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MEASUREMENT OF CROSS-SLOPE OF ROADS: EVALUATIONS, ALGORITHMS AND ACCURACY ANALYSIS

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ABSTRACT

The Topography and Photogrammetry section of the Department of Civil Engineering, Pisa University, Italy, in cooperation with the Geonetlab Research Centre of Trieste University, is developing several methods for the evaluation of road cross-slope. The measurements are carried out by means of instrumentation integrated on the Mobile Mapping Systems vehicle GIGI One (GPS Integrated with Glonass and INS One). Two different approaches are used. The first one involves the use of a low cost monoaxial laser scanner IBEO Ladar Digital Automotive (LD-A), synchronized with an Applanix Position and Orientation System for Land Vehicles (POS LV). For the second approach, the cross-slope is computed only from inertial system data, with a simplified algorithm that describes vehicle dynamics. The paper presents an accuracy assessment of both methods. The tests are carried out on two different datasets, namely on the national road S558 “Strada Nuova per Opicina”, joining Trieste to Opicina and the national road S11 “Aurelia” between Rosignano and Campolecciano, near Livorno. The control measurements involve several single point checks carried out with conventional surveying instrumentation. The paper shows that the new proposed algorithm allows to compute cross-slope with an accuracy of 0.4° or better.


INTRODUCTION

Mobile Mapping Systems (MMS) equipped with Inertial Navigation Systems (INS) that are coupled to Differential Global Positioning Systems (DGPS) have become quite popular for a range of applications including road evaluation procedures. The road geometric data typically obtained by the MMS are cross-slopes, grades of vertical curves and radii of curvature of horizontal curves. In this paper only the cross-slope measurement is evaluated.

The purpose of the cross-slope in a road is to help the drainage of rain water and to reduce the hydroplaning potential. The typical cross-slope requirement of a road is 2%. In addition, roads are sloped in the lateral direction to control the lateral wandering of vehicles travelling on a bend counteracting the centripetal forces acting on the vehicle. This construction feature is commonly known as the super-elevation of a curve.

The MMS used for these tests is the GIGI One (GPS Integrated with Glonass and INS One), operated by the Geonetlab Research Centre of Trieste University [5]. This vehicle is equipped with an Applanix Position and Orientation System for Land Vehicles (POS LV), an INS/DGPS strapdown system and a low cost monoaxial laser scanner IBEO Ladar Digital Automotive (LD-A). The Applanix output raw data are the following: the vehicle’s reference point (X, Y, Z) in WGS84 coordinates, the roll, pitch and yaw angles of tilts, the heading and acceleration components with respect to the body coordinate system. All these values can be recorded at a frequency of 200 Hz. The roll angle’s accuracy is 0.005° [6].

There are several algorithms that can calculate the grades and radii of curvature from three-dimensional coordinates of points on the road axis. Common data collection methods for cross-slope modelling include traditional (e.g. total station) surveys, GPS, vehicle-mounted ultrasonic or laser profilometer and airborne LIDAR. This article...
describes the calculation of the cross-slope through an algorithm developed by authors, using the output values of the Inertial Measuring Unit (IMU) for the tilt angles and acceleration only. The tests described in this paper aim at verifying the accuracy and precision of the measurements derived from this algorithm.

SURVEY METHODS AND ALGORITHMS

The cross-slope values can be obtained from the data collected by the MMS GIGI One vehicle by two different methods: the first one is based on an algorithm which computes the slope value simply from the data collected by the inertial system, on the basis of a simplified model of the dynamics of the travelling vehicle; the second is based on the use of a single axis laser scanner synchronised with the INS/DGPS system.

Cross-slope obtained from INS data only

The vehicle is represented as a rigid body, bound, rather than rigidly constrained, to a horizontally constraint plane by means of two springs, which simulate the right- and the left-hand wheel-suspension pair, respectively. The suspensions are assumed to have a linear elastic behaviour: they consist of a two-dimensional (mass-springs) system, in which the mass is a rigid body subject to rotation. With the model lying on an inclined plane and being subject to gravity and to a transversal force, it simulates a vehicle going along a curvilinear road section with a cross-slope \( \alpha \) (Fig. 1).

