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Integrating photogrammetry into raster and vector information systems for setting databases for engineering projects

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Abstract

The correlation methods presented here use 3D image processing techniques to set up virtual stereo models and integrate them in spatial digital information systems. The coordinates of any selected point are made available more accurately than by methods of photogrammetric restitution, and the user requires no training in stereoscopy. The metrical and documentary information generated here, in comparison with what is current, is better suited for the development of geo-spatial engineering projects. It is also of a quality to improve the execution of projects using automatic machinery. The developed techniques enable the project designer to build his data base interactively as part of the geometric design process.

Additional key words: applications in agro-engineering, automatic extraction of coordinates, digital photogrammetry

Resumen

Integración de procesos de fotogrametría en sistemas de tratamiento de la información raster y vectorial

Los procesos de correlación que se presentan tienen como objetivo configurar estéreo-modelos virtuales y su integración en sistemas de información mediante técnicas de tratamiento de imágenes en modo 3D. El resultado de estos desarrollos permite calcular las coordenadas de los puntos, directamente seleccionados por el usuario, con un nivel de precisión superior al que se obtiene en los métodos de restitución fotogramétrica y sin necesidad de un adiestramiento previo en estereoscopía. Estos procedimientos generan una información métrica y documental más adecuada para la elaboración del proyecto y contribuyen a mejorar la ejecución de obras con maquinas automáticas. Poder configurar la base de datos de forma interactiva con el diseño geométrico del proyecto es la conclusión más relevante de estos desarrollos.

Palabras clave adicionales: aplicaciones en agroingeniería, extracción automática de coordenadas, fotogrametría digital.

Introduction

Research into the integration of image analysis with GIS has contributed significantly to the capabilities of new cartographic applications (ISO/TC 211 N 1034, 2001). Of particular importance in this respect has been the design of automatic processes in the interactive manipulation of raster and vector information (Kraus, 1997), and also in the use of the true-ortho raster image which improves the presentation of metrical and documentary information (Braun, 2003).

It is of the greatest interest to make appropriate use of these developments in the numerous applications of land engineering (Lopez-Cuervo-Medina, 2004). The

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Abbreviations used: DEM (digital elevation model), GPS (global positioning system).

computer software systems considered most suitable to adopt the correlation techniques presented here are those known as 'Expert Systems' and 'Engineering Systems'. The former integrate existing raster and vector information and allow for the incorporation of data captured in real-time (Neumann *et al.,* 1997). Automatic positioning is established using GPS receivers, and the positional coordinates of the machine, together with the elements of agricultural interest, are recorded jointly and synchronously from various sensors (Monreal and López-Cuervo-Medina, 2005). 'Precision Agriculture' is the term that comes to mind when referring to setting up such a database of land plots and in particular when using this in agricultural practice.

The 'Engineering Systems' are used to configure the operational database in such a way as to provide a faithful definition of the geometry of the project and to ensure a high quality of execution with automated machinery (Ballester *et al.,* 2000; Castro and López-Cuervo-Medina, 2003). This requirement implies that the user should directly supervise both the raster information and the data acquired by topographic means. It also means that s/he should be able to obtain selective measurements in the course of the design work. The data base of the project is accessed by the computer installed on board the earth-moving machinery, and the relative coordinates are identified of the GPS antenna attached to the system. The functionality is to establish the discrepancies between the geometry of the project and physical reality, and to transmit orders to the hydraulic actuators for their correction. The three sensors which identify the position of the earth-cutting edge, in pitch yaw and roll, are monitored continuously, closing the control circuit to follow the geometric model established in the database. The most suitable method for establishing the exact position of the machinery on the terrain is based on global positioning systems. Equipment based on receptors both of the GPS and GLONASS systems can make use of up to 12 satellites more than in the NAVSTAR constellation, and can achieve accuracies of (1–3) cm in X,Y,Z in real time (Pappalardo, 2004).

The developments presented here are oriented to the calculation of the spatial coordinates of points directly identified by the user in a raster image. This is done within the system using algorithms for correlating images for virtual stereo-modelling. The ability to do this improves the accuracy and agility of the geometric design process in a land engineering project. The correlation algorithms use procedures similar to the photogrammetric method based on delimited points, and improve on the classical restitution methodology for measuring coordinates. This is because they do not depend on the methods of interpolation imposed by the principle of cartographic generalization (Chibunichev and López-Cuervo-Medina, 2005).

