PRECISE ESTIMATION OF ROAD HORIZONTAL AND VERTICAL GEOMETRIC FEATURES USING MOBILE MAPPING TECHNIQUES

Estimativa precisa de feições geométricas horizontais e verticais em rodovias usando técnicas de mapeamento móvel.

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ABSTRACT

This paper presents a software especially developed for the precise estimation of road horizontal and vertical geometric features, using the GPS/IMU data collected during the digital survey of road nets. The survey is based upon the geodetic positioning of a suitably equipped vehicle, moving along the road in a two way journey (forward/reverse). Firstly the acquired data is used to extract the centreline of the road and at the next level the parameters of the horizontal and vertical features of the road are computed. The estimation of the parameters is based on a least squares adjustment of the characteristic curves applied on the points forming the bearing and the inclination diagram of the road, whereas the final quality check of each curve fitting is performed in the corresponding segments of the horizontal and vertical alignment. Until today the software has been successfully applied at more than 600km of the National Greek road net, while the results of the processing verify that the total reproduction of the centreline of a road can be achieved with 20cm accuracy.

Keywords: Geometry; Surveying; Estimation; CAD; Software.

1. INTRODUCTION

The continuously increasing demand for spatial information during the past years has led to a technologic evolution in the field of digital mapping of road nets.

Nowadays the digital survey of roads is carried out using state of the art multi-sensors as well as advanced processing methods. The data collected during the survey is crucial not only for feasibility and environmental studies, but also for studies examining the safety of an existing road net and suggesting the necessary improvements. Moreover, it is a powerful tool for a variety of automotive applications.

The National Technical University of Athens (N.T.U.A.) has developed an integrated MMS suitable for the digital surveying of road nets (VEIS et al., 1995). The system is based on the geodetic positioning of a vehicle moving along the road in a two way journey (forward/reverse), suitably equipped with dual-frequency GPS receivers, providing the vehicle kinematics, two cameras and a VCR, for the real time recording of the road and its surroundings (e.g. traffic signs, power lines etc.). Recently an integrated GPS-INS unit was mounted on the vehicle in order to enhance the MMS capability in environments where the GPS solution is unavailable, such us urban canyons, rough terrains, forestry areas, etc. The acquired data is being analyzed and stored into a geo-database via especially developed software.

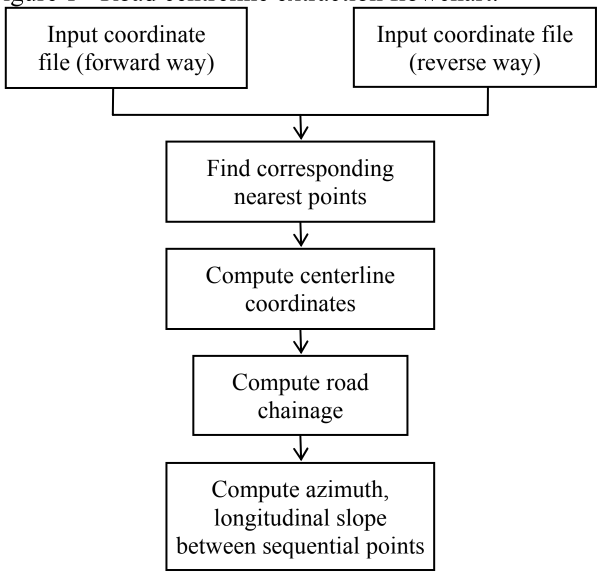
The fact that the evaluation of the stake out of a road is based on safety criteria formulated by factors such as the analysis of the traffic accidents in relevance to the geometry of the road, renders the precise estimation of the parameters of the geometric features of a road necessary. In recent years, several algorithms have been introduced for the geometric modelling of the centerline of a road, in the form of design elements (CHOI et al., 2007; GONTRAN et al., 2005; STRATAKOS et al., 2009). The high level of the algorithms dependence on the quality of data as well as on the road geometry characteristics remains, however, a major issue.

This work presents an integrated software suitable for the extraction of a road centerline geometry, in terms of a classical design layout. Geometric parameters such as the radius of a circular arc or the parameter of a clothoid curve are precisely defined, using the principles of a least squares adjustment. The whole process takes place in a graphical (CAD) environment, while the final result is the total reproduction of the road centerline geometry with an average accuracy of 20cm.

