A NEW CONCEPT: THE SOLID IMAGE

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ABSTRACT:

A photo image can be considered a central perspective of the acquired object with good approximation. If the internal and external orientation of the camera are known, in case of a digital image it is possible to establish the direction in the space of each object point represented by a pixel in the image. If only one image is available, it is impossible to determine the spatial X,Y,Z position of such object points, because the simple direction is insufficient: all the points along that direction would give the same image point.
By means of a dense digital elevation model (DDEM) of the acquired object, every pixel (and therefore every direction in the space) can be associated to the value of distance between the centre of perspective and the object point represented by the pixel itself. In this way each pixel can be referred to the 3D position of the corresponding object point in an absolute reference system.
The DDEM can be derived from an existing map or by the use of surveying instruments and procedures. Recently, a series of new instruments, based on the laser technology, have been introduced on the market, giving the possibility to obtain a DDEM in a quick and cheap way.
The integration of the DDEM geometric data with the image radiometric data suggests a new concept: the "solid image".
Definition, first results and applications of the solid image was presented in the ISPRS Comm..V, WG V/4 meeting in Ancona, July 2003. In addition, this paper describes the very recent further developments and the future activities on this field.

. INTRODUCTION

An image can be considered a central perspective of the photographed object. If internal and external orientation are known it is possible, for every pixel of the image, to determine the direction of its projecting ray in the space. If only one image is available, that direction is insufficient to reconstruct the 3D position of the object point (i.e. its X, Y and Z coordinates). In fact, all the points positioned along that direction in the space would give the same pixel on the image.
The recent introduction in the market of laser scanner sensors in the field of survey instruments allows dense digital elevation models (DDEM) of the object to be obtained.
The integration of the laser scanner data with the digital image data can give the possibility of associating a value of distance to every direction in the space, defined by each pixel. This distance is calculated as the distance from the perspective central point (the "taking point") and the object point represented by the pixel. If two angles defining a direction in the space and the above mentioned distance are known (these 3 figures are called "spherical" or "3D polar" co-ordinates), it is easy to reconstruct the spatial position (i.e. the X,Y,Z co-ordinates) of every point represented in the image.
The traditional RGB radiometric data of the image together with a 3D model acquired by the laser scanner lead to a new concept: the "solid image".
Advantage and potentials of this innovative product are due to the possibility of:

- getting the spatial position of points in the object reference system;
- direct and easy carrying out of correct 3D measurements on the image;
- obtaining a great deal of information in a simple and rapid way, using the high quality original images and any traditional photo viewer software available on the market.

Based on the solid image, it is possible to foresee several new applications: a second image of a stereoscopic pair can be created, a RGB coloured virtual 3D model can be carried out, etc.

2. THE SOLID IMAGE

2.1 Definition

A "true colour" digital image is made up of 3 matrixes, named R, G and B, each one containing one of the 3 fundamental colours (Red, Green or Blue).

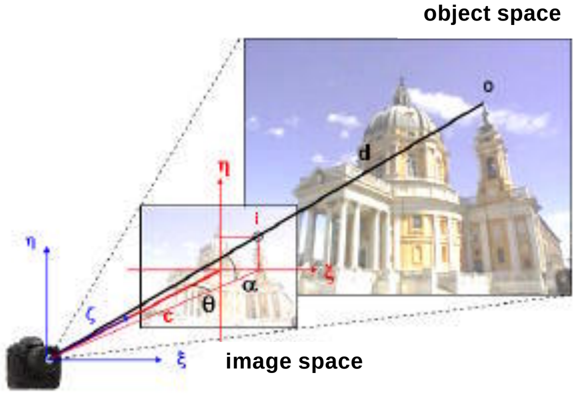


Figure 1. Relationship between image space and object space

The solid image is defined as a classical digital image that, in addition, records the distance values of the represented points from the taking centre. Assuming that the digital image is a central perspective of the photographed object and the internal orientation parameters of the image are known, if the distance between the perspective centre and the photographed object point is measured, the spatial position of each pixel can be computed in the ξ η ζ image reference system (see Fig. 1 and (1) and (2) equations):

$$q = \arctan \frac{x_i}{c}$$
$$a = \arctan \frac{h_i}{\sqrt{c^2 \cdot x_i^{\,2}}} \qquad (1)$$

$$x_0 = d \cdot \cos a \cdot sen q$$
$$h_0 = d \cdot sen a \qquad (2)$$
$$z_0 = d \cdot \cos a \cdot \cos q$$

where ξ_i, η_i are the image coordinates of the current pixel of the image, θ and α are the two angles that define the direction in the space, d is the distance value between the centre of the perspective and the object point, ξ_0, η_0 and ζ_0 are the 3D coordinates of the object point.

