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Geometry Information Extraction from Multiple Planes Based on Single Image

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Abstract

The measurement method based on a single uncalibrated image is a new research hotspot in recent years, which mainly uses the structure information contained in the image itself to realize the geometry information extraction of spatial objects. However, the previous studies always carried out measurement in a single plane. If we want to achieve the measurement of multiple planes, each plane needs to be carried out separately, so we need more known conditions, which is difficult to meet in many cases. Therefore, the original method needs to be further developed. In this paper, an algorithm model based on the single image measurement is proposed, which can use the known segments information in different planes, so as to achieve the multiple planes measurement using fewer known conditions. This algorithm reduces the quantity requirement of known conditions, and improves the original single image measurement model. The information required in the algorithm is usually easy to be obtained in structured scenes, which is useful for the user's on-demand measurement. In addition, the measurement can be repeated many times, thereby reducing the workload of field measurement. From experiments, the results show that the relative errors of indoor and outdoor distance measurement are almost both better than 3%.

Keywords

Single uncalibrated image, Geometric information, Cross ratio, Multiple planes measurement.

1. Introduction

Image is the most vivid and real source of information. More than 80% of human perception information of the world is obtained through the image. The image contains not only the basic feature information such as the spectrum, texture, and shape of the object, but also the spatial information such as the size, the spatial relation-ship, and the image depth change of different objects. In recent years, mining a variety of valuable information from images has become an important research direction, and the extraction of geometric information is one of the most important research directions.

According to the number of images used, geometric information extraction methods could be divided into two or more images measurement method and single image measurement method. The former recovers the three-dimensional structure information by two or more images with a certain degree of overlap for the same scene based on the principle of stereo vision, and realizes the extraction of

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geometric information of spatial objects. The key problems of such method are image matching, camera calibration and three-dimensional structure calculation etc. [1]. However, these problems have always been classic problems in the fields of photogrammetry, computer vision [2], photogrammetry. Moreover, this method generally requires expensive and professional measurement cameras, which is not suitable for popularization in the general public. Compared with the double or multi vision measurement system, the single image measurement does not need image matching, and does not need to know camera parameters in advance. In addition, with the widespread popularity of smart phones and the high development of network communication technology, the single image data resources are rich and easy to be obtained, which makes the measurement more flexible and convenient. In this promotion, the research based on single image has become one of the important research trends in photogrammetry, computer vision and other related fields.

The measurement method based on the single image is a new type of image measurement system developed in recent years, which mainly uses the scene structure information contained in the image itself to realize the geometric measurement of spatial objects [1]. There are two kinds of measurement algorithms based on the single image: indirect geometric measurement based on homography matrix determined by control points and direct geometric measurement based on invariants [3]. According to the different known conditions, the homography matrix can be solved either wholly or step by step. The direct geometric measurement based on the invariants avoids the complex process of solving the homography matrix, and establishes the internal relationship between the image and the real object based on some invariants such as cross ratio, vanishing line, virtual circle, etc. [4]. In 2000, Crisimisi [5] and Hartley [2] systematically analyzed the basic theory and technology of the single image geometry measurement, mainly including the projection between plane and image, the projection between three-dimensional space and image, the level of image transformation and the invariants maintained by level transformation, which laid a foundation for the later research. Lourakis [6] studied the use of coplanar circles for the measurement correction, and Johnson [7] studied the measurement of a single image using three different conditions, polygon, vanishing point and line, and circle. Sui [8] studied the geometric measurement method of the single image based on the principle of cross ratio, evaluated the accuracy of the measurement results, analyzed the error sources, and established the error prediction and correction model. Arslan [9] employed two methods of single image measurement, and evaluated the accuracy of single viewing techniques for the metric measurements on single images.

The measurement of the single image has been widely used in many applications. Hoiem et al. and Zhang et al. [10,11] carried out the research of 3D modeling from single image. Lu [12] proposed a two-stage training dense point cloud generation network to generating a dense point cloud from a single image.

Mendonca [13] introduced an application example of jet engine measurement with the single image. Koutsoururakis [14] studied 3D reconstruction of city using single view image. Hedau et al. [15] used a single image to restore the free space of the indoor scene. Single image measurement can solve the specific application problems, such as target recognition, historical scene reproduction, crime scene measurement, 3D modeling and other fields as well. Aguilera [16] made a spatial analysis of the crime scene with a single picture. Some scholars have used images to identify human height [17-21]. The methods had also been adopted in robot navigation through extracting of vertical lines of an indoor environment or estimating the three-dimensional position of the object on the floor based on a single camera [22,23]. Some recent studies had focused on utilizing smart mobile devices for distance measurement [24,25], which laid a foundation for the popularization of this technology.