2. ROAD CENTERLINE EXTRACTION

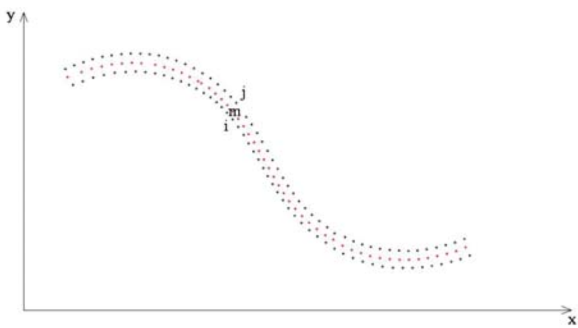
In the first step, the three dimensional coordinates which result from the GPS/IMU solution are transformed into cartesian coordinates referring to a national grid frame, e.g. the Greek transverse Mercator projection. The solution is a combination of both forward and reverse trajectories of the vehicle, thus the coordinates are right after reduced to the centreline of the road. The algorithm developed for the extraction of the road centreline executes the following procedures, as shown in Figure 1.

Figure 1 - Road centreline extraction flowchart.



At first, the corresponding nearest points of opposite ways (forward/ reverse) are automatically detected and next the centreline cartesian coordinates (x_m, y_m) and heights (h_m) are calculated using the average value of their coordinates (Figure 2, eq. 1). At the next step the road chainage (ch_m) is computed based on the distance between centerline sequential points (eq. 2). Two more geometric elements of the centreline necessary for the following procedure, namely the azimuth ($az_{m\text{-}m+1}$) and longitudinal slope ($s_{m\text{-}m+1}$), are computed. Their values result from the corresponding differences of sequential points horizontal coordinates (eq. 3) and heights (eq. 4).

Figure 2 - Centerline coordinates estimation.



$$x_m = \frac{x_i + x_j}{2}$$
$$y_m = \frac{y_i + y_j}{2} \quad (1)$$
$$h_m = \frac{h_i + h_j}{2}$$

where x_m, y_m = centerline cartesian coordinates
h_m = centerline heights

$$ch_{m+1} = ch_m + d_{m\text{-}m+1} \quad (2)$$

where $d_{m\text{-}m+1} = \sqrt{(x_{m+1} - x_m)^2 + (y_{m+1} - y_m)^2}$

$$az_{m-m+1} = a\tan\frac{dx_{m-m+1}}{dy_{m-m+1}} \quad (3)$$

(For $dx_{m\text{-}m+1} \geq 0$, $dy_{m\text{-}m+1} > 0$)

where $dx_{m\text{-}m+1} = dx_{m+1} - dx_m$
$dy_{m\text{-}m+1} = dy_{m+1} - dy_m$

$$s_{m\text{-}m+1}(\%) = \frac{h_{m+1} - h_m}{ch_{m+1} - ch_m} \cdot 100 \quad (4)$$

The process is completed when all the above elements are saved into an ASCII file, every line of which contains: road chainage, cartesian coordinates, height, azimuth, longitudinal slope (Table 1).

Table 1 - Centerline geometric elements sample file.

ch_m(m)	x_m (m)	y_m (m)	h_m(m)	$az_{m\text{-}m+1}$ (º)	$s_{m\text{-}m+1}$(º)
0.00	505131.25	3926066.00	25.88	87.0	-1.16
15.77	505147.00	3926066.75	25.69	89.1	-0.64
28.15	505159.38	3926067.00	25.59	90.4	-0.43
41.59	505172.81	3926066.75	25.50	91.1	-0.37
54.46	505185.69	3926066.50	25.42	91.2	-0.26

3. GEOMETRIC FEATURE PARAMETER ESTIMATION

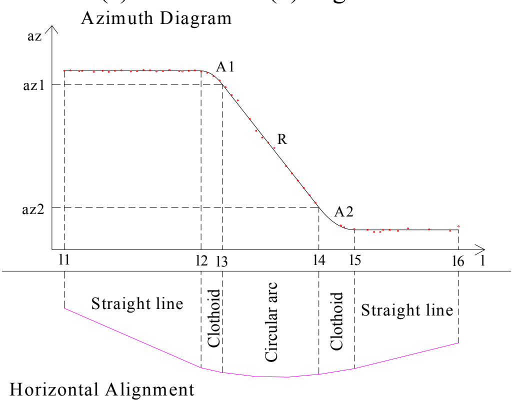
3.1 Basic Principles

The estimation of the horizontal and vertical features of a road takes place in a CAD environment, via software especially developed for this purpose. Firstly the angular diagrams of the road are drawn, namely the azimuth diagram showing the change of rate of the road horizontal features azimuth and the inclination diagram, where the change of rate of the vertical features longitudinal slope is depicted. Due to their simplicity, these diagrams offer an easy and effective way firstly to visually define each geometric element and then estimate its parameters.