The variables involved are:

- \( a \) transversal acceleration;
- \( m \) mass of the vehicle;
- \( G \) centre of gravity of the vehicle;
- \( l \) height of \( G \) above the inclined road;
- \( d \) offset of \( G \) in relation to the vehicle's axis;
- \( g \) gravity acceleration;
- \( k_s \) spring's elastic constant;
- \( h \) distance between the springs;
- \( \gamma \) total angle between the vehicle floor and the road surface;
- \( \alpha \) road's cross-slope.

The stresses are computed on the non-tilted configuration according to the usual procedures in mechanical sciences. The forces acting parallel to the inclined plane are the gravity component, \( g \cdot sin \alpha \) and the transversal acceleration \( a \), measured by the IMU. Hence, the momentum due to the lateral force is:

\[
M_l = ml (a - g \cdot sin \alpha)
\]

(1)

If the load is eccentric, \( (d \neq 0) \), there is a momentum due to gravity: the trim of the vehicle depends on the eccentricity, or asymmetry, of the load, and is assumed to

Fig. 1. Non-tilted and tilted configurations on inclined plane.
remain constant throughout the entire survey. Hence, the momentum due to the trim of the vehicle is:

\[ M_a = ml g \cos \alpha \]  \hspace{1cm} (2)

The resulting tilt momentum on the vehicle is:

\[ M = M_L + M_a \]

which yields the tilt of the vehicle (\( \gamma \)) compared to the non-tilted configuration:

\[ \gamma = -2 \frac{M}{k_s h^2} = -2 \frac{M_L + M_a}{k_s h^2} = -2 \frac{ml(a - g \sin \alpha)}{k_s h^2} - 2 \frac{mdg \cos \alpha}{k_s h^2} \]

and by defining

\[ \gamma_a = -2 \frac{mdg \cos \alpha}{k_s h^2} \]
\[ \gamma_L = -2 \frac{ml(a - g \sin \alpha)}{k_s h^2} \]

it is possible to define \( \gamma \) as:

\[ \gamma = \gamma_L + \gamma_a \]

Assuming small angles (\( \cos \alpha \approx 1 \)), the value of \( \gamma_a \) is constant.

\[ K = \frac{2ml}{k_s h^2} \]

(7)

The constant \( K \) incorporates the mechanical and geometrical characteristics of the vehicle and is introduced for convenience. Hence, the total angle \( \gamma \) between the vehicle floor and the road surface is:

\[ \gamma = -K(a - g \sin \alpha) + \gamma_a \]  \hspace{1cm} (8)

The roll angle of the vehicle is the angle between the reference plane of the vehicle and the horizontal plane. Therefore, the equation:

\[ \text{roll} = \alpha + \gamma \]

(9)

holds. Substitution of \( \gamma \) (Eq. (8)) provides the general equation relating \( \alpha, \gamma \) and roll:

\[ \alpha - Ka + Kg \sin \alpha + \gamma_a = \text{roll} \]

(10)

The road's cross-slope maximum value is approximately 6°. Assuming an approximation for small angle values (\( \sin \alpha \approx \alpha \)) we have:

\[ \alpha = \frac{Ka + \text{roll} - \gamma_a}{1 + Kg} \]

(11)

Hence, the cross-slope of the road is related to the transversal acceleration and roll values, as well as to the \( K \) and \( \gamma_a \) parameters, which depend upon the specific vehicle and can also change, for the same vehicle, from one survey to another. It cannot be excluded that these parameters vary as a function of environmental conditions, such as temperature and humidity. Besides, the spring elastic constant \( k_s \) incorporates not only the behaviour of the suspensions, but also that of the tyres, whose pressures vary with temperature as well as with their maintenance conditions. For the sake of simplicity, it is assumed that the geometrical and elastic characteristics of the vehicle do not change throughout a survey. For this reason, it is necessary to fix the current values of these parameters prior to the surveys. These operations are known as model calibration and can be carried out according to two procedures, depending on the availability of a laser scanner that is synchronised with the IMU.
Fig. 2. Calibration chart. Left: the vehicle’s path. Right: scatter plot of roll versus acceleration values, with linear regression curve.