As mentioned before, the measurement of the single image has achieved a lot of research results, and is still booming. However, there are still some problems remained. The most prominent problem is that the measurement is often carried out in a single plane in the past, which cannot meet the measurement for the real three-dimensional world, and the applicability of the algorithm needs to be further improved. In this paper, based on the invariant direct geometric measurement method, the

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method is extended to the distance measurement across a plane, which can realize the multiple planes stereo measurement, reduce the number requirements of the known conditions in a single plane, and expand the theoretical method of the single image measurement.

In this paper, the single uncalibrated image is taken as the research object, and an algorithm model based on the single image measurement is established. The algorithm needs a certain number of known conditions, including parallel lines, rectangles or circles, lines with known distance, etc. Under the constraints of known conditions, it can realize the distance measurement of the same line with the known line, the same plane with the known line, and extend to the measurement of multiple planes and multiple objects. Based on the algorithm research, this paper carried out the experimental verification with the actual scene. The information needed in this algorithm is usually easy to be obtained in the structured scene, which makes a useful exploration for the user's on-demand measurement, and the measurement can be repeated many times, which reduces the workload of field measurement. In addition, the future application of single image measurement is discussed based on image measurement.

2. Related Works

The algorithm based on projective invariant cross ratio is the most commonly used single image measurement algorithm, which requires a certain number of known conditions, including parallel lines, rectangles or circles, known distance segments, etc. Under the constraints of known conditions, it can realize the distance measurement of collinear with known line segments and coplanar distance measurement with known line segments. These basic theories are the basis of multiple planes measurement proposed in this paper.

2.1 Cross Ratio

The camera's imaging process is an innuendo transformation process from the three-dimensional space to the two-dimensional space, with changes in length, angle, and parallel relationships. As shown in Fig. 1, a set of parallel lines in three-dimensional space is usually no longer parallel after the transformation, but converges at a point, which is called the vanishing point. The vanishing point usually corresponds to a point in a straight line in three-dimensional space that is at an infinite distance. The line of two vanishing points is the vanishing line of the plane, and there is only one vanishing line in a plane. The vanishing point determined by parallel lines in all directions on the same plane is in a unique line. In Fig.1, Vp1 is a vanishing point determined by the intersection of one set of parallel lines, Vp2 and Vp3 are the different vanishing points determined by other sets of parallel lines, and the connection of the Vp1 and Vp2 is the vanishing line vl. The determination of the vanishing point can be achieved by the straight-line extraction of the intersection or the vanishing point detection algorithm.

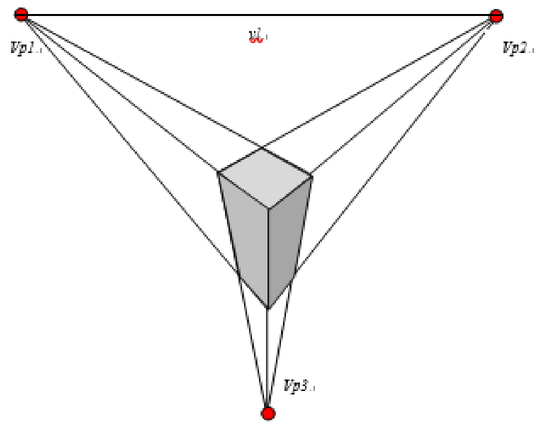

FIGURE 1. Vanishing points and vanishing lines. Vp1, Vp2 and Vp3 are the various vanishing points determined by different sets of parallel lines and the line between Vp1 and Vp2 is the vanishing line.

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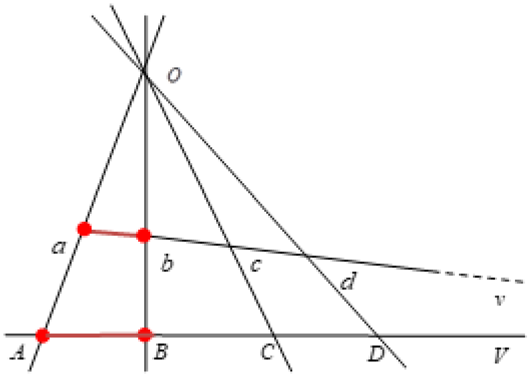

FIGURE 2. Cross ratio with four points. A, B, C and D are the points in the field, while the a,b,c and d are the corresponding points in the image.