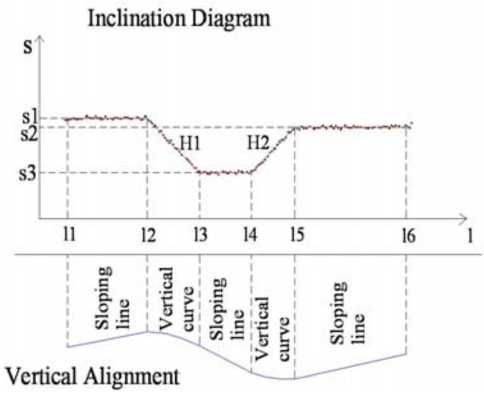
The horizontal alignment of the road consists of three different geometric elements; straight lines, circular arcs and clothoids. On the other hand straight sloping lines joined by vertical curves (concave or convex) are the main elements, forming the shape of a road along the third dimension. In the azimuth diagram straight lines correspond to lines parallel to the x-axis, circular arcs to inclined lines and clothoids to 2nd degree curves (parabolas), as illustrated in Figure 3a. Respectively, in the inclination diagram sloping lines correspond to lines parallel to the x-axis and vertical curves to inclined lines, as shown in Figure 3b.

Through a semi-automated procedure, the software enables the user to specify the beginning and the end of each geometric feature of the road and next the values of the parameters of the horizontal or vertical elements are automatically estimated using a least squares adjustment. In this way the length and the azimuth of straight lines, the radius of the circular arcs and the parameter of the clothoids are defined in the azimuth diagram. Respectively in the inclination diagram the length and slope of straight lines and the parameter of the vertical curves are computed.

Figure 3 – Horizontal (a) and vertical (b) alignment features.



(a)



(b)

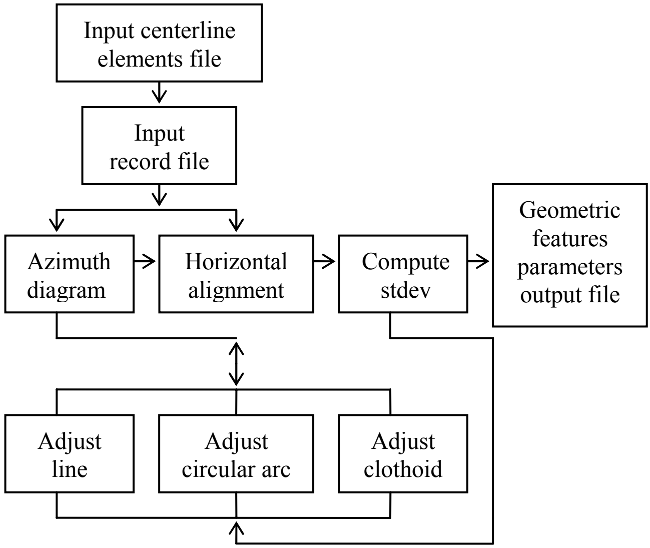
At the next stage of the process the estimated geometric features are drawn in the corresponding segments of the horizontal and vertical alignment of the road. The standard deviation between the geometric features and the centreline, which has been produced from the GPS solution, is the final criterion for the quality control of each curve fitting. The estimation of all geometric features leads to the total reproduction of the centerline of the road in a CAD environment, while in addition, the parameters of the geometric elements are saved into ASCII files.

3.2 Horizontal Geometric Feature Extraction

The software developed for the extraction of the horizontal geometric features functions in cooperation with two AutoCAD files. This way the estimation of the geometric parameters in the azimuth diagram as well as the adjustment of the curves in the corresponding horizontal alignment segment can be performed simultaneously.

The structure of the software is shown in Figure 4:

Figure 4 - Horizontal feature extraction flowchart.