If no scanner is available, $K$ and $\gamma_a$ are determined by driving circular paths and repeatedly passing at various velocities over the same calibration point, which can be marked on the ground. The angle $\alpha$ in Eq. (10), although unknown, is a constant for that calibration point: hence, the roll value is linearly related to the lateral acceleration. The constant $K$ can be obtained from the set of pairs $(a, \text{roll})$ as the slope of the linear regression curve. An example of a calibration diagram is shown in Fig. 2. Since $\alpha$ remains unknown the trim angle $\gamma_a$ cannot be fixed. For this reason, the calibration survey must be carried out on at least one spot with known cross-slope.

We can now analyse the case of a MMS vehicle fitted with a device that allows to compute the relative angle between the average planes of vehicle and road ($\gamma$). By defining the lateral acceleration $x$ as:

$$x = \left(-a + g \sin \alpha\right)$$

and by substitution of $x$ in Eq. (8):

$$\gamma = K x + \gamma_a$$

(13)

a value for the dispersion $(x, \gamma)$ is obtained, from which both parameters $K$ and $\gamma_a$ are obtained once a linear regression curve has been defined. In order to obtain a reliable linear regression curve, it is advisable to have a wide range of values along the $x$ axis. For this reason it is quite important that the vehicle is exposed to increasing lateral accelerations, starting from near zero to quite large (about $5 \text{ m/s}^2$), during the preliminary calibration phase. Fig. 3 is an example of calibration carried out this way.

Fig. 3. Scatter plot of $(x, \gamma)$ values and the linear regression curve.

Generally, the $\gamma_a$ values are nearly zero so that, assuming that the measures of roll and lateral acceleration provided by the IMU are exact, the cross-slope values are basically depending on the $K$ values. In order to define the relationships between the
cross-slope results and possible errors in the fixing of the value of \( K \), the behaviour of the \( a(K) \) function is analysed.

The assessment of the errors \( \Delta \alpha \) in the determination of the cross-slope \( \alpha \) is based on:

\[
\Delta \alpha = \frac{d\alpha}{dK} \Delta K
\]

where

\[
\frac{d\alpha}{dK} = \frac{a - g(\text{roll}) - \gamma_a}{(1 + Kg)^2}
\]

\[
= \frac{a - g\text{roll}}{(1 + Kg)^2} + \frac{g \cdot \gamma_a}{(1 + Kg)^2}
\]

\[
= \alpha'(K) + \alpha'_a(K)
\]

The first term \( \alpha'(K) \) of the derivative depends on the value of \( K \) and the basic values of the lateral dynamics of the vehicle, which vary along the path. Hence, the maximum value of \( \alpha'(K) \) has been determined for a winding and long survey with appropriately \( K = 0.009 \text{ rad s}^2/\text{m} \) (mean value obtained during calibration).

For a given value of \( K \), the second term of the derivative in Eq. (15) basically depends on the trim angle alone, which does not vary along the path. Hence, the fixing of the maximum value of \( \alpha'_a(K) \) involves the assignment of a value to \( \gamma_a \) so that, \( \gamma_a \) being very close to zero, it can be assumed, in this case, that \( \gamma_a = 1^\circ \). Hence, we have:

\[
\max(\alpha'(K)) = \frac{230^\circ}{K_{\text{unit}}}
\]

\[
\max(\alpha'_a(K)) = \frac{8^\circ}{K_{\text{unit}}}
\]

(16)

from which

\[
\left| \frac{d\alpha}{dK} \right| \leq \frac{238^\circ}{K_{\text{unit}}}
\]

(17)

Assuming a 10% error in \( K \), we get \( \Delta K = 0.0009 \text{ rad s}^2/\text{m} \), which results in an error \( \Delta \alpha \) of only \( 0.21^\circ \). Hence, a less than perfect estimate of \( K \) doesn't necessarily have a large effect on the precision of the cross-slope determination [2].