Before and after projection, there are also some spatial relationships and properties that remain unchanged, such as collineation, tangents, intersections, cross ratio, and so on. As shown in (1), cross ratio is defined as the ratio of the distance ratio of four collinear points. As an important invariant variable, the cross ratio can be directly used for the measurement of geometric information from the single image. As shown in Fig. 2, points A and B are called base points, points C and D are called divided points. By convention, the uppercase letter here represents the point in the field, while the lowercase letter represents the corresponding point in the image. S represents the distance between two points. CR is the cross ratio which can be calculated with (1) and remains the same before and after the projection.

$$CR(AB,CD) = \frac{S_{AC}S_{BD}}{S_{AD}S_{BC}} = cr = \frac{S_{ac}S_{bd}}{S_{ad}S_{bc}} \tag{1}$$

2.2 Collinear Distance Measurement Algorithm

As shown in Fig. 2, replacing one of the four collinear points with the vanishing point, V in the figure is the vanishing point of line AB, and the cross ratio equation can be transformed into the following form:

$$cr = CR(AB,CV) = \frac{S_{AC}S_{BV}}{S_{AV}S_{BC}} = \frac{S_{AC}S_{BV}}{(S_{AB} + S_{BV})S_{BC}} \tag{2}$$

When the numerator and denominator of the above equation are divided by S_{BV}, the vanishing point is usually located at infinity, and S_{BV} tends to infinity, so the above equation can be simplified as the following:

$$cr = \frac{S_{AC}}{(S_{AB}/S_{BV} + 1)S_{BC}} = \frac{S_{AC}}{S_{BC}} = \frac{S_{AB}+S_{BC}}{S_{BC}} = \frac{S_{ac}S_{bv}}{S_{av}S_{bc}} \tag{3}$$

The value of cross ratio in the above equation can be calculated by the distance on the corresponding image on the right side of the equation. If the field distance between the two points B and C is known, the distance between the other two points A and C can be calculated, and the distance between the two points A and B can also be calculated as shown below:

$$S_{AC} = cr ? S_{BC} \tag{4}$$

$$S_{AB} = (cr - 1)S_{BC} \tag{5}$$

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$$S_{AC} = S_{AB} + S_{BC} \tag{6}$$

Therefore, when the length of the line segment is known, the distance between any two points on the line can be calculated by using the principle of cross ratio invariance. For example, the distance of CD can be calculated by (7) and (8).

$$CR_2 = CR(CD, AV) = \frac{S_{AC}S_{DV}}{S_{CV}S_{AD}} = \frac{S_{AC}S_{DV}}{(S_{CD} + S_{DV})S_{AD}} = \frac{S_{AC}}{S_{AD}} = cr_2 \tag{7}$$

$$S_{CD} = S_{AD} - S_{AC} \tag{8}$$

2.3 Distance Measurement Method in a Plane

2.3 1 Coplanar Distance Measurement in a Plane including Rectangle

(1) Length and width of the rectangle are known

As shown in Fig.3, there is a rectangle ABCD in the plane P, and the length and width of the rectangle are known, then the length of any line segment P1P2 coplanar with the rectangle can be calculated. The steps of the algorithm are as follows:

a) The distance of the collinear line BJ4 could be calculated from the known length of AB;

b) The distance of the collinear line CJ2 could be calculated from the known length of BC;

c) From the Pythagorean theorem, the distance of the hypotenuse J2J4 of the triangle BJ2J4 is obtained;

d) The distance of the segment P1P2 could be calculated by the collinear distance measurement algorithm.

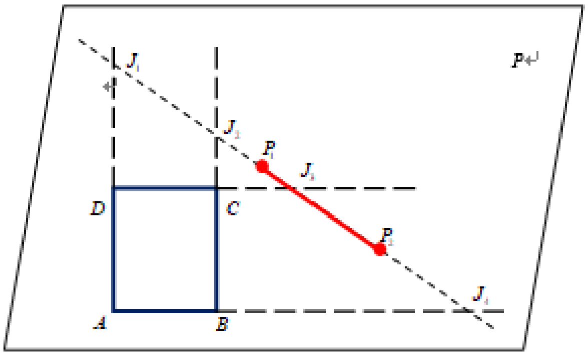

FIGURE 3. Coplanar distance measurement with known rectangle. The length and the width of the rectangle are known, P1P2 is a random line segment in the same plane.

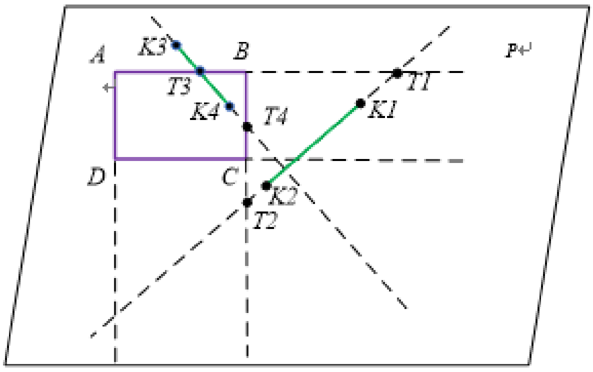

FIGURE 4. Coplanar distance measurement with unknown rectangular and known nonparallel line segments. The length and the width of the rectangle are unknown, K1K2 and K3K4 are known.

