EXTRACTION OF ROAD GEOMETRIC PARAMETERS FROM HIGH RESOLUTION IMAGES VALIDATED BY GEODETIC TECHNIQUES

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ABSTRACT

The knowledge of road geometric data provides the main input for safety evaluation of highways. Moreover, Art.13 of the Italian new Road Code requires an implementation of Road Cadastre, for which the knowdlege of the road network - in terms of georeferenced planimetric and altimetric alignments - is needed. In this paper high resolution images have been analyzed in order to develop automatic techniques for the extraction of road geometric parameters.

Different algorithms and remote sensing methodologies have been tested starting from the study of the already proposed techniques in order to choose the most suitable one in the Italian particularly complex landscape. Special attention has been paid to the problem of filtering images, in order to reduce radiometric data complexity and noise.

Road sections in the Friuli Venezia Giulia Region have been chosen as a field test to validate the geometrical parameters extracted from the images. Different geodetic techniques, also in real time kinematic mode, have been applied to validate the obtained parameters. Finally the extracted features have been superimposed on digital images to be used for GIS (Geographical Information System) applications.

Keywords: road cadastre, road safety , road alignment, high resolution satellite images, Geographical Information System.

1. FOREWORD

The knowledge of road alignment has became a basic question to develop accurate studies on road safety. As shown in several studies there is a close correlation between road geometrical characteristics, drivers' behaviour, and road accidents.

Drivers' behaviour can be represented by the operative speed. Operative speed analysis lets evaluate the consistency of the road geometry relating to drivers' expectations and thus identify possible anomalies in road geometry.

The operative speed on road elements can be obtained through models that correlate the geometric characteristics to the speed values. In general, speed is a function of geometrical parameters such as the radii of curves and tangent lengths, the width of a road section, etc.

These elements can be derived from technical cartography with a certain accuracy considering that the real road signing determining drivers' guide is not visible on cartography. For this reason, other techniques are often used for the survey of the geometrical elements.

Furthermore, the administrations managing roads need to know the consistency and conditions of their roads for instance to plan maintenance and road safety improvement work.

This need was already stressed in Article No. 13, sub-section 6, of the Italian Highway Code that provides for the obligation - for the road owners - to institute and update the cartography, the Road Cadastre, and relative pertinences according to the rules established by a special decree issued by the Ministry of Works, after hearing the Superior Council of Works and the Research National Council.

Moreover, Article No. 225, sub-section 1, of the Code provides for the institution of a National Road Archive at the Ministry of Works, and, for it, the General Inspectorate for the Circulation and Road Safety.

Article No. 226, sub-sections 1 to 3, and the implementation regulation (Article No. 401) give further indications on how the archive and its contents have to be organized. The Archive has to include all the data relative to the technical and legal conditions, with indications on vehicular traffic, accidents, acoustic and atmospheric pollution. The relative data must be given to the road agencies, extracting them from their own road information systems, and other sources.

It is thus possible to infer that the data included in the National Road Archive actually rely on the Road Cadastre ones.

The Cadastre is particularly needed by the owner agency for a better knowing, and a better managing of its own road network.

The Archive is instead needed at central level to have a unitary picture of the National Road Network, its consistency, its security and service levels, in order to give sufficient and homogeneous information to the people managing the programming choices.

The Road Cadastre represents the inventory of all the real and public road properties present on the national territory.

It consists of a forming phase, meant to produce the characterizing elements of the road geometric properties, by means of cartographies and databases. A subsequent activation phase has to allow the saving of all data categories that can be used to build a National Archive of the Roads as well as to develop activities such as the classification of the road network according to Article No. 2 of the Code, the planning of works, maintenance managing and investment planning.

The Cadastre represents the minimum compulsory content of a Road Information System that each Agency will have to set up for a more efficient management of its road heritage.

A particular attention must be paid to the fact that the Cadastre is to include the elements relative to the road geometrical characteristics and these elements need to be updated.

In conclusion, the road geometric characteristics and, in particular, the geometrical characteristics of the road axis, as well as the width of the roadway and the shoulders must be defined, both for the definition of the operative speeds and for the Cadastre.

These characteristics cannot be extracted with high accuracy from the technical cartography, because it is not possible to reconstruct the signing from this. It is thus necessary, as said above, to use different surveying techniques.