Cross-slope obtained from INS/DGPS – laser scanner integrated data

The IBEO Ladar Digital Automotive (LD-A) laser sensor (Fig. 4) is a Class 1, rotating laser distance meter, running on 12V DC power supply, with ARCnet and CAN interfaces for data transmission, plus an RS-232 interface for firmware updates. Its range is about 40 m for surfaces with a reflectivity \( \geq 5\% \) and about 250 m with reflectors, while its stated precision is 5 cm and the field of view \( 360^\circ \) [9]. This instrument is aimed at vehicle applications, in particular for fixed or moving obstacles detection. The distance meter has been attached on a console at the rear end of the MMS GIGI One vehicle in order to survey the cross section of the road.

In this particular case, the position and trim of the vehicle at any moment during the scan can be obtained via an independent circuit, generating a pulse of adequate amplitude at regular intervals, which, after being triggered via software from the start of the scan, travels to a DIO (Digital Input Output) port on the Applanix positioning system [3], which records the scan time.

It can be assumed that the points of the section obtained by the laser scan are orthogonal to the road axis, since the \( X \) axis of the local reference system roughly points in this direction. In consequence, the condition to be applied to the \( X \)
coordinates of the point cloud, in order to extract only the points belonging to the roadway, is the following:

\[
\left( \frac{D}{2} - e \right) < X < \frac{D}{2}
\]  

(18)

![IBEO Automotive laser sensor.](image)

where \( D \) is the road width and \( e \) is the horizontal distance between the centre of the local reference system (i.e., the centre of the laser scanner) and the road axis (Fig. 5).

![Position of MMS and laser (L) relative to the road.](image)

CS: centre line; D: width of road; X, Y: laser coordinate system; E, N: geodetic coordinate system.

In addition, a condition is applied to the \( Z \) coordinates, in order to filter out any disturbances due to passing vehicles:

\[-3 m < Z < -1.5 m\]  

(19)

The estimation of the cross-slope of the road for the laser method is by least squares approximation of the laser sensor readings using a linear fit [2]. All the laser measurements obtained from the vehicle are referenced to the coordinate system originating from the centre of laser system. Therefore, Eq. (20) is used to convert the \((x_i, z_i)\) coordinates in the laser coordinate system to the vertical and horizontal \((X_i, Z_i)\) coordinate system. The roll angle values from the INS are used for this purpose.

\[
\begin{bmatrix}
X_i \\
Z_i
\end{bmatrix} =
\begin{bmatrix}
\cos(\text{roll}) & \sin(\text{roll}) \\
-\sin(\text{roll}) & \cos(\text{roll})
\end{bmatrix}
\begin{bmatrix}
x_i \\
z_i
\end{bmatrix}
\]  

(20)

The resulting point group is subdivided into two sub-groups, representing the two halves of the road; the cross-slope is calculated as the angular coefficient of the linear regression line:

\[
a = \arctan \left( \frac{n \cdot \sum_{i=1}^{n} X_i \cdot Z_i - \sum_{i=1}^{n} X_i \cdot \sum_{i=1}^{n} Z_i}{n \cdot \sum_{i=1}^{n} X_i^2 - \left( \sum_{i=1}^{n} X_i \right)^2} \right)
\]  

(21)
Cross-slope obtained from manual measurements

To collect the control data, a SOKKIA SET330R total station was used to take sample measurements. This total station has an angular accuracy of 3” if measured in 2 faces and a distance accuracy ±(3mm+2ppm) in reflectorless mode. The cross-slope values obtained with the total station from a set of point measurements of the road section have a greater precision than those using the other proposed methods and can be regarded, for our purposes, as true values.

