A NEW APPROACH FOR GENERATING A MEASURABLE SEAMLESS STEREO MODEL BASED ON MOSAIC ORTHOIMAGE AND STEREOMATE

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ABSTRACT:

Digital orthoimage (or orthophoto) is a type of information-rich digital products and has found applications in many fields. However, digital orthoimage itself is a 2-dimensional product and therefore it is insufficient for many applications. On the other hand, the traditional stereo model of photogrammetry formed from a pair of overlapping aerial photographs offer the possibility of both 3D measurement of terrain surface and terrain objects. However, it cannot be used a plan like the case of digital orthoimage and the model size is usually limited to the stereo pair. To take the advantage of both, the concept of stereomate was introduced by Collins in 1968. It is a new image with additional relief displacement. The total amount of relief displacement at each point of the stereomate is exactly the same as the sum of two relief displacements at the same position on both images of the stereo pair. That is, if this stereomate is used together with the orthoimage, one is still able to reconstruct a 3D surface of the area precisely. The main limitation with the current practice is that if more than one stereo pairs are used to generate the stereo orthophoto pair, the solution is not rigorous and thus leads to low accuracy of 3D measurement in highly mountainous areas although reasonable accuracy of 3D measurement can be achieved in areas with low relief. This paper introduces the concept of "measurable seamless stereo model", which is formed by a mosaic orthoimage and a mosaic stereomate (i.e. mosaics of a whole block of aerial photographs), with the lineage (image coordinates on original photograph and the orientation parameters of the original photograph) of each pixel on both mosaic orthoimage and a mosaic stereomate recorded. Such a measurable seamless stereo model not only provides seamless 3D landscape environment but also offers the rigorous and thus accurate 3D measurement of any object and feature visible in the measurable seamless stereo model without explicit orientation procedure. Experimental results that the accuracy of 3D measurement from the "measurable seamless stereo model" proposed in this study is about 20 times higher than that from the traditional orthoimage pairs and is nearly similar with that in the original photo-pair model.

1. INTRODUCTION

Digital orthoimage (or orthophoto) is a type of information-rich digital products and has found applications in many fields, such as urban planning. However, digital orthoimage itself is a 2-dimensional product and therefore it is insufficient for many applications (Blachut and van Wijk, 1970; Baltsavias, 1996) because it is a two-dimensional (2-D) representation of the 3-dimensional (3D) terrain surface and terrain objects. A commonly used 3-dimensional representation of terrain surface is digital terrain model (DTM) but DTM has two limitations, i.e. a lack of texture information for interpretation purpose and no representation of terrain objects. Also it is not possible to use DTM as a 2-D plan. On the other hand, the traditional stereo model of photogrammetry formed from a pair of overlapping aerial photographs offer the possibility of both 3D measurement and texture information for interpretation. However, it cannot be used a plan like the case of digital orthoimage and the model size is usually limited to the stereo pair.

Indeed, it is very desirable to have a product which has the advantages of orthoimage (i.e. information-rich, possible for 2-D measurement), stereo model (i.e. possible for 3D measurement) as well as DTM (i.e. 3D representation of a large area).

It is noticeable that the stereomate introduced by Collins (1968) at the National Research Council (NRC) of Canada serves part of the purpose. The stereomate is a complementary image to an orthoimage. It is a new image with additional relief displacement. The total amount of relief displacement at each point of the stereomate is exactly the same as the sum of two relief displacements at the same position on both images of the stereo pair. That is, if this stereomate is used together with the orthoimage, one is still able to reconstruct a 3D surface of the area precisely. Simplicity and efficiency of using stereo model are of particular interest and value for many users (Blachut, 1976). The idea was great and this promotes Sarjakoski (1990) to claim that digital stereo imagery can be taken as a map product in the future in practical applications.

Different aspects and applications of stereo orthophoto pair were discussed (Blachut 1976, Collions and van Wijk, 1970). The 3D measurements from the stereo orthophoto pair have also been discussed (Kraus et al., 1979; van Wijk, 1979). It is noticeable that there are some limitations with the current practice of stereo orthophoto pair, i.e.