Once the azimuth diagram and the horizontal alignment are drawn (Figure 5), the parameters of straight lines and circular arcs are computed, using the indirect observations method. The following equations (eq. 5, 6) are used for the computation of the straight lines azimuth and the radius of the circular arcs (R) respectively:

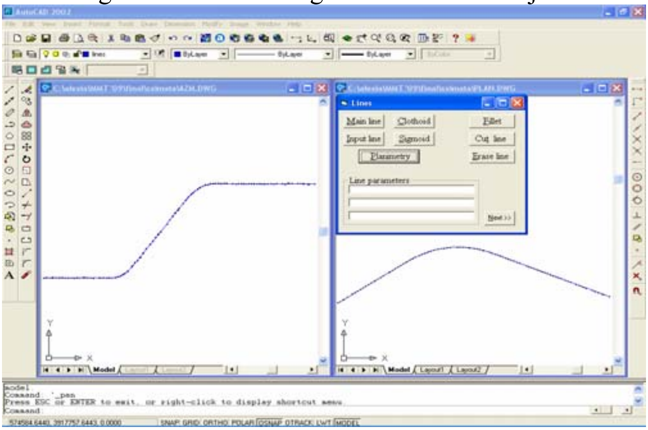
$$a\hat{z} = \frac{1}{n}\sum_{i=1}^{n} az_i \qquad (5)$$

where az_i = the azimuth of each observation
n = the number of points

$$a\hat{z}_0 + ch_i \cdot \frac{1}{\hat{R}} = az_i + u_i \qquad (6)$$

where $az_0, \frac{1}{R}$ = the line co-efficients
ch_i = the chainage of each observation
az_i = the azimuth of each observation
u_i = the residual of each observation

Figure 5 - Horizontal geometric feature adjustment.



In the next stage the parameter of clothoid curves (A), connecting straight lines to arcs and vice versa are calculated, using the equation describing the 2nd degree parabolas in the azimuth diagram (eq. 7):

$$az - az_o = \frac{L^2}{2A^2} \tag{7}$$

where az = the azimuth at the end of the clothoid

az_o = the azimuth at the beginning of the clothoid

L = the length of the clothoid

Subsequently, the cartesian coordinates of the features are computed, using the analytical equations of straight lines, arcs and clothoids. At this stage the features are adjusted in the horizontal alignment of the road, while the standard deviation (stdev) between each curve and the centerline is calculated, based on the well-known equation (eq. 8):

$$stdev = \pm\sqrt{\frac{[uu]}{n}} \tag{8}$$

where u = the vertical distance between the centerline point and the curve

n = the number of points

Finally, the parameters of all horizontal geometric features are saved into an ASCII file, as shown in Table 2. Each line of the file contains the chainage at the beginning and at the end of each feature, the corresponding azimuths, the radius of the circular arc, the parameter of the clothoid, the cartesian coordinates of the beginning and of the end of the feature and finally the standard deviation between the curve and the centerline of the road:

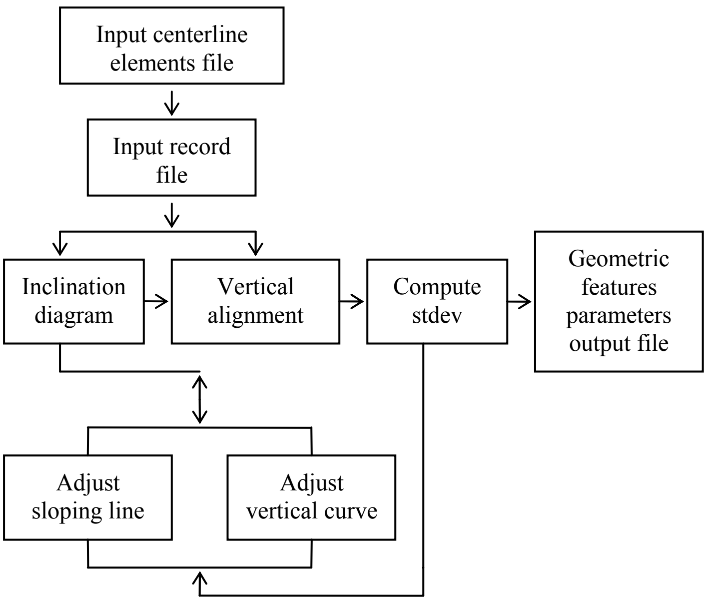
Table 2 -Horizontal geometric feature parameters sample file.