EXPERIMENTAL RESULTS

The experimental data discussed here were collected during two survey sessions. The first was performed in July 2006, on the national road SS1 “Aurelia” between Rosignano and Campolecciano, near Livorno, for a total of 12 km. The second was performed in February 2007, on the national road SS58 “Strada nuova per Opicina”, near Trieste, for a total of 7 km. The national road SS1 was surveyed by MMS once in each direction and by total station in 17 cross-sections. The national road SS58 was surveyed by MMS, with INS and laser scanning data, three times in each direction and by total station (21 cross-sections).

![Fig. 6. Scatter plot of cross-slopes (abscissa) and differences between INS - manual cross-slope determinations.](image)

Validation of computed cross-slope values

The validity of the measurements obtained by the developed algorithm was initially checked for any correlation with the values of the measured angles. For this purpose, the deviations between INS measurements and the ‘true’ reference values, obtained from the total station, were determined. Figure 6 shows the dispersion of these deviations for 145 available data pairs. The correlation between the deviations (on the ordinate) and the cross-slope values (on the abscissa) is, in effect, zero for a sample of fair significance. It can therefore be assumed that the algorithm successfully determines the cross-slope and that the calculated values are independent from the value of the slope itself and from the path covered by the surveying vehicle.

Comparison between manual and INS measurements

Since there is no correlation between the cross-slope values and the differences between INS and control measurements, the distribution of these differences was analysed. Figure 7 shows the values of the cross-slope obtained from the INS and the total station data for the 145 check points.
A statistical analysis was then carried out on the heterogeneous sample of the cross-slope values. The distribution of the measured deviations (Fig. 8) has a standard deviation of 0.26° (0.4%) and a mean of +0.03° (0.05%). Hence, it can be assumed that the algorithm is not affected by systematic errors and gives an acceptable precision for the determination of cross-slopes. Note that the control sections were selected on roads with old and new pavements.

If we restrict the statistical analysis to cross-sections on new pavements, better results are obtained. This subset of the distribution of measurement deviations has a standard deviation of 0.18° (0.3%) and a mean of 0. It includes only 50 of the total of 145 check points.

Comparison between laser and INS measurements

Due to time constrains, the number of control sections surveyed by the total station, although relevant, is not comparable to that of the INS determination, which can be carried out at the rate of the INS/DGPS system, i.e. up to 200 Hz. The survey on the national road SS58 includes a cross-slope determination by INS/DGPS every 1 m, totalling of 41088 measurements, as well as the data collected by the IBEO laser.
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scanner. In three passages in both directions of the 7 km long section of road, 5300 cross-slope determinations were obtained with the laser scanner.

The values obtained with these techniques were compared, excluding the laser data referring to the opposite lane, which show high noise levels due to passing cars. A comparison was then performed between the 2650 laser measurements and three sets of 2650 INS measurements each, corresponding to the same road profile, for a total of 7950 samples.

![Graph](image)

Fig. 9. INS and laser measurements on a curve.

![Graph](image)

Fig. 10. Scatter plot of INS - laser measurements versus cross-slope

Figure 9 shows the comparison of the two techniques for the national road SS58 section between km 0+460 and km 0+600. The values obtained by laser scanning were chosen as reference to check for the absence of correlations between the cross-slope values and the differences between the laser and INS data. As the scatter plot in Fig. 10 shows, no such correlation is evident. It can be again assumed that the INS measurements are not dependent upon the value of the slope itself.

The distribution of the deviations for the 7950 samples (Fig. 11) shows a standard deviation of 0.38° (0.7%) and a mean of +0.07°. The equivalent mean was 0.03° in the comparison between INS and total station measurements, and was small enough to assume that no systematic errors had occurred. The comparison of laser vs. INS measurements shows yet again a positive mean value of the differences, slightly greater than the value in the comparison between total station and INS. This highlights a problem related to cross-slope measurements. Lanes are not usually planar surfaces, and their cross-section is better represented by a curve, rather than by a straight line.
Both laser scanner and total station measure to several points in the cross-section, and the measured cross-slope is that of a straight line fitting those points.

Fig. 11. Deviations frequency distribution of differences of INS-laser data.