Material and methods

General methodology

Progress in digital photogrammetry, and in the techniques for 3D imagery, has established a basis for the development of the methodology of correlation. The software is designed to achieve a significant improvement in the measurements used in the construction of the databases for the project, as also to optimize the use made of them on integration into the information systems. In this respect an analysis is made of the methodology best fitted to the achievement of the desired results.

The principles underlying the determination of the coordinates X,Y,Z in the correlation process correspond to the concept of identified photopoints in photogrammety. Their accuracy depends on the quality of the algorithms employed for correlation, and on the rigour applied in generating the stereo-models in the digital photogrammetry equipment.

In the models produced by photogrammetry, the mean square errors (σ) in the determination of the coordinates of points (x, y, z) in the terrain from a pair of photographs are expressed mathematically by the formulae:

$$\sigma_Z = \frac{Z}{f}\frac{Z}{B}m_p \approx \frac{Z}{b}m_p$$

$$\left.\begin{array}{l} \sigma_X = \sqrt{\left(\frac{x}{f}\right)^2 \sigma_z + \left(\frac{Z}{f}m_x\right)^2} \approx \frac{Z}{f}m_x \\ \sigma_Y = \sqrt{\left(\frac{y}{f}\sigma_z\right)^2 + \left(\frac{Z}{f}m_y\right)^2} \approx \frac{Z}{f}m_y \end{array}\right\}$$

where *B*=aerial base, *b*=aerial base in the image, *f*=focal length, (x,y,z) coordinates of the point in the image reference system, and m_x *and* m_y are the errors of measurement of the coordinates X,Y in the image, and m_p is that of the determination of longitudinal parallax *p.*

These expressions are of a hypothetical nature, since they depend on the rigour of formulation of the photogrammetric models (Krauss, 1997; Chibunichev and

López-Cuervo-Medina, 2005). The correlation procedures that have been developed permit the control of these models insofar as they prescribe that the photogrammetric results be accompanied by the callibration parameters of the camera, the internal and external orientations, and the coordinates of the control points and of the points of aero-triangulation. These data, which are necessary for the automatic generation of the virtual stereo-models in the computing system, enable the a-priori control of the quality of the photogrammetric models. This makes it possible to estimate, correctly, the accuracy of the points measured by correlation.

The accuracy specified for photogrammetric results is based on the preceding formulation and is related to the graphical representation of the Z coordinate by means of contour lines, and to the criterion that the admissible error should not exceed one third of the difference in height between adjacent lines. This maximum error should be less than 0.3 per thousand of the flying height, while for identified photopoints the acceptable error is 0.2 per thousand of this height. In the latter case, where points are directly measured on the photogrammetric model, the given mathematical formulae hold rigorously, and the accuracy of the derived coordinates x,y,z is improved.

In the construction of ortho-photographs, when the aim is for an accuracy of the Z coordinate similar to that obtained in processes of correlation, it is necessary to set up a digital elevation model (DEM) of great complexity. The correlation procedures improve the metric and documentary information where required by the survey, and when the accuracy sought is beyond the reach of the methods proposed, then these help to delimit the zones whose longitudinal and transverse profiles should be determined by topographic means.

When taking measurements of points from aerial photographs, there is special difficulty in areas with extensive vegetation which hinders the correct appreciation of the terrain. To mitigate the deficiencies produced in photogrammetric surveys for road construction projects in such situations, the Department of Public Works in Mexico (Secretaría de Obras Públicas de Mexico, 1971) published a set of standards, still in force, in the *Manual de Proyecto Geométrico de Carreteras*.

Table 1. Conditions of wooded ground cover for which photogrammetric survey methods are acceptable for road-building projects

Mean height of vegetation (m)	Mean diameter of foliage (m)	Mean tree separation C-C (m)	Mean number of trees ha^{-1}
5	5	12	60
10	6	15	50
15	7	18	40
20	8	23	20
30	8	29	12

According to these standards, photogrammetric methods are considered viable on densely overgrown terrain when the height of the mass of vegetation does not exceed 0.10 m, whereas for heights above 0.10 m and up to 1.00 m, it becomes necessary to apply correction using topographical methods on the ground. In wooded areas with growth above 1 m in height, photogrammetric measurement may be acceptable depending on the density of growth, as detailed in Table 1.