- The extent of stereoscopic view of these stereo models is applicable only in the overlapping area of the photo pair, as the stereo orthophoto pair is still based on photo pair.
- If more than one stereo pairs are used to generate the stereo orthophoto pair, the solution is not rigorous and thus leads to low accuracy of 3D measurement in highly mountainous areas although reasonable accuracy of 3D measurement can be achieved in areas with low relief.

In practice, the area of interest often covers more than one stereo pair, therefore, a rigorous solution which will enable us to perform accurate 3D measurement from the stereo orthophoto pair of large area would be of great help (Wang, 2001; Li et al., 2002). Indeed, this paper aims to propose the concept of "measurable seamless stereo model", which is formed by a mosaic orthoimage and a mosaic stereomate (i.e. mosaics of a whole block of aerial photographs), with the lineage (image coordinates on original photograph and the orientation parameters of the original photograph) of each pixel on both mosaic orthoimage and a mosaic stereomate recorded. Such a measurable seamless stereo model not only provides seamless 3D landscape environment but also offers the rigorous and thus accurate 3D measurement of any object and feature visible in the measurable seamless stereo model without explicit orientation procedure.

Following this introduction is a review section, which examines the limitations of existing solutions, then the concept of measurable seamless stereo model is introduced and the principle described. Then the procedures for measurable seamless stereo model and algorithm of accurate measurement are presented. An experimental testing is also reported at last.

2. A CRITICAL ANALYSIS OF EXISTING METHOD

The stereo orthophoto pair was introduced in 1960s (Collins, 1968; Blachut, and van Wijk, 1970). A stereo orthophoto pair is formed by an orthoimage and a stereomate (Collins, 1968). The stereomate is usually produced from the neighboring images (left or right) within a flight strip by artificially introducing horizontal parallaxes, but it can also be produced from the same image. If it is produced from the same image, the objects not included in the DTM (like buildings, etc.) will appear lying on the terrain when the orthoimage and stereomate are viewed stereoscopically.

The horizontal parallax is introduced usually as a linear function of the height. The formula is as follows:

$$P = k \bullet h \qquad (1)$$

Where h is the terrain height; k is an optional factor. k = tan (α), and α is the angle of oblique projection. Usually α is chosen as tan (α) = B/H, namely the base-height ratio.

For a more rigorous agreement the original parallaxes with the introduced parallaxes, the projection angle α should vary with the terrain height (Wang, 1990), so the parallax is introduced as a nonlinear function of the height (Wang, 2001). The mathematical formula is as follows:

$$P = \frac{Bh}{H - h} \qquad (2)$$

Where:

B is the base line of stereo model
H is the flying height.
h is the terrain height

In addition, a special parallax function -- a logarithmic function has also been proposed by Collins (1970) as follow:

$$P = B \bullet \ln\left(\frac{H}{H - h}\right) \qquad (3)$$

Where:

B is the base line of stereo model
H is the flying height.
h is the terrain height

3D measurement in a stereo orthophoto pair has been discussed by Collins (1969), Kraus et al. (1979) and van Wijk (1979). The traditional measurement method is that the height can be directly derived from the parallax without the need for DTM and the planimetric coordinates can be acquired from the orthophoto. The height measurement accuracy is better than the accuracy of DTM. The accuracy of the height measurement from stereo orthophoto pair is two or three times more accurate than the DTM which was used for their generation (Kraus et al., 1979, Kraus 1984; van Wijk, 1979). The is because the errors in the orthophoto and its stereomate caused by DTM errors will have the same sign and therefore be partly cancelled out in the computation of parallax.

The traditional measurement method is very simple but not rigorous. The accuracy of measurement on the stereo orthophoto pair is not able to reach the level when measuring the stereo model formed by the original images. When the terrain is flat, good results are achievable, however in mountainous areas, with the decrease of orthoimage accuracy, the errors may become too big to be acceptable for high-accuracy applications. Table 1 illustrates the variation of measurement results with terrain type. (The data sets are described in section 5).

Table 1. The 3D measurement error of the stereo orthophoto pair model in different terrain types

Landform	Error	X (m)	Y (m)	Z (m)
Flat Area	|MAX|	1.72	1.70	1.83
	RMS	0.92	0.91	0.99
Hill Mountainous Area	|MAX|	4. 44	4. 38	7. 45
	RMS	2.83	2.77	3.94

To summarize, the existing method is based on photo pair and the 3D measurement is a simple computation. That cannot meet with the requirements of a large area in practical applications. Wang (2001) and Li et al. (2002) have ever discussed an approach for generating a seamless stereo model, however, it is very complex and inconvenient in practical applications.