Surveys performed by the MMS, on the other hand, yield a slope that is related to the contact points between the wheels of the vehicle and the road. Assuming that the MMS path is in the centre of the lane, the values obtained by the different methods vary little and, as in this case, the mean of the deviations differs only slightly from zero. The standard deviation between INS and total station measurements is 0.26°, while the one between INS and laser measurements is 0.38°. The difference is quite small and can be attributed to the lower precision of the laser data used as reference in the second case, compared with total station-based topographic surveys. The data collected in the national road SS58 survey show that the difference between the INS and other data is greater on road sections with old pavement than on road sections with new pavement [4].

Fig. 12. INS cross-slopes on a tangent with and without moving average filter.
Use of filtered data

The MMS measurements show a high noise level, due to the unevenness of the road pavement, which is large in sections with old pavement, which represent the greater part of the road network. In these cases, discrete INS data can lose their meaning, unless the high-frequency signal resulting from the roughness of the pavement is investigated. The discrete data can be conveniently filtered by a moving average to obtain a local average trend of the cross-slope values. A window of ten values has been applied for the moving average. It is possible to use other windows for the moving average depending on the specific requirements. Figure 12 shows a tangent of a road with old pavement, with an obvious cross-slope averaging at about −1.4° (2%).

Figure 13 shows a series of two bends, one to the right and one to the left. The filtered data clearly show the transition between the bends with a tangent in which both lanes of the roadway have a cross-slope of about −1° (2%).

![Cross-slope graph](image1)

Fig. 13. INS cross-slopes in two bends, with and without moving average filter.

![Cross-slope graph](image2)

Fig. 14. Detail of cross-slopes on a curve with and without moving average filter.

Figure 14 shows a subset of the data in Fig.13, referred to the left-hand lane. In this case, the filtered data is adequate for a geometrical study of the bend.
CONCLUSIONS

Both traditional and GPS-based field surveys yield highly accurate results, but are time consuming and pose safety risks for data collecting operators. Many MMSs are equipped with profilometers and state-of-the-art sensors (e.g. ARAN-Automatic Road Analyzer technology) as well as an IMU similar to the one implemented on MMS GIGI One, yielding a millimetre-range precision in the determination of the vertical position of the points at ground level, and therefore a precision in the cross-slope determination greater than that achieved by the algorithm presented in this paper by one order of magnitude. In fact, such profilometers are also used for wheel rut depth as well as IRI (International Roughness Index) measurements [7].

LIDAR technology, integrated with airborne GPS and inertial measuring systems, can also yield road surface models. The accuracy of cross-slope values computed by means of such models is similar to that achieved with the proposed algorithm (~ 0.7%) [8].

The analysis of the collected data shows that the algorithm developed by the authors to compute cross-slopes only from INS data provides excellent accuracy and acceptable precision. The data also highlighted the presence of a high-frequency signal noise, caused by the unevenness in road pavement. In the theoretical model the pavement is taken as an ideal planar surface, inclined by the cross-slope. Besides, the comparisons can not ensure that the sections under investigation are always exactly the same in all methods used – total station, laser scanning and INS. The sections being compared could be shifted by tens of centimetres, due to the finite precision in the georeferencing of the sections.

It had be expected that surveys performed on roads with new pavement differ from those carried out on roads with old pavement; in the first case, the road surface is even, the measurements show less noise and the values obtained by the INS can be more easily compared to those obtained by the total station. Data collected on roads with old pavement are affected by a higher noise level, due to the unevenness of the surface, which can affect the theoretical determination of the cross-slope and, more significantly, the comparison to other surveying methods.

To improve the precision analysis for the INS method new tests are under development, including an “ad hoc” analysis for the different type of pavement maintenance. This will result in two precision information: one for the ‘ideal’ condition of a road with new pavement, and one for the ‘real’ condition of a road with significant roughness. In order to get more values for comparisons in the same section, surveys will be performed on shorter legs and repeated several times. Also a greater number of sections will be surveyed by a total station or by a terrestrial 3D laser scanner.

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