracy is much higher, a dual frequency GPS receiver was incorporated in the system. Due to the lack of obstructions to the GPS signal in beaches a sub-decimetric positional accuracy is possible in the differential phase processing.

A direct georeferencing system, previously developed at the University of Porto, included a Litton LN-200 IMU (Tomé et al., 2002, Cunha et al., 2003) and is planned to be adapted to the current MMS. At the moment for operational reasons the system did not incorporate any attitude measuring system. Since the GPS positioning in this environment is very accurate, consecutive positions along the trajectory were used to obtain two angles (azimuth and inclination), leaving as unknown the roll angle. This may not be a problem when operating the vehicle in a flat road. However that will not be the case in beaches and dunes. The errors introduced in heights and possible solutions are treated in the following section.

2.2 Determination of 3D positions

The system requires several calibration procedures in order to obtain 3D coordinates in a well defined cartographic reference system. The first step is an internal camera calibration, which has to be frequently done, since the cameras are frequently moved. A fast method, based on collecting pictures of a flat panel with rigorous pattern, was developed. It is described in detail in Madeira et al. (2009). The lens used has a relatively large radial distortion that could be well modelled. Figure 3 shows an example of an image in its original form and after correction of radial distortion.

A relative orientation is also carried out with any two images where well distributed conjugate points can be obtained. This leads to a camera reference system which, due to the orientation
of the cameras and the knowledge of the base length, is relatively close to a vehicle reference system fixed to the navigation system. Small offsets (shifts and angles) have to be determined. They can be obtained with some control points or they can be approximately measured, within the required positional accuracy.

The mathematical formulation of the coordinate transport between the different reference systems and the orientation methods involved are well described in the literature (Ellum and El-Sheimy, 2002, Grejner-Brzezinska, 2001). Once image coordinates of a point are measured on a pair of images, relative coordinates are calculated. The main error source at this stage comes from the small size of the base distance between the two cameras (1 m), which will be normally much smaller than the distance to the point measured. In this particular system configuration (sensor resolution and focal distance), a point at a distance of 10 meters will be imaged with a pixel size of 2.5 cm. The accuracy of the distance (σD), as a function of parallax accuracy, is given by expression (1):

$$\sigma_D = \frac{D^2}{B \cdot f} \cdot \sigma_{\text{parallax}}$$  \hspace{1cm} (1)

where B is the base distance (approx. 1 m) and f is the focal distance (2.2 mm in the present configuration). At a distance of 10 m, and assuming an accuracy of 1 pixel (0.0056 mm) in the parallax, the distance will have an accuracy of 25 cm. However, the accuracy in other directions (lateral and vertical) will be much better, at the level of the pixel size on the object. Provided that the interior and relative orientations are accurate, the vertical component, which is the more relevant for the present situation, has at this stage a very good accuracy.

Further errors can be introduced when transporting to a mapping reference system. First there is the transport from the camera reference system to a vehicle reference system defined by the navigation system, but this is a matter of calibration that can be easily solved. Then there is the accuracy of position and attitude determined by the navigation system. In terms of position, as it was referred before, the dual frequency, differential GPS positioning is very accurate in the seaside environment, since there are few obstacles to signal propagation. Centimetre accuracy is easily achieved.

From a given point of the trajectory, the tangent vector (tx, ty, tz) can be calculated, for example taking the previous and next points. The azimuth (α) and inclination (β) angles can be calculated by expressions (2):

$$\alpha = \arctan\left(\frac{t_y}{t_x}\right), \quad \beta = \arctan\left(\frac{t_z}{\sqrt{t_x^2 + t_y^2}}\right)$$  \hspace{1cm} (2)

Notice that since the system is operated at short distances (e.g. 10 to 20 m) the required accuracy is not very high (0.1 degrees at 20 m correspond to 3.5 cm).

In order to convert from the vehicle to the mapping coordinate system another rotation angle would be needed (rotation around the trajectory direction), when the vehicle moves with some lateral inclination, which is frequent in beaches and dunes. The error introduced in height by considering that rotation as zero is more severe for points far from the image centre. For example, for a point 10 metres to the side of the trajectory, a lateral inclination of 5 degrees would correspond to a height error of 0.87 m.

In the present system configuration, an expedite solution was found, making use of the horizon line, which is normally seen in the images (see fig. 4). When the operator detects that the lateral inclination is large the software tool allows for its approximate estimation by picking two points on the horizon line.

Other solutions, based on low cost attitude measuring systems, are being analysed. For the present application an angular accuracy of 0.1 degrees is sufficient.

### 2.3 Processing software

Once the sequence of video frames acquired in the field are downloaded to a computer, they are treated by a software tool developed using Matlab, specifically for this MMS (Madeira et al., 2007). Figure 4 shows the graphic user interface (GUI) of the program.

The program allows for the display of left and right frames, at selectable speed, display position and orientation data and calculate 3D coordinates of conjugate points. This task is semi-automatic since the user interacts with one of the images and the conjugate is obtained automatically by correlation. For the particular use in beaches it is possible to define a line on one image, and the program extracts regularly spaced points in order to build profiles.

This program can interact with GIS point database, in the sense that attributes and positions can be stored. It also allows for an existing point database to be projected onto the frames, which are marked with signs of existing points.

![Figure 4. GUI of the Matlab program created](image)

In order to solve the problem of not having all the required attitude angles, a button was created to determine, if needed, the lateral inclination by the horizon line.

### 3. ASSESSMENT OF SYSTEM OPERATION IN BEACH ENVIRONMENT

The MMS described is being used in a coastal monitoring program near the city of Porto in Portugal. It is an area that has suffered in recent years severe changes due to the ocean dynamics. Within this monitoring program, digital aerial photography is acquired twice a year, before and after winter. High resolution DTMs are automatically extracted with a vertical accuracy of 10 to 20 cm.