ch_s(m)	ch_e(m)	az_s(°)	az_e(°)	R(m)	A(m)	x_s(m)	y_s(m)	x_e(m)	y_e(m)	stdev(m)
20086.96	20453.81	55.742	55.742	0	0	574060.69	3918094.00	574363.89	3918300.50	0.196
20453.81	20569.21	55.742	63.85	0	216.92	574363.89	3918300.50	574462.14	3918360.85	0.274
20569.21	20845.28	63.85	102.643	407.74	0	574462.14	3918360.85	574731.08	3918392.69	0.223
20845.28	20995.09	102.643	113.169	407.74	-247.15	574731.08	3918392.69	574871.95	3918342.36	0.246
20995.09	21539.07	113.169	113.169	0	0	574871.95	3918342.36	575372.06	3918128.34	0.204

3.3 Vertical Geometric Feature Extraction

The structure of the software developed for the extraction of the vertical geometric features of a road is illustrated in Figure 6:

Figure 6 - Horizontal feature extraction flowchart.



At first the inclination diagram and the vertical alignment of the road are drawn (Figure 7) and next the parameters of the vertical features, namely the slope of straight lines and the radius of vertical curves (H) are computed, using the following, corresponding equations (eq. 9, 10):

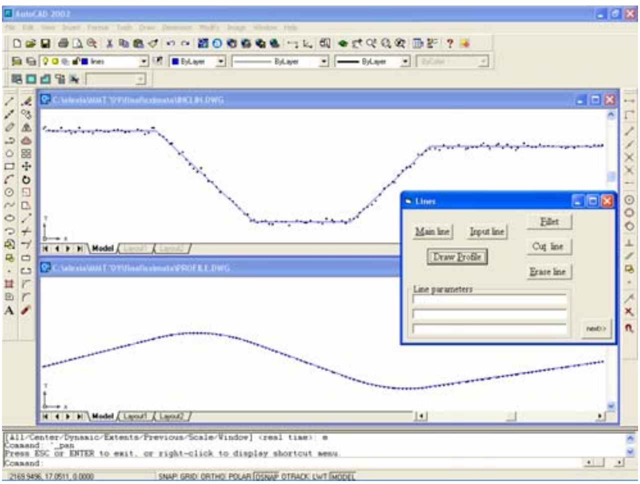
$$\hat{s} = \frac{1}{n}\sum_{i=1}^{n} s_i \tag{9}$$

where s_i = the longitudinal slope of each observation
n = the number of points

$$\hat{s}_0 + ch_i \cdot \frac{1}{\hat{H}} = s_i + u_i \tag{10}$$

where s_0 and $\frac{1}{H}$ = the line co-efficients
ch_i = the chainage of each observation
s_i = the longitudinal slope of each observation
u_i = the residual of each observation

Figure 7 - Vertical geometric feature adjustment.



In the next stage the heights of the vertical features are computed, using the analytical equations of sloping lines and vertical curves. At the same time the features are adjusted at the vertical alignment of the road, while the standard deviation between each curve and the centerline is calculated, based on the distance between each centerline point from the curve (eq. 8).

The process is completed when all parameters are saved into an ASCII file containing the chainage at the beginning and at the end of each feature, the corresponding heights, the radius of the vertical curve, the slope at the beginning and at the end of the feature and finally the standard deviation between the curve and the centerline of the road (Table 3).

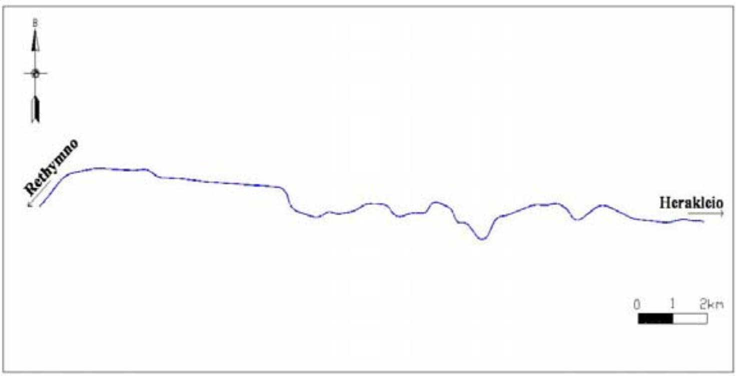
Table 3 - Vertical geometric feature parameters sample file.