3. THE PRINCIPLE OF "MEASURABLE SEAMLESS STEREO MODEL"

For a photographic block, many stereo models can be formed by stereo pairs. Figure 1 illustrates a block consisting of three strips, with six stereo models in each strip.

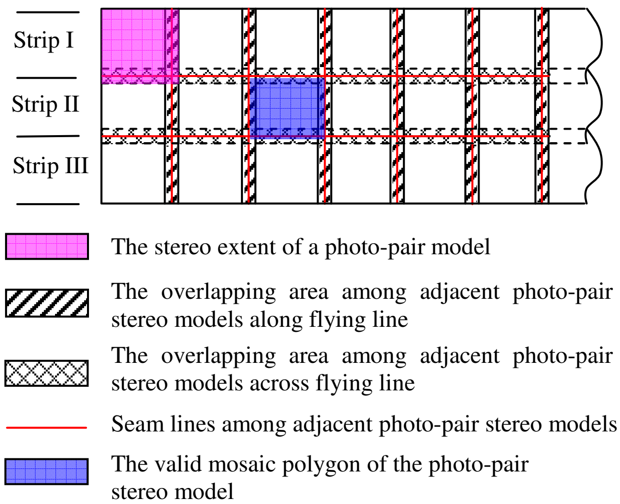

Figure 1. The arrangements of photo-pair models

In this figure, the overlapping area between two adjacent images is called the stereo extent; and a line in the overlapping areas between two adjacent stereo models is called a seam line. The polygon area formed by the seam lines of every stereo model is called valid mosaic polygon of the model.

The mosaic of othoimages of all the valid mosaic polygons in effect covers the whole block seamlessly. Two such seamless mosaics could be produced. One is produced from all the left images, leading to a left mosaic, and the other produced from all the right images, leading to the right mosaic.

To produce a stereo view, parallax needs to be introduced to one of the mosaic (e.g. the right mosaic) to form a so-called mosaic stereomate. The value of the parallax for each pixel is a function of the height at its position. Then the left mosaic and the mosaic stereomate form a seamless stereo model.

Such a seamless stereo model is good enough for visualization purpose. However, for accurate measurement, it is not good enough, as discussed in Section 2. Therefore, such a seamless stereo model is still not measurable in a sense.

To make the accuracy as high measurement, the following strategy is adopted here in this study:

- The 6 orientation parameters of each image are recorded in a file (i.e. orientation file);
- The linage of each pixel on both the mosaic orthoimage and mosaic stareomate is recorded. That is, for each point (pixel) on the seamless stereo model, the system knows (a) the (original) left and right images where it is derived; (b) the orientation parameters of both images; and (c) its image coordinates on both images.
- With such information, when measurement is performed, the ground coordinates of each point on the seamless stereo model is directly computed from original stereo-pair instead of the image coordinates on the mosaic orthoimages and mosaic stereomate.

Such a seamless stereo model is called the measurable seamless stereo model.

4. PRACTICAL ASPECTS OF A MEASURABLE SEAMLESS STEREO MODEL

4.1. The generation procedure of measurable seamless stereo model

The flow diagram for generating a measurable seamless stereo model is given in Figure 2. The procedure can be divided into three major processes:

- First, to produce the left and right mosaic orthoimages: When such two images are viewed stereoscopically, the terrain is seen to be flat;
- Second, to introduce parallax to form a mosaic stereomate: the horizontal parallaxes are computed according to a DTM. Figure 2 illustrates the procedure;
- Third, to index the lineage of each pixel on both the mosaic orthoimage and mosaic stereomate.

More detailed explanation of the steps expressed in Figure 2 is given as follows:

(i). Generating digital orthoimage: Orthorectfication for every aerial image in the block is performed to produce the orthoimage using the interior and exterior orientation elements and DTM. This can be done at a digital photogrammetric workstation. The extent of the orthoimge is decided according to the valid extent of the aerial image.