Recent developments with airborne laser scanners have brought some improvements in the measurement of terrains of the kind mentioned (Hofmann *et al.,* 2002). Nevertheless, the accuracy required for setting up the databases may need the application of topographic methods for the measurement of certain elements. New technologies for the capture of digital images, obtained simultaneously with the measurements made with a total station, incorporate additional documentary information of great importance for the faithful rendition of the terrain; information on the operational environment of the station and the selected points. These measurements are made in zones selected by the surveyor to improve certain points determined by correlation. When using such equipment involving a total station together with image capture, the coordinates of the station location can be adjusted to the reference system of the survey by means of prior measurements with GPS receivers (Han and Rizos, 1997; Hofmann-Wellenhof, 1997). This method of working does not require the setting up of the classical polygonal path, it facilitates data capture in rough terrain, and documents the position of each point for its correct interpretation. Modern equipment of the type of Topcon-Imaging are particularly well suited to this type of application.

Tests were carried out to evaluate the possibility of integrating these processes in an information processing system. They were done on the engineering system Stereo SLC. This software, developed by the authors (De-Blas-Gutierrez-de-la-Vega, 2004; López-Cuervo-Medina, 2004), has a design similar to applications under MS Windows (Operating system Windows XP, RAM minimum 1024 KB), and provides a user interface which is generally familiar.

The salient characteristics of the system are:

– Coupling of automatic processes with a development of techniques of image processing.
– The stereo-models are generated with epipolar images constructed using internal and external orientation parameters, and applying the collinearity equations for a constant value of Z.
– Stereoscopic vision, which has been employed traditionally for the measurement of coordinates in three dimensions, has been substituted by the construction of virtual models for which measurements are established using processes of correlation without the need for practice in stereoscopy.
– Creation of a new format for images (.alx) allowing agile visualization and manipulation without resorting to compression which reduces resolution.
– The capability of converting from the new image format .alx to the standard .bmp, and similarly with a corresponding new vector format .adb to the standard .dxf.
– The system takes the form of a simple tool, simple in its use, which ensures that it can be learned rapidly.
– Simplifies the manipulation of the information of the survey through the use of specially designed navigators.

Programme description

Design of the process of correlation

The correlation software creates and operates on virtual models without presenting a stereoscopic image. These models are presented visually showing only one of the images from the stereoscopic pair, the other remaining hidden. Thus the selection of a point for measurement is effected exclusively from the monoscopic image shown. The identification of the homologous point in the other image, permitting measurement of the parallax p_x, is carried out using the correlation algorithms.

The stereo-models are calculated from the epipolar images using the internal and external orientation parameters, and applying the collinearity equations for a constant value of Z. The absolute coordinates of the photopoints to be measured are obtained applying the one-dimensional correlation process in the normalized images (López-Cuervo-Medina, 2003).

In the process of correlation for identifying homologous points, the region searched is limited to the neighbourhood of the epipolar lines, the space over which the formulae for one-dimensional collinearity are applicable. The proposed criterion is based on the cross-correlation of 'brightness' or pixel values. The cross-correlation ρ is calculated from the covariance (σ_{LR}) and variances ($\sigma_{L,}$ $\sigma_{R,}$) of 'brightness' centred on the candidates for homologous points in the left (*L*) and right (*R*) images respectively. The correlation is calculated for each radiometric component (colours R,G,B), and their arithmetic mean ρ is taken as a measure of the homology of the candidate points:

$$\rho = (\rho_R+\rho_G+\rho_B) / 3;$$

The software makes available three procedures for carrying out the correlation process. One is automatic, whereby, after selecting the point of interest in the visible image, the calculation of the coordinates in the virtual model is executed without further intervention. Another is semi-automatic; here the region to be searched is reduced, limiting the number of pixels intervening in the calculation. The intention in this case is to facilitate identification of the point and to guarantee a sharp peak of correlation. The third is manually driven, as is usual in the measurements taken in digital photogrammetry using stereoscopic models.