The definition of road axis is in fact not expressly given by the ministerial Act of 1/6/2001 (Modalities of institution and updating of the Road Cadastre). The technical specifications give only an "illustrative definition of the road element", starting from which it is possible to give an enumerative definition:

- In the case of road cross section organized in a single carriageway with two run directions, the road axis is given by the separation axis between the internal lanes with opposite run directions (that does not necessarily coincide with the geometric axis of the roadway, nor with the section geometrical axis);
- In the case of a road cross section organized in a single carriageway with one run direction, the road axis is given by the geometric axis of the roadway (that does not necessarily coincide with the geometric axis of the section);
- In the case of road cross section organized on two separate carriageways, and if one decides to represent the road segment with a single road element, the road axis is given by the axis of the median.

The definition of the road axis of interest in the Road Cadastre thus depends on the definitions of roadway and lane for which it is possible to refer to the ministerial decree of 11/5/2001, which gives the "functional and geometric rules for road construction" [Ministero delle Infrastrutture e dei Trasporti, 2002]. According to these rules the roadway is "the part of the road used for the running of vehicles; it is made up of one or more lanes, is paved and delimited by signing". A lane is instead the "longitudinal part of the road, normally limited by signing of adequate width to let the running of a single vehicle".

Some corollaries of practical interest follow from this definition, namely:

To be able to correctly detect the road axis, the signing must be complete and present. Should that not occur and, for instance, the geometric axis of the pavement is assumed even if signing is absent, then the rule prescription has not been followed;

Signing remaking involving important changes in the lane width can invalidate a pre-existing Cadastre (even when other parameters required for the Cadastre, like roadway width, travel direction, and the number of lanes, are not changed);

As the materializations of the axis points is not provided for, it is necessary to give a documentation of the road situation at the time of the surveys, together with the data given for allowing the operation of testing that will consist in a “congruence check with the national geodetic networks”.

Direct and indirect techniques allowing to extract both the axis, and the signing width can be applied to obviate that.

The techniques adopted up to now for these aims foresee instrumented vehicle running along the road. The vehicle positions, surveyed by GPS, allow to reconstruct the geometric parameters of the elements (including measures of signing).

Together with this technique, the potentiality of the geometric characteristic survey obtained through the analysis of high resolution satellite images was experimented by the Authors.

This technique also allows to survey the signing, and thus overcome the uncertainty deriving, for instance from the analysis of cartography. At the same time, it cuts the acquisition time with respect to the GPS surveying. This technique could furthermore be used to check the accuracy of the signing lay-out.

2 EXISTING STUDIES

The extraction of roads from spatial data sources, such as aerial or satellite images has been in scope of research for more than twenty years now. Many approaches are based upon edge detection or texture analysis techniques (Dial et al., 2001). Other methods make use of dynamic programming, or LSB-Snakes to further improve the results of the road extraction process (Grüen, 1997).

Recently, the adoption of knowledge-based approaches seems to gain more importance by means of rules and models (Hinz et al., 2001).

Predefined information is acquired at a general global level (e.g. connectivity) and at a local level (e.g. context), respectively (Hinz and Baumgartner, 2002; Vosselmann, 1997).

In addition, valuable properties can be taken from other existing spatial data sources such as vector data (Zhang et al., 2001). However, little work has been done so far from laser scanning data on the extraction of continuous surfaces like roads. (Pattnaik et al., 2003) suggest laser scan data to gather information on road inventory. Information from a street database is acquired to set up predefined regions along roads. Subsequently, least squares regression is applied to those regions in order to compute appropriate values for longitudinal and transversal slopes. Apart from that, few approaches investigate discontinuities such as break lines and introduce constraints such as curvature or slope for the extraction of linear features.

The availability of images with resolutions close to that of aerial photographs make them suitable for a variety of applications ranging from water quality monitoring to monitoring of urban changes.

The excellent characteristics of such data, like its high resolution (1 m), real time data availability, three-dimensional measuring possibility by stereographic observations, flexibility of data acquisition, the high sensitivity of 12bit and the availability of multi-spectrum covering up to the near-infrared rays, has helped remote sensing make in roads and in technological areas where satellite remote sensing was rarely considered as an option (Kumagai J., et al. 2001) .

Derivation of data such as road network data can be useful in the car navigation systems. So far, the extraction of the road information was mostly carried out manually by the operators, resulting in rather high costs.