(ii). Constructing photo-pair stereo models: stereo photo-pair models are built in block area according to the adjacent relationship between aerial images along flying line. Every photo-pair stereo model contains a left and a right original aerial image.

(iii). Choosing the seam lines among adjacent models: The seam lines can be automatically chosen or by manual. As the image surface objects are displaced along the radiation from the nadir, in order to make seamless mosaic, the seam lines should keep away from such objects. But the seam lines cannot exceed the overlapping area among adjacent stereo photo-pair models.

(iv). Constructing the valid mosaic polygon for every stereo photo pair model: The valid mosaic polygons are automatically constructed according to the relationships between the seam lines and the seam lines or between the seam lines and edge lines.

(v). Generating left and right mosaic orthoimages: The left and right mosaic orthoimages are made separately according to the valid mosaic polygon of every photo-pair model in the photographic block area.

(vi). Introducing the horizontal parallaxes for one of the two orthoimages: X-parallaxes are introduced to one of the mosaic orthoimages according to the DTM of the area.

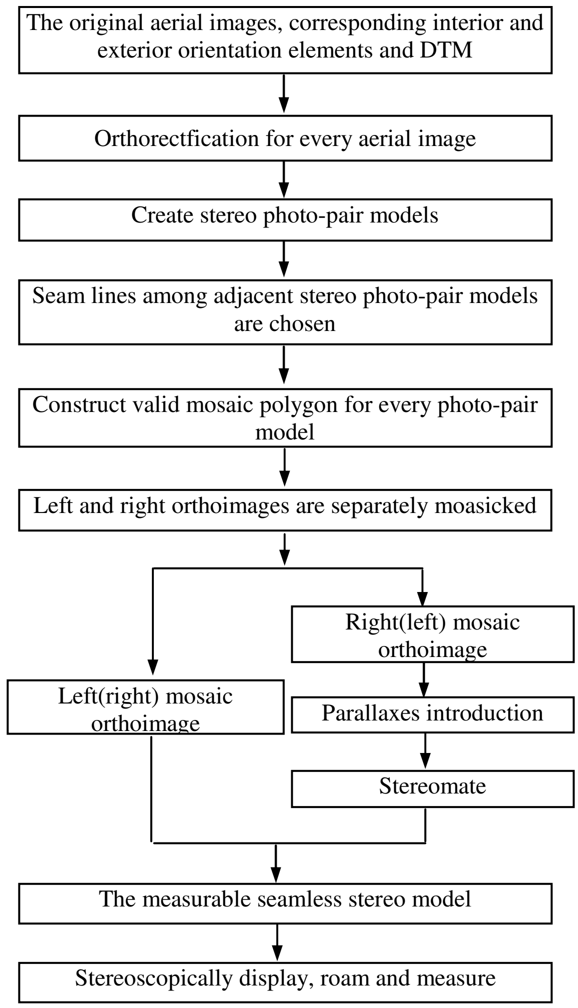

Figure 2. The generation procedure of the measurable seamless stereo model

After the above steps, a moasic orthoimage and a mosaic steromate are produced and they can be used to form a seamless stereo model, which covers the whole block. The stereo model has been absolute oriented (geo-referenced). Some operations such as displaying, zooming, roaming and stereoscopic viewing can be implemented using the stereoscopic device. However, it order to perform accurate 3D measurement, the linage of each pixel is recorded as the metadata of the measurable stereo model.

4.2. 3D measurement in measurable seamless stereo model

The process for measurement on such a measurable seamless stereo model is illustrated in Figure 3.