In the automatic procedure, the point to be measured is selected in the right hand image, the only photogram of the model which is visualized on the screen, and the process proceeds automatically on activating the correlation option. For checking, a small window is opened to show the same region in the left hand image, and the point giving the best correlation is highlighted. The quality of the measurement is a function of the coefficient of homology. In the semi-automatic method, the window with the left image shows the vicinity of the point to be identified, and the operator is required to move this point to within the correlation zone in order to trigger the correlation process. This procedure is recommended for points which do not have a sharp geometrical definition, as may be the case when located within uniform textures, as on a road surface, or where the relief of the terrain leads to great differences in what is seen of the point in the two images. The semi-automatic option is the most appropriate for operators who are not experts in photogrammetry because of the ease with which the homologous points can be identified to validate the process. In the manual procedure it is necessary to correctly identify the homologous point in left-hand image. This option is of interest for measurements in urban areas because of the differences that arise between the array of points around the selected right hand point, and the arrays presented over the search area in the left hand image. In such a situation identifying the homologous point by maximizing correlation, as is done in the automatic and semi-automatic procedures, becomes inviable.

In all three of the procedures described, the results of the process can be checked by observing the relief of the stereoscopic model in the auxiliary window. The absence of parallax at the centre of the model indicates satisfactory correlation. The result of the calculation of the coefficient of homology $\rho = (\rho_R+\rho_G+\rho_B) / 3$, account having been taken of the radiometric components (R,G, B), is displayed beside the coordinates of the point, and takes a value in the range $(1 \geq \rho \geq 0)$.

Figure 1 shows the procedure for semi-automatic measurement. On the right hand side of the screen is shown the right hand image of the virtual model identifying the point selected to be measured. On the left hand side an auxiliary window is displayed showing that part of the left hand image which completes the stereomodel. It is within this image that the operator is required to indicate the approximate neighbourhood of the point to be measured. Here it is not necessary to indicate its exact location, but only the pixel matrix to be searched. The auxiliary window which appears on the lower part of the screen presents a stereoscopic image of the zone studied, and although it does not intervene as such in the automatic process of correlation, it does contribute a documentary value for the appreciation of the operator, and is of help in the overall control of the procedure.

Correlation processes have been one of the most important innovations in digital photogrammetry, and they are often introduced in many systems in order to achieve automatic operation in image processing (Mikhail, 2000). The software presented here uses algorithms of the same kind, but its originality lies in the incorporation of the virtual model in the information system and in the manner of directing the process.

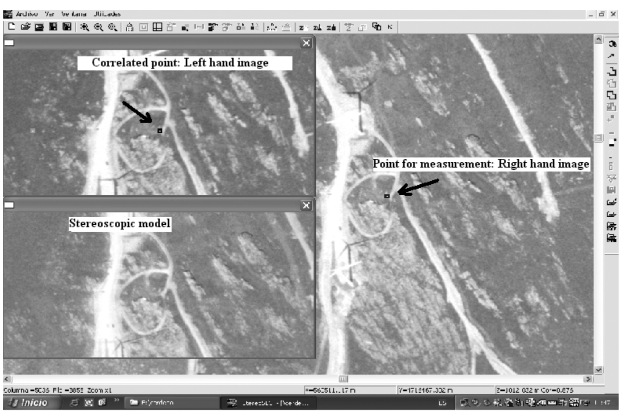

Figure 1. Configuration of the screen in the semi-automatic procedure for correlation.

Raster information

Contributing to the design of the correlation programme a new format (.alx) has been adopted for the storage of the images in raster form. It is based on the partition of the image into blocks of 128×128 pixels and the construction of a pyramidal hierarchy of images adjusted by Laplacian filters. This structure allows for the processing of images with great efficiency and without loss of resolution, and moreover it guarantees good results from the processes of correlation. The file has a header with information of the orientation parameters, the axes of reference, image and pixel size, number of images in the hierarchy and the counts of the rows and columns in the image. This format allows for enlargement of the images without appreciable loss of sharpness in the localization and definition of points on the terrain. Photograms having a resolution of 5-7 µm can be enlarged by a factor of 8 to 10 maintaining an acceptable resolution. Such enlargements do not affect the accuracy of the process, and they are of use only for enabling the accurate visual identification of points of the image. This is the criterion adopted for establishing the resolution for the photograms of the virtual models.

Integration of the information

The data captured by correlation are recorded in a survey project file together with the documentary codes and symbols, and they can be integrated with the available raster information. The ortho-photo shown in Figure 2 includes a digital elevation model in the same coordinate reference system, represented by contour lines and points measured by correlation. The files with the measurement of selected points and with the DEM are recorded independently and retain the accuracy of the database generated by correlation. This manner of presenting the information, as is also the case with any organization of raster or vector data in mosaic fashion, makes it easy, with the help of navigators, to analyse the documentation of the totality of a survey project.