The distance values are stored in an additional matrix that has the same size as the RGB ones (in terms of rows and columns). Therefore a "solid image" consists of a 4 level matrix: **RGB** and distances **d** (see Fig. 2).
Distances of the object points are obtained from a dense 3D model (DDEM), easily acquired by a laser scanner. To calculate these distances, the laser scanning and the photo should be taken from two points close each other, in order to reduce the number of pixels that are not visible from the scanner (hidden areas) and therefore not determined in their 3D position.

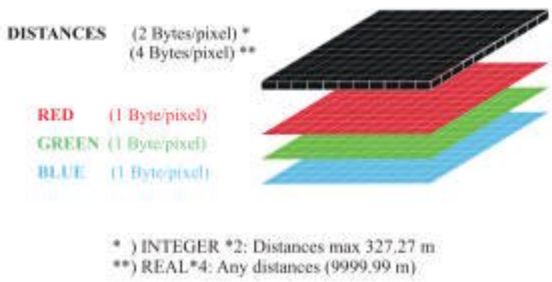


Figure 2. Structure of the solid image

If the external orientation parameters (X_0,Y_0,Z_0, ω, ϕ, κ) are also known, it is easy to transform the 3D image co-ordinates into the absolute system XYZ, by a simple roto-translation.

2.2 Image calibration

In order to fill the matrix "d" with a correct value of the distance to every object point, it is necessary to calibrate the image. The calibration process consists of the estimation of the internal orientation parameters of the camera. In architectural surveys, often cameras are not metric. In this case, the lens distortion parameters have to be determined.
This can be achieved by measuring the image coordinates for a sufficient number of points, the object coordinates of which are known (control points). The procedure can be completely automatic if a laser scanner is used for this purpose.

Some reflecting targets are placed on the object. The laser scanner is able to measure, in addition to the 3D point positions, the reflectivity of the object. Special reflecting targets (*markers*) have the property to almost totally reflect the laser pulse, while natural points do not do the same. If the marker size and their mean reflectivity are known, it is easy to determine the marker's position in the laser DDEM and in the image, in a completely automatic way. Once the marker's position is defined, one can estimate the calibration parameters of the camera and its external orientation by using a classic bundle solution.

2.3 Projection of the cloud of points

If the internal and external image orientation parameters are known, it is possible to project the DDEM ("cloud of points") onto the digital image. The mathematical model used for this operation is the central perspective model. The radial distortion components Δξ and Δη the are added to the collinearity equations:

$$x = x_0 + \Delta x - c\frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$
$$h = h_0 + \Delta h - c\frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)} \qquad (3)$$

The distortion components are modelled by:

$$\Delta x = (x - x_0) \cdot (k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6)$$
$$\Delta h = (h - h_0) \cdot (k_1 \cdot r^2 + k_2 \cdot r^4 + k_3 \cdot r^6) \qquad (4)$$

where ρ is the distance from the centre of the image (radius) and k_1, k_2 and k_3 are the radial distortion coefficients. Other types of distortion have not been considered.

2.4 Interpolation of the distance matrix

The density of the pixels in the digital image is usually greater than the density of the cloud of points obtained by the laser scanner device. For this reason, when the laser points are projected onto the digital image, the distance matrix is not completely filled in every element: the values of distance are associated only to some pixels.
In order to fill the distance matrix it is necessary to integrate the missing values with an interpolation procedure.

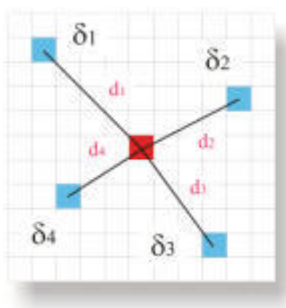


Figure 3. Interpolation of the distance matrix

The "average weighed method" has been used. The four nearest pixels, which the value of distance is known, are considered (see Fig. 3).

The computation of the interpolated value of distance is carried our by the formula:

$$d_{i,j} = \frac{d_1 \cdot d_1 + d_2 \cdot d_2 + d_3 \cdot d_3 + d_4 \cdot d_4}{d_1 + d_2 + d_3 + d_4} \qquad (5)$$

where i,j are the indexes of the current pixel, δ_i are the distance values to the object points and d_i are the distances, on the image, between the pixel i,j and the pixels used for the interpolation.

Special procedures are foreseen to avoid "edge effects" in case of relevant discontinuities.