The possibilities of an automating extraction of road parameters have been studied by many authors. If one considers that the contrast in shade value between the road and the surroundings is quite strong, one possibility is that the image of the aerial photograph is split up into meshes. Road features are extracted through the Maximum *A Posteriory* probability technique and a Dynamic Programming technique for each mesh.

Several researches include the tracing of the starting segments of the roads in the mesh with the road feature to automatically extract the major roads.

Kumagai J. and others (Kumagai J., et al., 2001) carried out the automatic extraction of roads in regions containing some areas and road features, by applying some image processing techniques.

A road extraction semi-automated system based on dynamic programming and least squares B-spline (LSB)–snakes has been suggested by Grüen and Li, 1997. The automatic completion of road networks based on the generation and checking of link hypoteses given in (Wiedemann and Ebner, 2000) (Wallace et al., 2001) present an approach designed for a wide variety of imagery. It is based on an object-oriented database which allows the modelling and adoption of relations between roads, as well as of other objects. Road extraction by means of statistical modelling in the form of point processes and Reversible Jump Markov Chain Monte Carlo was suggested by Stoica et al., 2004.

Some of the suggested techniques are suitable for the extraction of roads in mostly agricultural, and arid areas - the latter also including mountainous regions- based on line/edge extraction, generation and checking of connection hypotheses, and global grouping detailing.

In general, a single model for automatic road extraction is insufficient, due to the large differences in the appearance of roads in different areas. It could be useful to distinguish between the following areas: agricultural, mountainous, and desert.

It could be noticed that in mountainous areas roads are strongly affected by topography. Roads often turn with large curvatures, or even with sharp bends. In the images, roads are mostly represented as bright lines and only seldom as dark lines.

In desert areas, roads mostly appear as bright or dark lines with few disturbing objects. The distinction from other linear objects is often difficult.

In agricultural areas roads appear as elongated structures. They often have no bar-shaped profiles in the images, but can be seen directly as collinear edges of field borders.

Other authors suggest to extract linear features through the Steger sub-pixel line and edge extractor. The extracted features are split up into segments with curvatures below a given threshold. The resulting lines and edges from all image channels are then fused to single data sets. Connections are built up from these data sets.

W. Goemann e al. (1997) use polynomial interpolation for the detection of lines to determine pixels belonging to road structures in the satellite images. This is a standard method for ridge detection. The image is regarded as a function I (i, j). Lines are detected as ridges and ravines in this function by locally approximating the image function by its second-order Taylor polynomial. The polynomial is used to approximate first and second-order derivatives of the image function from the Hessian matrix of the Taylor polynomial.

The gradient and curvature information in each pixel is used to classify a pixel in a number of topological classes based on its sign or magnitude. Line points are mainly characterized by a high second directional derivative, i.e. a high curvature perpendicular to the line direction.

The performance of the detector for a given dataset, and the relevant parameter set that gives optimal results can be found. Moreover, the error propagation can be used to analyze the influence that perturbations on the intensity values have on the estimation of the parameters (W. Goemann et al., 1997).

3 METHOD STUDY CASES

3.1 Survey of Road Geometries through an MMS (Mobile Mapping System)

The survey of road geometries by means of an MMS for Road Cadastre compilation has been first carried out at a prototype level by the Centre of Excellence for the Research in TeleGeomatics of the University of Trieste, for the Friuli Venezia Giulia Region, surveying some provincial roads in the four Provinces of the Region.

The methodology has been then adopted by other administrations, which assigned the surveys to firms equipped with MMSs, in order to compile the Road Cadastre in the territories of their competence.

In the present paper the road geometric parameters determined through the surveys made by the MMS of the University of Trieste, GIGI-One, have been used and compared with those extracted from the analyses done using the satellite images, and the relative project values.

As for absolute positioning, MMS uses the POS LV (Position and Orientation System for Land Vehicles) System of Applanix Corporation. This is an integrated GPS/INS (Global Positioning System/Inertial System) system able to give, instant by instant, the vehicle's position and asset. An odometer is present in addition to the GPS and the Inertial System, giving the run distance during the intervals in which GPS signals are not available. The data coming from the different sensors are integrated, evaluating their availability and consistency, by a Kalman filter in order to always give the best solution. GPS data are acquired at a rate of 1 Hz. The inertial system and the odometer send data to the System at a rate of 200 Hz.

The position data are referred to the centre of the footprint of the back left tyre of the vehicle.