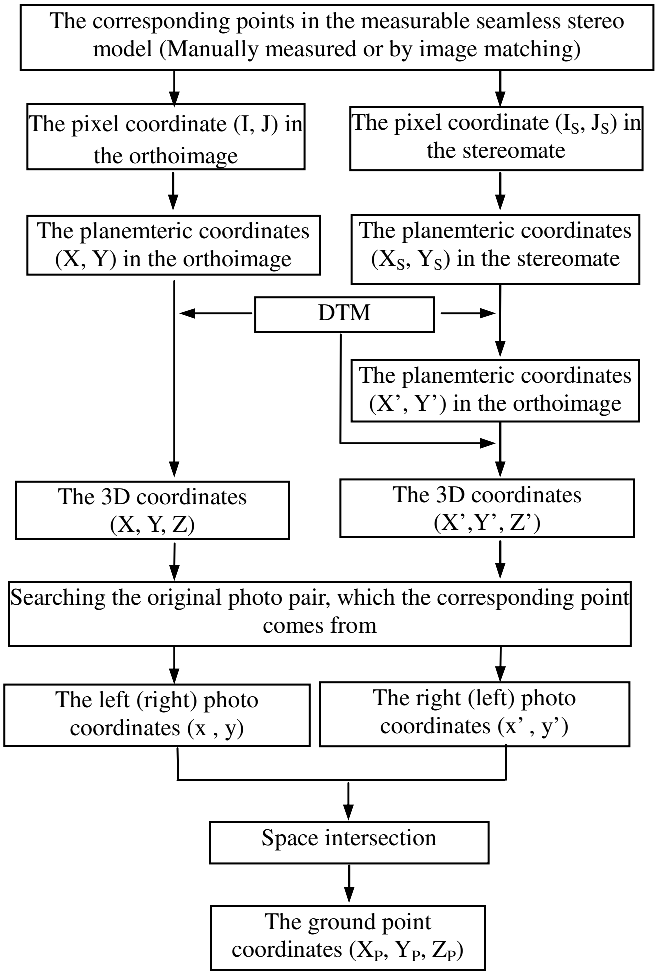

Figure 3. The 3D measurement in measurable seamless stereo model

The 3D measurement steps in detail are as follows.

(i). For a given point on the stereo model, the corresponding point on the stereomate is found by image matching. The image coordinates are recorded separately as (I, J) in the mosaic orthoimage and (I_s, J_s) in the stereomate.

(ii). The pixel coordinates are separately transformed to ground planimetric coordinates, to become (X ,Y) and (X_s ,Y_s).

(iii). For the planimetric coordinates (X_s ,Y_s) in the stereomate, the planimetric coordinates (X',Y') in the orthoimage before introducing parallaxes can be computed according to the parallax function and DTM.

(iv). For the planimetric coordinates of a corresponding point pair, (X, Y) and (X', Y'), the heights Z, Z' are bilinearly interpolated from DTM. The 3D coordinates of the corresponding point (X, Y, Z) and (X', Y', Z') are then obtained.

(v). The valid mosaic polygon to which the corresponding point belongs is searched according to the planimetric ground coordinates (X, Y) in the orthoimage. Then the original photo pair, from which the corresponding point comes, is also searched according to the valid mosaic polygon.

(vi). The coordinates (X, Y, Z) and (X', Y', Z') can be transformed into photo coordinates (x, y) and (x', y') using the known interior and exterior orientation elements of the photos according to collinear equation.

(vii). The ground point (X_P, Y_P, Z_P) can then be computed according to the forward intersection.

5. EXPERIMENTAL TESTING

According to theory and procedures described in the previous two sections, a prototype the software SOD (Stereo Orthoimage Database) is developed. Using in Visual C++.

Two sets of data with different photo scales and terrain types are used to test the presented method and the software. The parameters of the data sets are listed in Table 2. The pixel sizes of the orthoimages for data sets I and II are corresponding approximately to the footprint of the raw image pixels.

Table 2. The experimental data sets parameters

Item	Data Set I	Data Set II
Principle distance	153.710mm	304.034mm
Photo scale	1:25,000	1:8,000
Format	23cm X 23cm	23cm X 23cm
Overlap	60%	60%
Photo type	Panchromatic	False Color
Pixel size	25um	25um
Average flight height	4,225m	2,090m
Landform	Hill mountain	City area
GSD of DEM	12.50m	5m
GSD of orthoimage	0.65m	0.2m
Data Range	Five strips with five stereo models per strip	Three strips with nine stereo models per strip

Figure 4 shows the result of the measurable seamless stereo model generated from Data Set II. Figure 4a illustrates the valid mosaic polygons of the stereo photo-pair in the block area. Every stereo pair has a valid mosaic polygon. Figure 4b is the measurable seamless stereo model in red and green complementary color mode. The stereo model can be directly observed with red/green glasses. The 3D measurement of terrain surface points and objects are performed on both two data sets.