3. THE "SOLID IMAGE MAKER"

3.1 The developed software

In order to create and visualise the solid image and to manage its first applications, a specific software, named Solid Image Maker, has been implemented (in Visual Basic 6.0).

This software allows:

- to merge the DDEM (acquired by a laser scanner) with the corresponding digital image and its calibration parameters;
- to fill the distance matrix by projection and interpolation;
- to explore the solid image and to display in real time the XYZ co-ordinates of each pixel pointed by the cursor
- to create the 3D model of the object in some drawing formats (VRML – Virtual Reality Modelling Language, DXF, ...);
- to create an artificial stereoscopic pair of the object.

4. A FIELD TEST: THE TETRARCHI STATUE

4.1 A field test: the Tetrarchi statue

The complete procedure for the construction of a solid image has been tested, using as a test area the Tetrarchi statue, a famous sculpture placed in the San Marco's Square in Venice (see Fig. 3 a).

The Tetrarchi group, also known as the "Four Moros", is a marble sculpture on the outside of San Marco's basilica in Venice, next to the "Porta della Carta" of "Palazzo Ducale". The statue represents, according to tradition, the four governors of the Roman empire (IV ac century – under Diocletian emperor).

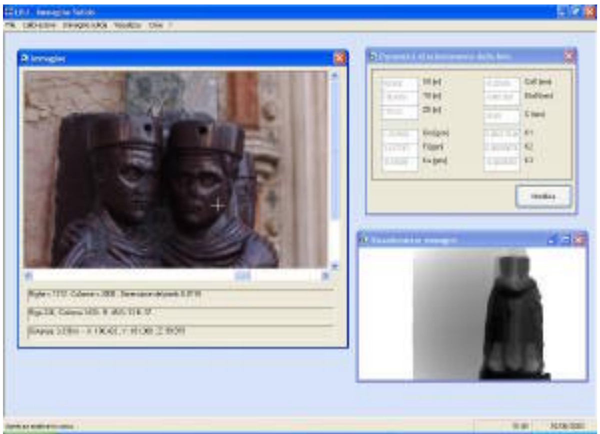


Figure 4. The solid image maker software: some windows.

Fig. 4 shows some of the many windows available to the user. Note the one on the left, where the XYZ co-ordinates of the pixel pointed by the cursor (cross shaped) are displayed in real time.

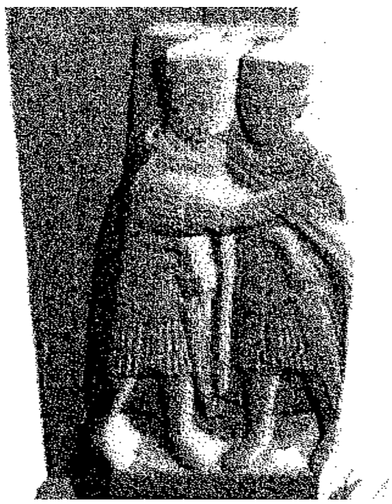
4.2 Survey operations and instruments

A complete survey of the statue has been performed in order to obtain the solid image of the sculpture. Some reflecting targets (markers) has been placed on the object for the automatic calibration process.

A Riegl LMS-Z420 laser scanner has been used for the DDEM acquisition (see Fig. 5 a). This instrument has an accuracy of ± 5 mm in the distance measurements. The minimum angular step is 10 mgon.

The laser scanner acquisition of the statue has been carried out from a mean distance of about 4 m and with angular steps of 20 mgon. The time required for the scanning was about 20 minutes. The acquired point cloud has been filtered with a specific software developed last year by the our research group.

a)



b)

Figure 5. Surveying of the Tetrarchi Statue. a) The Riegl LMS-Z420 Laser Scanner
b) The obtained points cloud (DDEM).

This software is able to eliminate outliers and gross errors that are present in the laser acquisition. Figure 5 b) shows the filtered 3D model.
Photos have been taken using a Nikon D1X digital camera equipped with a 28 mm fixed focus lens.

Figure 6. The taken image

A classical survey of the statue has also been carried out, in order to check the new procedures, comparing the results.

4.3 Image calibration

As the first step, the image calibration was carried out. The image size is 1312 pixels in height and 2000 pixels in width, the resolution is 300 dpi, corresponding to a pixel size of about 12 μm.
Some high reflecting targets have been placed on the statue, allowing the automatic calibration of the image. The estimation has been performed using a bundle approach, by means of a software package made by our research group.
In addition, the lens radial distortion coefficients have been estimated.

The obtained results are shown in Tab. 1.