In order to evaluate the repeatability of the run trajectories, some tests have been performed, driving without any bonds, on the centre of the lane. Tests have been performed both in situations of nearly simultaneous trajectories (few minutes between a passage and the next one, in order to have the same satellite geometry), in different days, and with different satellite constellations. The maximum differences between the so surveyed trajectories are in the order of 50 cm.

In the case of two-lane highways, as well as in the case of a road with two carriageways, and to obtain the road axis, the road must be run in both directions, on symmetric lanes with respect to the axis, driving the MMS on the middle of lanes and computing the axis using the mean of the two trajectories.

In the case of a single carriageway road, and if the road axis is materialized by the white line, the survey can be easily run keeping the instrumented wheel on the line. Should signing not be present, it is possible to choose to have the output of the positioning data in correspondence of a predefined point along the vehicle axis, keeping the vehicle as much as possible in the centre of the lane during the survey.

Trajectories run by different drivers according to the above surveying guidelines have been compared showing that there is not a relievable influence on the acquired data sets.

Each trajectory is formed by a seeding of points, interpolated every 1 m. The progressive, longitudinal and transversal slopes, as well as the curvature expressed as punctual attribute are given for each point, besides the planimetric coordinates in the chosen reference system and the ellipsoidal height.

In the examined cases, the radius is punctually determined for each trajectory, according to the mathematic definition, on the basis of the seeding of points obtained by the survey, thus as the radius of the circle passing through three points: the central point is the examined point, the forward and backward points are at a distance of 20 m from it. This has been done - instead of considering three following points of the seeding - in order to smooth the driving effect. The trajectory followed by the vehicle is in fact never perfectly super imposable to road geometries, but, as shown by repeated runs, it is a good index of the mean trajectory followed by the vehicles.

The so determined radius and, consequently, the curvature values are thus affected by a certain level of noise to be filtered. A null curvature is assigned to the points where the curvature is less than a threshold value (in the examined cases $k_s = 0.001\ m^{-1}$). Straight roads are identifiable like consecutive points with null curvature.

A filtering technique is set up here to identify the possible arches with constant curvature from the points seeding, thus indicating the "*curvature*" attribute in a segmented instead of a punctual way.

The following is available for each trajectory, besides other data, i.e. the Easting and Northing coordinates, the curvature (computed as inverse of the radius) and the radius, ordered by the progressive distance.

If the axis has been determined like the mean of two trajectories, the value to be considered for the radius, referred to each axis point, is the one obtained from the mean of the two starting values.

It is immediate to identify the initial and final progressive of the tracts with a null curvature, and thus the length of the straight road segments; the initial and final progressives of the elements with a different curvature from zero are so identified. These elements are analyzed one by one. The radius - function of the progressive is considered for each of them. The first derivative of the thus defined radius function, has to be null in the elements where the radius is constant. This does not happen in practise due to the trajectory uncertainty, consequent to the driving and to the described methodology used for the punctual radius determination. The first derivative is not zero, but it fluctuates around the zero value due to the radius punctual value fluctuations. A threshold for the first derivative value has thus been considered, below which it is considered as zero (first derivative < 12 in the performed test). If an interval of the radius function exists where the first derivative is zero, the radius value and the initial and final points of the constant radius curvature have to be determined in this interval.

The radius can be determined as the mean value of the punctual radii in the central half of the element with a different curvature from zero. When the R radius is known, the centre of the circle with R radius can be determined, passing through two points belonging to the seeding, whose punctual radius has been used for the calculation of the mean radius.

If the circle centre C is known and the equations of the two straight lines preceding and following the curve are determined like linear regression of the points belonging to the same straight line, then the distances between the C centre and the straight lines can be computed. These distances can be indicated like R + ΔR. Once these values are known, it is possible to determine the clothoid parameter A like a function of them, connecting the straight line and the tract with curvature at a constant radius:

$$A = \sqrt[4]{24R^3 \Delta R \left(1 + \frac{3\Delta R}{14R}\right)} \qquad \text{(Eq. 1)}$$

S_1 ed S_2 , the lenght of the curves with variable radii, and the curvilinear abscissa at the beginning and at end of the arc with constant curvature can be computed from equation $RS = A^2$.

The described methodology has been tested on curves with known parameters, both in case of curves with constant radii connected by clothoids, and in case of curves with constant radii inserted directly on the straight lines.