For Data set I, twenty ground points were selected to the accuracy test. These points are separately measured from measurable seamless stereo model and from the original photo-pair model at the SOCET SET v4.4.0 of Leica Geosystems, Inc. The latter is used as the benchmark for accuracy assessment. The maximum error and RMS error are listed in table 3. Figure 5 illustrates the error distribution of these twenty points.

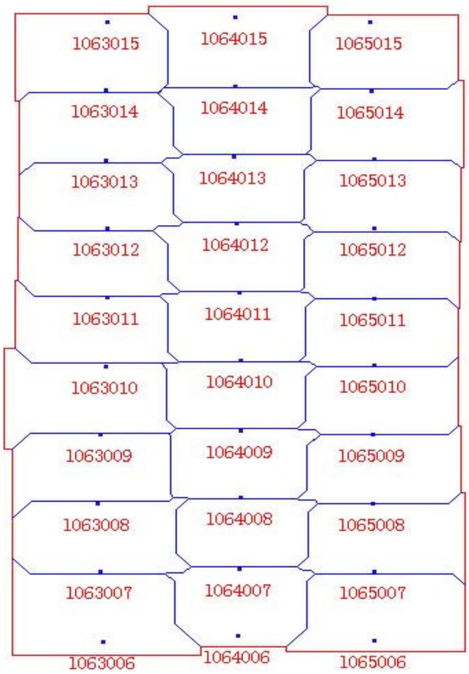

Figure 4 a. The valid mosaic polygons in a block area

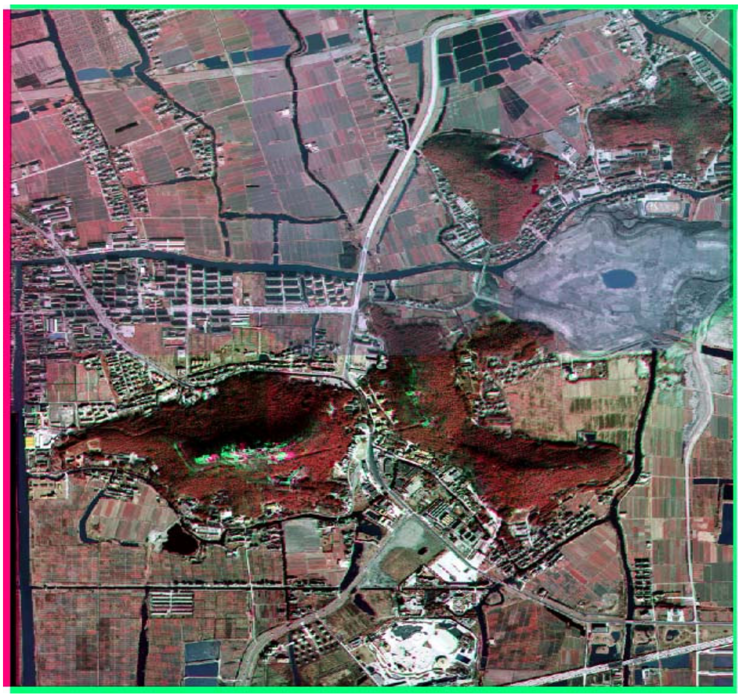

Figure 4 b. The measurable seamless stereo model

Figure 4. The experimental results

Table 3. The error of |MAX| and RMS of terrain points

	X (m)	Y (m)	Z (m)
|MAX|	0.083	0.074	0.084
RMS	0.044	0.042	0.045

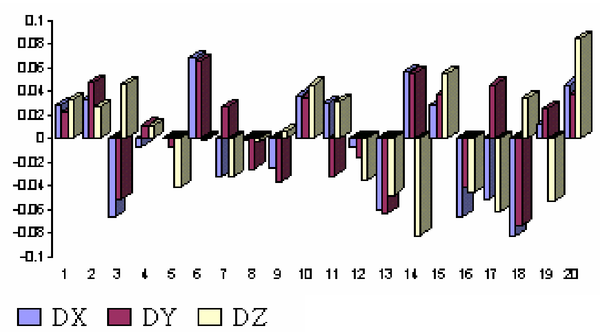

Figure 5. The error distribution diagram of terrain points

For Data set II, the twenty houses were selected for testing. The heights of these houses have been measured from the original photo pairs at the SOCET SET v4.4.0 of Leica Geosystems, Inc. The positions of these points are located the corner of the house roof. That is, twenty house roof corners are measured in the measurable seamless stereo model. The maximum error and RMS error are listed in table 4. Figure 6 illustrates the error distribution of these twenty points.