The MMS is used with higher frequency in order to detect elevation changes, especially after storms. The video dataset
also is itself an important tool for other qualitative analysis of the coastal area situation, with potential for evaluating eco-morphodynamic changes.

3.1 Assessment of vertical accuracy with GPS points

Several accuracy tests were done in order to assess if the methodology described meets the required accuracy. Two tests were done with sets of points measured with the MMS and with a dual frequency GPS receiver, in static mode. The first set was composed of 10 points along a flat road near the beach (measured at average distance of 8 meters from the vehicle). As expected, the planimetric accuracy is relatively low, with standard deviations of 40 cm, predominantly in the line of sight direction. The height errors are much smaller. Table 1 contains the statistics of the height errors.

<table>
<thead>
<tr>
<th>Errors in height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum: -0.13</td>
</tr>
<tr>
<td>Maximum: 0.18</td>
</tr>
<tr>
<td>Average: -0.01</td>
</tr>
<tr>
<td>Std. Dev.: 0.09</td>
</tr>
</tbody>
</table>

Table 1. Statistics of height errors for a set of 10 check points measured with the MMS in a flat area

This test reveals a decimetre accuracy level for height determination. However, this was a very special situation, where there was no significant lateral inclination and the points were all very well defined.

Another test, closer to the real operation environment, was carried with points on a beach survey. Well defined check points were not easy to find and only six points were considered. Figure 5 shows one of the points.

Heights were determined by the default method, i.e., assuming roll angle of zero, and then with corrections determined with the horizon line. Table 2 contains the errors (differences to the GPS height), which are referred as $\Delta h_0$, for the first case and $\Delta h_1$, for the second. The table also shows the distances from the vehicle.

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Dist (m)</th>
<th>$\Delta h_0$ (m)</th>
<th>$\Delta h_1$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.3</td>
<td>+0.66</td>
<td>+0.04</td>
</tr>
<tr>
<td>2</td>
<td>8.5</td>
<td>-0.25</td>
<td>-0.15</td>
</tr>
<tr>
<td>3</td>
<td>11.1</td>
<td>-0.70</td>
<td>-0.09</td>
</tr>
<tr>
<td>4</td>
<td>8.3</td>
<td>+0.70</td>
<td>+0.07</td>
</tr>
<tr>
<td>5</td>
<td>14.7</td>
<td>+1.54</td>
<td>+0.14</td>
</tr>
<tr>
<td>6</td>
<td>23.0</td>
<td>-2.45</td>
<td>+0.14</td>
</tr>
</tbody>
</table>

RMS: 1.40

Table 2. Height errors for a set of 6 check points on the beach: without ($\Delta h_0$) and with ($\Delta h_1$) correction of inclination

3.2 Comparison of MMS and DTM heights

Within the coastal monitoring program referred before, digital aerial photography was obtained with a ground resolution of 10 cm, using a camera ZI-DMC, in November 2008. A DTM was obtained automatically and has a vertical accuracy of 15 cm. This DTM (small sample in figure 6) acts as reference for this coastal monitoring program.

A survey was carried out with the MMS, after the winter. Some comparisons were made of heights obtained from the DTM and with the MMS. Four areas were chosen, one in which changes were known to be small (zone 1) and three were there were depositions of sand (3 to 4). The test areas were chosen such that video images had a negligible roll angle, assessed by the horizon line. Table 3 contains, for the 4 test areas, the statistics (number of points, average and standard deviation) of the height differences, $\Delta h$, obtained.

<table>
<thead>
<tr>
<th>Zone ID</th>
<th>No. of points</th>
<th>Average $\Delta h$ (m)</th>
<th>Std. dev. $\Delta h$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>0.12</td>
<td>0.22</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>0.38</td>
<td>0.17</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1.09</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>0.61</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 3. Statistics of height differences (MMS-DTM) for sets of points in 4 different areas

As it can be seen, when no correction of the roll angle is applied, errors are very large and not acceptable within the requirements for this MMS. After the correction the errors are significantly reduced (RMS of 0.13 m, for the 6 points) and are within the requirements. Unless that the system can be operated with small roll angle, further developments are needed in order to determine full attitude of the system. The most feasible solution is the inclusion of a second GPS antenna, or the exploitation of L1 carrier phase measurements of the CAM-SYNC GPS antenna, which in the present system configuration are not being used.

4. SUMMARY AND CONCLUSIONS

A Mobile Mapping System was adapted to use in surveying beaches and sand dunes in coastal areas. It is a very low cost
system, that operates in a moto-quad vehicle, appropriate to
move in this environment. It includes two low cost video
cameras, connected to a data-logging computer.
The navigation system is based only on a GPS dual-frequency
receiver, that achieves a very accurate positioning in kinematic
mode, due to the lack of obstacles in coastal areas. It allows for
estimation of orientation from the trajectory, except for the roll
angle. That would be acceptable if operating the vehicle on flat
ground, i.e., with no lateral inclination. That is not the case in
beaches and dunes where a temporary solution was found
making use of the horizon line. However this process does not
allow for an easy automation of large volumes of data
collection.
The system is being improved in order to incorporate the
determination of roll angle making use of phase measurements
made by two single frequency, low cost phase receiver identical
to the one used in the CAM-SYNC.
Several accuracy assessments of height measurements were
made. It was possible to conclude that, in the present
configuration, the system can perform at two decimeter
accuracy level in beach environment, which allows for
detection of sand movements after storms. However, the system
has the potential for some improvement in height accuracy.
The system has proven to be effective as a standalone
monitoring tool or as a complement to less frequent aerial
surveys.

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