The computed radius values result to be the same as the project ones in both the cases.

In this first test phase the equation of the two straight lines before and after the curve has been determined not like linear regression of the points belonging to the same straight line, but, graphically, like straight lines passing through two points of the same seeding. This approximation gives a lower accuracy in the ΔR computation, and consequently in the clothoid parameter and its length. Nevertheless the so obtained values are very close to project ones.

The MMS, running along the road to be surveyed, describes a variable radius curve, even when it is not present. The ΔR values resulted in these cases to be in the order of 20 ÷ 30 cm. These values could be reduce to zero, thus excluding the presence of a curve with variable radius, implementing the algorithm to determine the straight line equations like linear regressions of the points seeding.

3.2 Road extraction from satellite images

The availability of a large number of high resolution satellite images gives a new instrument to extract roads and road features in a semi-automatic way. These images give a resolution from 60 cm to 1m that is near the one of the aerial photographs usually adopted for cartography. One of the goals of this paper is to test that sort of data capability to provide information about road conditions and characteristics.

QuickBird images with a geometric resolution of 60 cm have been used, while the spectral resolution is 4 bands (three in the visible spectrum - blue, green and red - and a band in the near infrared wavelength). The chosen colour depth is 8bit/pixel.

The first step is road recognition. Two strategies for road extraction have been tested: the first one based on the concept of spectral signature, and the second based on the Fractal Dimension of the image treated like a numerical matrix.

The “spectral signature” is the core concept of all remote sensing techniques. It is based on the idea that each object on an image has a peculiar reflectance that can be observed and analyzed looking at the Digital Number that the object has on each recorded band. In particular, it is quite easy to separate non vegetated areas from the vegetated ones using their great difference in reflectance in red band and near-infrared band (NIR) that are respectively the third and the fourth in QuickBird satellite. A combination of these two bands in an index called NDVI (Normalised Difference Vegetation Index) is largely used in remote sensing to perform a separation of green and non-green areas. NDVI is calculated as follows:

$$NDVI = NIR\text{-}RED/NIR+RED \qquad \text{(Eq. 2)}$$

where NIR and RED are the Digital Number of each pixel in the Near Infrared band, and the Red band, respectively. It has been used to have a basis on which roads can be separated from the other types of soil uses, considering that, in the area under examination, the main roads were built inside a largely wooded area. After calculating this index, it was possible to use it as a basis for a typical classification by a single band (the newly calculated NDVI “band”). A bias value able to separate vegetation from roads can be found in it. Both these techniques were useful in our case, because of the peculiar soil use of the area. Where several types of non vegetated land are found, the use of a multi spectral classification is required, otherwise it would be very difficult to separate roads from other soil coverages, typical of urban areas, such as roofs, concrete, bare soils, etc. An unsupervised classification of the NDVI map, using an Euclidean Distance algorithm and then an isolation of road representing class, into a black and white map has been carried out for this project (Figure 1).

Even the Fractal Dimension of this area has been calculated on the NDVI map, because it represents a combination of bands, it so includes much more information than a single band. The FD will be considered a measurement of the complexity of digital number distribution over an area, which means that, within the scale of the image, a regular distribution of values on the artificial soil coverage (as roads are) and a more irregular distribution on the natural areas were expected.