Table 1
camera orientation parameters and lens distortion

Image orientation parameters			
external			
X_0	99.982 m		
Y_0	100.699 m		
Z_0	103.220 m		
ω	1.018592 gon		
φ	3.437747 gon		
κ	-0.19099 gon		
internal		radial distortions	
ξ_0	-3.776 mm	K_1	0.000175488
η_0	-3.677 mm	K_2	0.00000076
c	28.890 mm	K_3	-0.00000003

Tab 1. Camera orientation parameters and lens distortion

From the radial distortion coefficients the lens radial distortion curve has been obtained, as shown in Fig. 7.

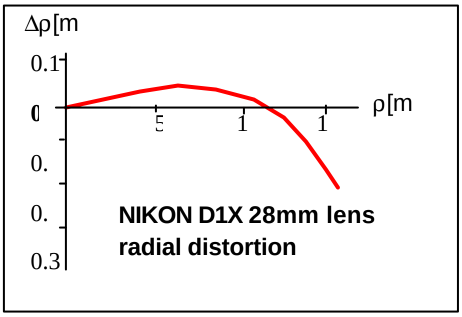


Figure 7. The lens radial distortion curve

4.4 Projection and interpolation

Once the internal and external image orientations are known, the projection of the point cloud onto the image and the interpolation of the distance matrix can be carried out.
The distance matrix can be represented as a grey scale image, where the grey levels are proportional to the distances (black = shortest distance, white = longest distance). (see Fig. 8).

a)

b)

Figure 8. Distance matrix image. a) after the projection process – b) after the interpolation process.

In order to verify if the projection and interpolation processes have been carried out in a correct way, it is possible to display the RGB original image and the above mentioned “distance image” in a same window. It is also possible to superpose the two images.

These functions are offered, for example, by the ENVI software (Environment for Visualizing Images, by Research Systems Inc). (Fig. 9).

Figure 9. Overlap between the original colour image and the grey distance matrix

Once the solid image has been built, the main important result is achieved: for each pixel, it is easy to compute in real time the XYZ position of the object point in an absolute reference system and to display the 3 coordinates on the screen (see Fig. 10).

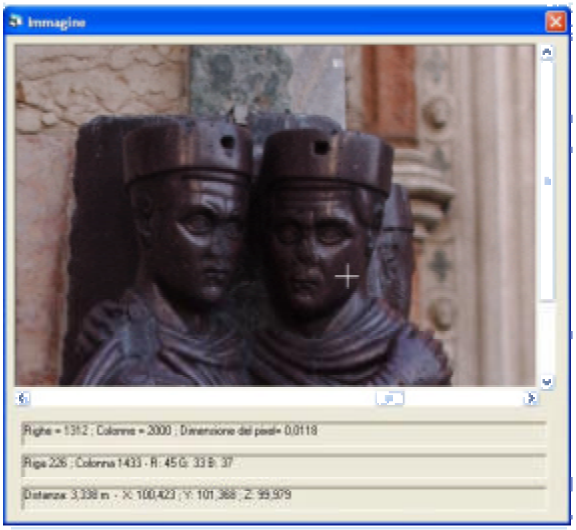


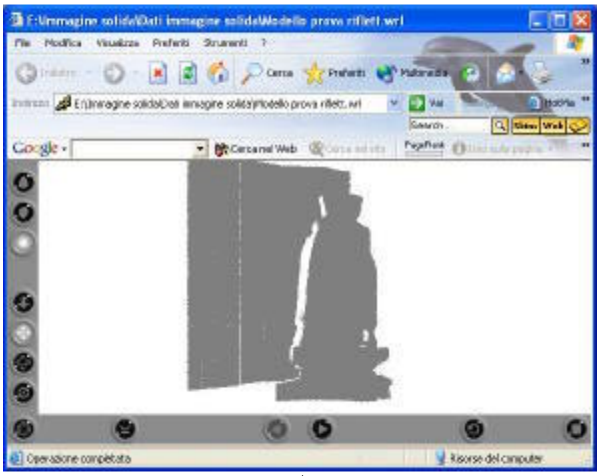
Figure 10. The solid image and the cursor giving the XYZ object co-ordinates of the pointed pixel