ch_s(m)	ch_e(m)	h_s(m)	h_s(m)	H(m)	s_s(°)	s_e(°)	stdev(m)
20391.33	20821.83	33.14	44.11	0	1.461	1.461	0.071
20821.83	21197.72	44.11	42.09	-6091.23	1.461	-2.076	0.095
21197.72	21573.35	42.09	28.47	0	-2.076	-2.076	0.121
21573.35	21864.23	28.47	24.98	5999.03	-2.076	0.842	0.103
21864.23	22546.51	24.98	35.01	0	0.842	0.842	0.117

4. DATA PROCESSING - ACCURACIES ACHIEVED

Until today the software has been successfully applied at more than 600km of the National Greek road net. The necessary field measurements were mainly collected by the MMS developed by the N.T.U.A. and more recently by the PosLV 420 system produced by Applanix Corp (GIKAS et al., 2008). In this paper the results of the processing of a 23km long segment of the northern road net of Crete connecting Rethymno to Herakleio are shown (Figure 8). The specific road was selected due to its various geometric characteristics, thus the results of the process and analysis of the data are indicative of the accuracies achieved with the method described.

Figure 8 - 23km long part of the road connecting Rethymno to Herakleio.



More thoroughly, the road comprises a typical cross section of two lanes at each direction, crossing rural and under populated areas. The horizontal alignment of the road consists of 124 in total geometric features, namely 38 straight lines, 38 circular arcs, 47 clothoids and 1 sigmoid. The corresponding vertical alignment of the selected section consists of 22 sloping lines and 21 transition curves.

The results of the processing of the acquired data are summarized in Tables 4 and 5. The minimum, maximum and average values of the à posteriori standard errors (σ) deriving from the estimation of the geometric parameters in the azimuth diagram, as well as the standard deviations of the geometric features in the horizontal alignment of the road are presented in Table 4. The corresponding values of the standard errors in the inclination diagram and the standard deviations in the vertical alignment respectively are shown in Table 5.

Table 4 - Horizontal geometric feature adjustment deviations.

		Azimuth diagram		Horizontal alignment
Straight lines	min σ_{az}	0.05º	min stdev	0.045m
	max σ_{az}	0.50º	max stdev	0.417m
	$\overline{\sigma}_{az}$	0.28º	$\overline{\text{stdev}}$	0.191m
Circular arcs	min σ_R	0.4%	min stdev	0.028m
	max σ_R	5.5%	max stdev	0.416m
	$\overline{\sigma}_R$	1.8%	$\overline{\text{stdev}}$	0.228m
Clothoids	min σ_A	0.05%	min stdev	0.055m
	max σ_A	0.5%	max stdev	0.384m
	$\overline{\sigma}_A$	0.2%	$\overline{\text{stdev}}$	0.239m

Table 5 - Vertical geometric features adjustment deviations.

		Inclination diagram		Vertical alignment
Sloping lines	min σ_s	0.04%	min stdev	0.036m
	max σ_s	0.16%	max stdev	0.175m
	$\overline{\sigma}_s$	0.11%	$\overline{\text{stdev}}$	0.109m
Vertical curves	min σ_H	0.9%	min stdev	0.035m
	max σ_H	5.8%	max stdev	0.151m
	$\overline{\sigma}_H$	3.6%	$\overline{\text{stdev}}$	0.082m

The deviation values reveal the final quality of the adjustment; the final accuracy of the horizontal features adjustment is 20cm, while the adjustment of vertical features is performed with even better accuracy, reaching 10cm. Latter can be explained by the fact that the change of rate of the vertical features slope is much more gentle compared to the change of rate of the horizontal features azimuth.

An additional valuable conclusion results from the error values in the azimuth and inclination diagrams. The uncertainty in the estimation of a straight line azimuth is 0.3° and of a circular arc radius 2%. Finally the estimation of a straight line slope or of a vertical curve radius is performed with an accuracy of 0.1% and 3.6% respectively.

5. CONCLUSIONS

This article presents an integrated method for the precise estimation of road horizontal and vertical geometric feature. In the first step the field measurements collected by an MMS moving along the road in a two way journey are used to extract the centerline of a road and next the parameters of the horizontal and vertical feature of the road are precisely estimated via software especially developed for this purpose. The final product of the software is the total reproduction of the road with an accuracy of 20cm. The information provided is crucial not only for missing or incomplete records of a road geometry database but more importantly for decisions concerning the road safety.

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