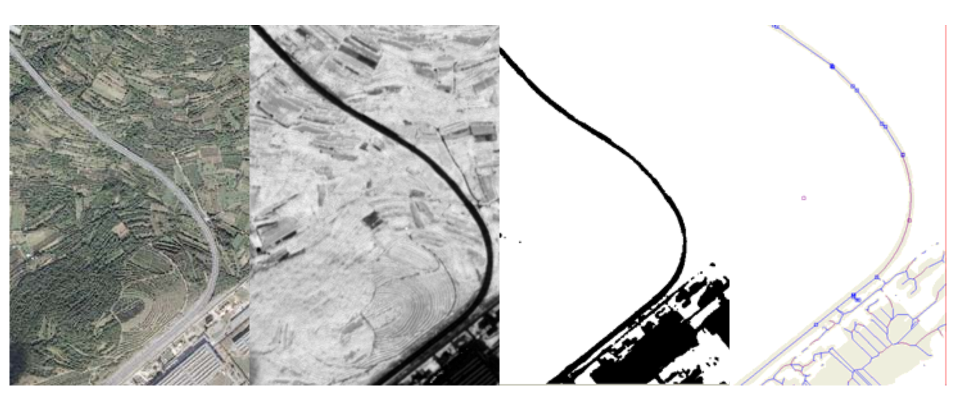

Figure 1 Road extraction through NDVI map classification

If the FD is regarded as a measure of input data roughness, the DN matrix can be imagined as a topographic surface, where higher or lower values of reflectance (or NDVI) can be found as peaks or valleys: the bigger the differences in value between near pixels, the higher the fractal dimension of this area. The “Triangular prism surface method (TPSA)” was used to calculate the fractal dimension of this area (Figure 2). It considers the “topographic surface” as written above, splits it up into cells, according to a regular grid, and measures their areas. Each cell is not considered as a plane surface, it is instead calculated as a prism where z coordinates of base vertexes are the DN of the pixel located on the corner of the cell, and prism height is the mean of corner values.

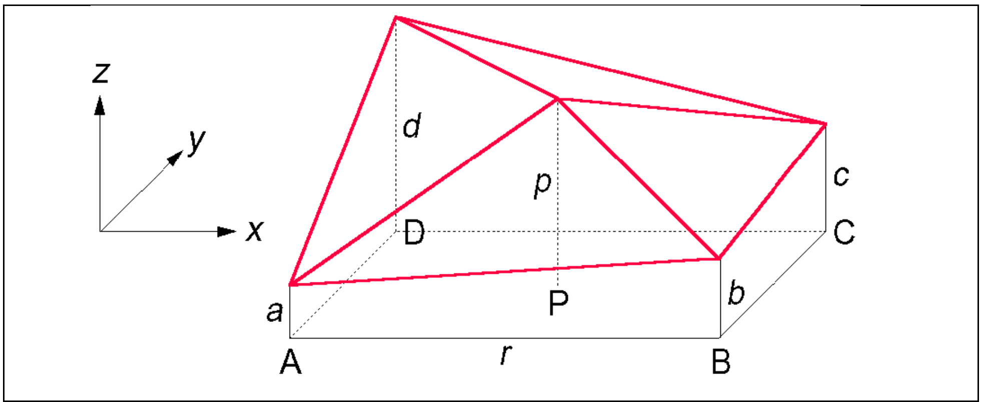

Figure 2 Triangular Prism Surface Method

The area is calculated many times, according to grids of different scales so that the bases of the prisms always have different numbers of pixels every time. The calculated area is then expressed through a logarithmic scale by means of a proper software routine (Altobelli, Pucci Poppi, 1998), and correlated with the respective dimensions of the cells on which it was calculated. The so obtained regression line coefficient is related to the Fractal Dimension as expressed below:

$$FD = 2 - b \qquad \text{(Eq. 3)}$$

where b is the linear regression coefficient.

Roads are expected to have a lower FD than the other kind of soil coverage in the used images, so that it is easy to separate them from other areas, and it so happens. What was initially not considered is that the highest difference in the Digital Numbers occurs exactly around the road margins, describing the change of soil usage, from artificial coverage to vegetation. A classification based on fractal dimension thus leads to the identification of road borders, rather than an identification of the road path from which the road axes can be obtained, as happens with the classification based only on spectral signature (Figure 4).