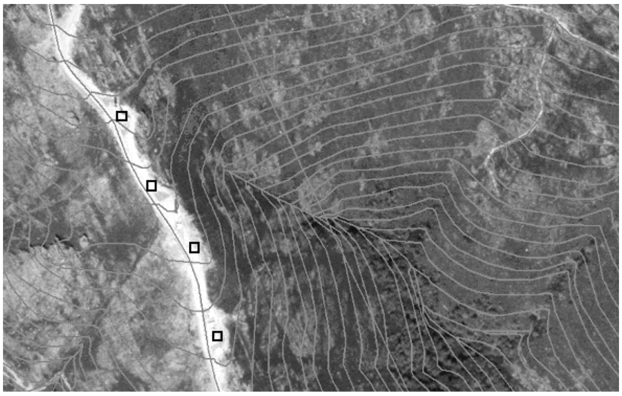

Figure 2. Ortho-photo with superposed contours and marks of selected points.

Results

The experiments reported here were carried out to evaluate the accuracy of measurements produced by the correlation process under the control of the operator. The accuracy was estimated comparing the results for selected points obtained in two ways: on the one hand with measurements made in the field using a total station Topcon GPT-7001 (angle accuracy: ± 1^{cc}, laser accuracy ± 5 mm), and on the other with measurements using the correlation process on the correctly identified points on images obtained synchronously.

In the course of work in the field, the control points are chosen to stand out with the greatest clarity possible (Fig. 2). Nevertheless, their position as identified in the images is not guaranteed to coincide exactly with their position in the terrain. The corresponding and eventual displacements have a greater impact on the planimetry than on the determination of the Z coordinate given the characteristics of the terrain. In the set of 50 points controlled, the correlation coefficient reaches values in excess of 0.9, a value sufficient to permit an estimation of the quality of the results produced by the process tested.

The images employed in the tests have the following characteristics: scale of the photograms 1:35000; proportion base/height ≈ 1/3; focal length 152 mm; size of the pixel 7 μm. These parameters assign a value to the mean-square error of the Z coordinate as follows:

$$\sigma_Z = \frac{Z}{f}\frac{Z}{B}m_p \approx \frac{Z}{b}m_p = 0.7 \text{ m}$$

The discrepancies found between the values obtained by correlation and those obtained by field surveying (Topcon GPT-7001) appear in Table 2 and produced a mean error in the Z coordinate of 0.80 m. This value, which is close to the mean square error theoretically expected (σ_z = 0.7 m), is better than the accuracy obtainable by pure photogrammetry in the measurement of photopoints, which, when applied to the test photograms, give the following estimate: $\sigma_z = 0.2 \times H / 1000 \approx 1.05$ m (H = 5300 m).

As shown in Figure 3, the measurements in the field were carried out directly without a prism, and with photographic recording, using a total station GPT-7001 (Topcon Imaging). These images, which have no more than documentary value, help in the identification of the selected point, and are produced synchronously with the measurement of coordinates, which justifies their low resolution. The documentation for each observation point consists of the position and code. It is recorded for all measured points together with an over-all view with

Table 2. Results for the control points

	Correlation				GPT-7001			Discrepances		
	X	Y	Z	ρ	X	Y	Z	ΔX	ΔY	ΔZ
1	561033.135	4712619.426	886.269	0.979	561033.575	4712619.916	887.006	0.440	0.490	0.737
2	561045.602	4712591.957	880.139	0.950	561046.172	4712592.465	879.449	0.570	0.508	0.690
3	561047.689	4712555.443	871.048	0.955	561047.421	4712556.047	871.698	0.650	0.604	0.268
4	561039.215	4712522.617	862.898	0.802	561038.512	4712521.375	862.150	0.703	1.242	0.748
5	561046.338	4712503.490	856.824	0.963	561046.987	4712502.920	856.115	0.649	0.570	0.709
6	561043.225	4712471.270	848.581	0.907	561043.755	4712471.651	848.001	0.530	0.381	0.580
7	561042.151	4712444.552	843.450	0.940	561042.573	4712444.149	842.725	0.422	0.403	0.725
8	561044.653	4712420.171	838.311	0.944	561044.142	4712420.685	839.262	0.511	0.514	0.951
9	561050.672	4712372.570	832.075	0.959	561050.171	4712373.372	831.263	0.501	0.702	0.812
10	561055.043	4712339.630	828.006	0.967	561055.661	4712340.210	828.748	0.618	0.580	0.742
…	…	…	…	…	…	…	…	…	…	…
50	560929.297	4711809.849	744.339	0.944	560929.899	4711810.441	743.536	0.602	0.592	0.803