5. SOME APPLICATIONS

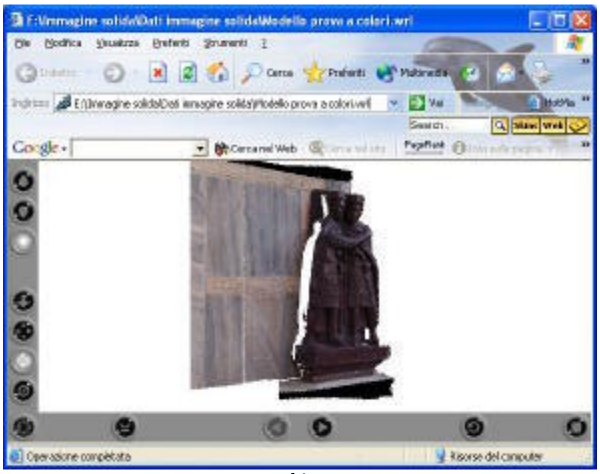
5.1 A coloured 3D model

One of the possible opportunities offered by the solid image is the creation of a 3D model of the represented object. The R, G and B radiometric values and the 3D coordinates are in fact known for each pixel of the image. When this information is known, it is possible, in a very simple way, to create a three-dimensional model to which a radiometric value corresponds to every object point in the space. The mathematical model used for this operation is the central perspective model.

One of the 3D models that is possible to create with the Solid image Maker software is a VRML (Virtual Reality Modelling Language) model. This 3D model can be visualized with specific software for browser web (for example the COSMO player or the CORTONA VRML player for Explorer or Netscape).



a)



b)

Figure 11. a) The 3D model – b) The 3D RGB coloured model – VRML model shown with CORTONA VRML player for browser web.

All these display devices are found free of charge in Internet. This type of software has a great drawback: the model can only be visualized, but not measured.

In the case where the metric aspect of the represented object is considered to be much more important than its simple visualization, using the solid image maker it is possible to export the 3D model in some other graphic formats (for example DXF and ASCII text file formats). In this case it is not possible to associate a radiometric values to each point in the space. The model will therefore not be coloured.

5.2 An artificial stereo pair

Another product obtainable from the solid image is an artificial stereo pair. This couple of images is obtained by fixing a taking base that can be chosen by the operator. The mathematical model used for this operation is the central perspective projection.

The software developed by the authors allows to project the solid image onto two new images forming a stereoscopic pair.
The interior orientation parameters of the two new images are the same as the original image while the external orientation parameters are slightly varied in order to realise a "normal taking", with the base imposed by the operator and the axes of the virtual cameras perpendicular to this base and parallel to each other (see Table 2).

	left image	right image
X_0 [m]	99.782	100.182
Y_0 [m]	100.699	
Z_0 [m]	103.220	
ω [gon]	1.018592	
ϕ [gon]	3.437747	
κ [gon]	-0.19099	

Table 2 - External orientation parameters of the two images

The obtained stereo pair is show in figure 12.
After having projected the solid image onto each of the two new images, it is possible to notice that some pixels of the image do not own a radiometric value.

a)

b)

Figure 12. The artificial stereo pair
a) left image b) right image.

This is due to the fact that the new images are obtained by a re-sampling process and therefore they need an interpolation phase to give a complete result. Another type of lack of information in some pixels could be due to perspective reasons: changing the projection centre, some areas hidden in the original image become geometrically visible, but there is no information available in these pixels.
In this case the holes must be represented as they are (for ex. in white), because an interpolation process would be meaningless.

6. CONCLUSIONS

Solid images open the road to a series of new products in the field of architectural and land surveying applications. A solid image makes possible:

- to determine in real time the position of any point in a 3D reference system, using a common PC;
- to carry out three-dimensional correct measures (lines, areas, volumes, angles, …), just selecting some points on the image;
- to allow even unskilled users to easily plot profiles, sections, plans, by using simple drawing functions able to manage the solid image structure;
- in general, to integrate the high quality original colour image with the 3D geometry of every point represented in the photo.

The first recent applications concern the development of a software package for the creation of the solid image, its artificial stereo pair and its use as a 3D model.
A wide series of further practical applications can be foreseen.

REFERENCES

- P. Boccardo G. Comoglio. **New methodologies for architectural photogrammetric survey** - International Archives of Photogrammetry and Remote Sensing, Vol. XXXIII, Part. B5/1
- L. Bornaz, A. Lingua, F. Rinaudo. **A new software for the automatic registration of 3D digital models acquired using laser scanner devices** - ISPRS Symposium Commission V– Corfu Greece September 2002
- L. Bornaz, A. Lingua, F. Rinaudo. **High resolution digital image orientation using laser scanner data** - ISPRS Commission – Corfou September 2002
- S. Dequal. **Un concetto innovativo: l'*immagine solida*** - Bollettino SIFET - (accepted for printing 2003
- L. Bornaz, S.Dequal. **The solid image: A new concept and its applications** - ISPRS Commission V, WGV/4 – Ancona 01-03 July 2003
- Krauss **Fotogrammetria**, vol. 1, Levrotto e Bella Torino

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