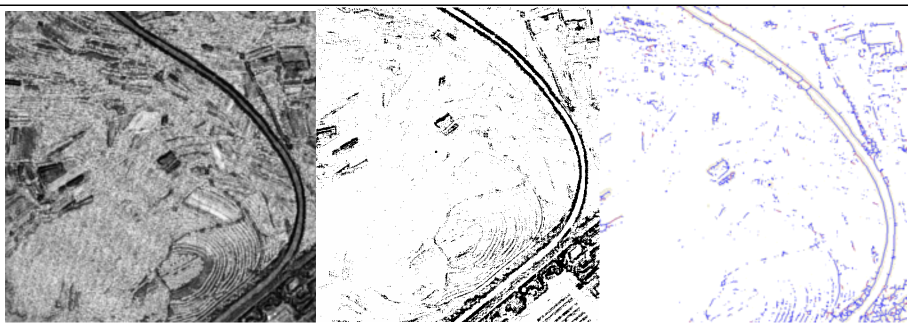

Figure 3 Road extraction through Fractal Dimension Techniques

The last step of this road identification process consists of the vectorisation of some of the extracted features in order to compare those results with the ones obtained through the other survey methods. The types of comparable data are for example radii of curves. The vectorisation of the map is probably the hardest part of those image analyses, because classified maps often present some sort of “erosion” of the road path, due to the presence of the shadows of trees on the border. The eroded pixels sometimes cause an error in the vectorisation. Vectorisation softwares are really sensible to any small changes towards the main orientation of pixels to be vectorised, a little abundance or lack in the road border therefore leads to an interruption in the direction of the extracted lines, or to a misinterpretation of it, such as in tracts where junctions with side roads are present). The map that should be provided to the vectorising software therefore needs a quite important “cleaning” job, to avoid this problem as much as possible, being careful not to change the real road aspect.

Another aspect of roads that could be observed and obtained from satellite images is relative to road horizontal signings. These lines are clearly visible in high resolution images, even if the nominal pixel dimension could not theoretically permit it. This is possible because of the high difference in reflectance between white lines and black asphalt. The digital number of a pixel containing a line can be considered as a weighted mean of the values of the asphalt alone and the line alone. The radiometric difference is so high that the influence of a thin white area in the pixel causes a remarkable increase of the DN (note that in our case, with 8bit images, a low reflectance is converted into a DN value near 0 and a high reflectance has a DN near 255).

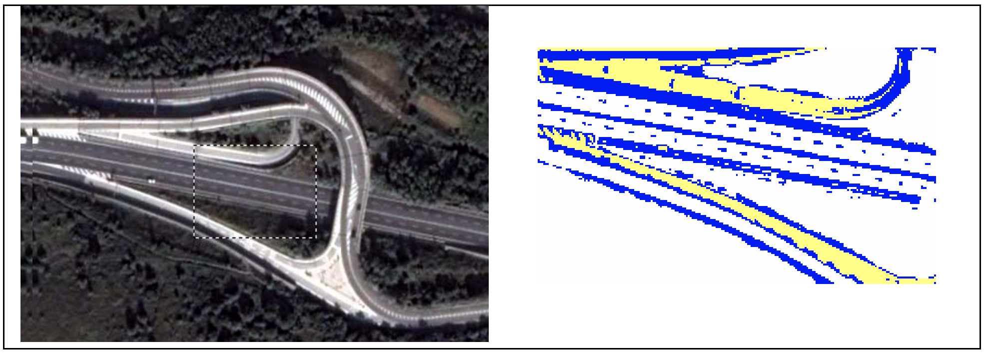

Figure 4 Particular of road signing extraction

The easiest way to extract this type of road feature for geometric purposes is through its manual digitalisation. The image is inserted in the used coordinate projection system by means of a proper GIS software, and the road lines are digitalized in a vector file. Otherwise, they can be extracted through a spectral based classification and another raster file can be obtained, which is a qualitative representation of road signing characteristics, and could be particularly useful to check the signing aspect, e.g. brightness, straight positioning etc. (Figure 4).

This type of file cannot be used to precisely control the geometric characteristics of road signing, because the size of the pixel in the input map - as explained above - is wider than the extension of the signs themselves, so line positioning inside the pixels is not certain.

4 CONCLUSIONS

The goal of this paper was to test and compare different road survey methods in order to select the more suitable one under certain conditions.

After the tests shortly described above, it can be said that Mobile Mapping System (MMS) surveys can lead to a complete description of curve geometries with a good accuracy, even when curvature radii are variable (clothoid), as frequently happens on motorways. Similar results were obtained in radius determination through Remote Sensed Images where the radius is constant, and the expected accuracy was reached considering the image geometric resolution (Table 1). The analysis of road geometries through Remote Sensing Images could be useful when on site surveys are not possible. Up to now, the exact ending point of the straight lines could not be found by means of remote sensing data, and clothoids parameters could not be calculated. The adopted software and techniques have to be implemented in order to calculate these types of parameters. On the other hand, satellite images can provide further information such as road signing distribution or condition.

Table 1 Comparative values between design alignment, MMS and Remote Sensing Surveys

	Curve radius	First Clothoid parameter	First Clothoid length	Second Clothoid parameter	Second Clothoid length
Project Information	250 m	160	102,4 m	160	102,4 m
MMS survey	250 m	154	95 m	161	104 m
Remote Sensing survey	252 m	not detected	not detected	not detected	not detected

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