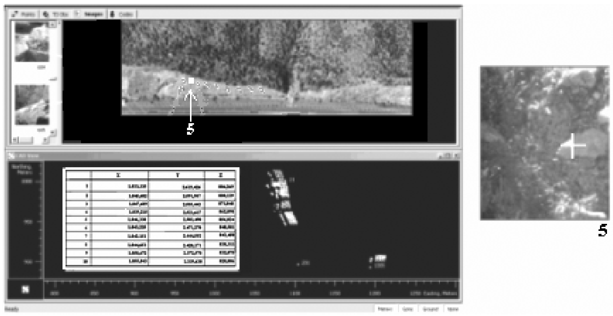

Figure 3. Detail of the documentation obtained with total stations and recording of photographs.

their representation in a plan. A GPS receiver was used to identify the coordinates of the root vertex of observation, together with those of another point of reference, in order to integrate the coordinates of the total station into a unique system of reference.

Discussion

The results obtained under the control of the correlation process can be judged using the errors in the Z coordinate as a measure of quality. These show that there is an improvement in the accuracy of measurement of position of the selected points with respect to the classical procedures of photogrammetric restitution. The procedure presented here, given its digital nature, is independent of the criteria of generalization and allows the database to be configured with greater accuracy and in compliance with the criteria of the user. This is of special advantage in relation to the methods based solely on the cartographic representation of the data. The cartography as generated for the preparation of the project is not in question. What is important is the availability of complementary measurements, executed interactively in the course of design work, which improve the quality of the database and are of help in the execution of the project with automated machinery.

DEMs, when generated using conventional photogrammetric procedures, require the definition of break-lines in order to achieve acceptable fidelity in 2.5D mode. There the value of the Z coordinate is calculated by interpolation, and in consequence the accuracy is inferior to what is obtained using correlation procedures for selected points within in defined patches.

The file format designed to carry the image information allows for presenting big enlargements, which are helpful for interpretation, and which enable an acceptably sharp selection of points on the terrain. It allows for speedy access and manipulation of the data, and does not limit the accuracy of the correlation process; characteristics which facilitate the exploitation of the raster information.

The requirement for greater accuracy in the data, and the need for reliable supervision in their capture and in their revision, justifies the choice of the techniques presented here for engineering systems. Their use has developed greatly in the application of automatic remodelling in civil engineering work. In the field of agro-engineering they are enabling the automatic control of machinery in the profiling of terrain for golf-courses, platforms, irrigation, linear earthworks, the control of canal digging by excavators, profiling embankments, laying beds for excavations and making rural roads with motorised levelling equipment, among others.

For making selective measurements on the terrain, it is considered preferable to use total stations with synchronised recording of images rather than to use GPS receivers. The justification is not so much in the accuracy obtained, which can be considered as practically similar, but in the documentary value of the photograph of the point measured, and especially in the viability of measurement in uneven terrain. The use of such equipment facilitates the measurement, without using a prism, of abrupt elevations, embankments and inaccessible features. The preliminary marking of points for measurement can also be dispensed with.

The developments presented here enable the integration of correlation techniques in the digital modelling of terrain. They improve the accuracy of measurement of the coordinates of selected points, and allow for work on the construction of the date base and on the engineering project design to proceed jointly and interactively. Of the optional modes of working with the correlation algorithm which have been developed, the semi-automatic mode is considered the most generally useful as it allows the user to supervise the process directly.

These developments promote the combined and interactive use of raster and vector information. They enhance the metrical and documentary contribution of the raster image, and enable the setting up of more reliable geometries for the execution of land engineering work in 3D.

The fact that the database can be built as needed, under the direct supervision of the user, and in the course of project design, makes for high quality in the project, and optimizes accuracy in the task of marking out the work site.

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