Table 4. The error of |MAX| and RMS of non-terrain points

	X (m)	Y (m)	Z (m)
|MAX|	0.075	0.080	0.105
RMS	0.046	0.047	0.067

As it can be seen from Tables 3 and Table 4, the RMS errors are very small. It means that the measurement results from the measurable seamless stereo model are nearly similar with those in the original photo-pair model. Compared with Table 1, it can be found that the accuracy of 3D measurement greatly improved.

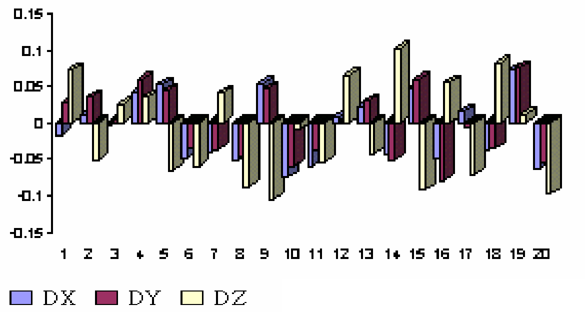

Figure 6. The error distribution diagram of non-terrain points

6. Discussions

The measurement of 3D coordinates using orthorectified stereo images (two orthoimages of the same region (DTM) from each of the images of a stereo pair) has been discussed by Baltsavias (1996). The accuracy of object coordinate determination from the orthorectified stereo images is as high as that achievable when using the original unrectified digital images if the measuring accuracy in the original and ortho-images is similar (which will be the case if the ortho-images pixel size is similar to the scanning pixel size). The correct X, Y, Z measurement still can be made, even if the underlying DTM is with the blunder error (Baltsavias, 1996).

As the coordinates inverse transformation from stereomate to the orthoimage by the parallax function and DTM is a rigorous computation process, the measurement accuracy from the measurable seamless stereo model is completely dependent on the measurement accuracy in the orthorectified stereo images.

That it to say, the measurement accuracy in the measurable seamless stereo model can reach a level as high as that of the ordinary stereo model if the pixel size of the mosaic orthoimage is similar with the scanning pixel size of the original aerial images. Those collusions are very valuable. It means that the measurement accuracy only relies on the orientation elements of the photos and the geometric quality of the photos but has nothing to do with DTM which is used for generating orthoimage and stereomate. This will make the measurable seamless stereo model become more practical in practical applications, especially in these applications that the high measurement accuracy are required, because the acquisition of completely error-free DTM is a hard job (Li, et al., 1996).

The experimental results obtained from this study are consistent with the above accuracy analysis.

7. Conclusions

In this paper, the concept of a measurable seamless stereo model is proposed and the method for generating such a model and algorithm for accurate 3D measurement on such a model are presented. The experimental results illustrate that high accuracy of 3D measurement in such a measurable seamless stereo model is achieved. If compared with the traditional methodology, it can be found that the improvement in accuracy is great, i.e. by 20 times.

Though the stereo orthophoto pair is not a new concept, yet the measurable seamless stereo model is a new idea because it provides the possibility of additional function, i.e. accurate 3D measurement, apart from the seamless stereo view and traditional 3D measurement from the seamless model based on an orthoimage and its stereomate. The high accurate measurement is achieved by making use of the stereo pairs, through recording the lineage of each pixel in the mosaic orthoimage and mosaic stereomate.

From practical point of view, the photogrammetric system with such a measurable seamless stereo model function can be easily integrated into GIS. Such an integrated system provides a new practical and economical approach to stereoscopically render terrain features in a large area and allow users to carry out accurate three dimensional measurement of any objects and features visible for 3D information acquisition, data updating and/or other applications such as 3D design, analysis and photo-interpretation, in many fields such as planning, forestry, electric power, geology and so on.

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