(2) Length and width of the rectangle are unknown

Sometimes the above method will not be effective, when the side length of rectangles in the image cannot be obtained, or only two groups of parallel lines perpendicular to each other are known. However, when there is a rectangle and two other nonparallel lines with known length in the image, the above algorithm could be further extended. The basic idea is to establish the relationship between the two known line segments and the two rectangular side lengths firstly, and then the rectangular side length could be obtained by solving the equations simultaneously. By this way, the geometric measurement of any line segment in the plane can be realized according to the previous algorithm.

As shown in Fig. 4, the side length of rectangular ABCD on plane P is unknown, but there are two nonparallel lines K1K2 and K3K4 with known length on the plane. After extending the corresponding line, they intersect with each other at T1, T2, T3, T4.

Assume the known lengths of K1K2 and K3K4 are l1 and l2 respectively, and the unknown lengths of AB and BC of the two sides of the rectangle are s1 and s2 respectively. According to the algorithm of collinear distance measurement, the lengths of T1T2 and T3T4 can be calculated from K1K2 and K3K4, and the line segments BT1, BT2, BT3 and BT4 can be calculated from the lengths of AB and BC. Let T1T2=k1×l1, T3T4=k2×l2, BT1=k3×s1, BT2=k4×s2, BT3=k5×s1, BT4=k6×s2. In the above equations, k1, k2, k3, k4, k5, k6 are coefficients related to the cross ratio in the image.

Since both BT1T2 and BT3T4 are right triangle, equations can be formed according to Pythagorean theorem as followed:

$$\begin{cases}\left(k_3\times s_1\right)^2+\left(k_4\times s_2\right)^2=\left(k_1\times l_1\right)^2\\\left(k_5\times s_1\right)^2+\left(k_6\times s_2\right)^2=\left(k_2\times l_2\right)^2\end{cases}\tag{9}$$

The two sides of the rectangle can be obtained by solving the above equation. If the rectangle is a square, the equation can be solved only by the length of a line segment, and then the distance between any two points on the plane can be measured based on the above method of knowing the side length of the rectangle.

2.3.2 Coplanar Distance Measurement in a Plane including Circle

The circle can also provide the known conditions for the plane measurement. After the projection, the circle in the three-dimensional space will deform, and usually becomes an ellipse. However, the external rectangle of the circle still keeps the general properties of the rectangle. Therefore, as long as the image of circular circumscribed rectangle is obtained, the measurement can be realized by the method based on rectangle.

The lines and points on the plane where the circle is located satisfy the polar geometric relationship of the (10) with respect to the mapped ellipse e of the circle:

$$d=E\times vp\tag{10}$$

Where E is the coefficient matrix of the elliptic equation, d is the diameter of the circle, vp is the vanishing point determined by a group of parallel lines perpendicular to the diameter d as shown in Fig. 5. There is an antipolar relationship between the diameter d and the vanishing point vp with respect to the ellipse E. That is to say, given a diameter d, the corresponding vanishing point vp can be obtained. Conversely, given the ellipse equation E and the vanishing point vp, the corresponding vanishing point vp can also be determined.

Therefore, the steps of coplanar distance measurement including circle are as follows:

a) The points on the ellipse are extracted to fit the ellipse equation;

b) From the elliptic equation and a known diameter, the vanishing point in the direction perpendicular to the diameter is obtained according to the antipolar geometry relationship;

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c) Another vanishing point in the direction of diameter can be found out from the line parallel to the diameter;

d) Another diameter is obtained by using the vanishing point and the elliptic equation;

e) The circular circumscribed rectangle can be found out from two diameters;

f) The distance to be measured is realized by the coplanar distance measurement algorithm based on the rectangle.

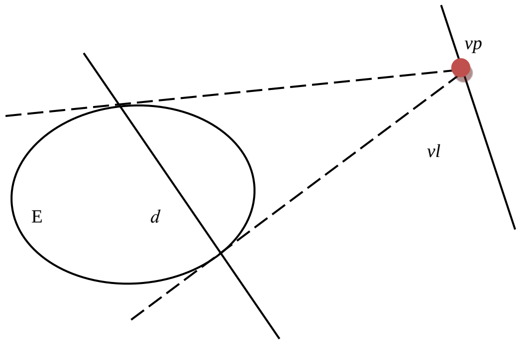

FIGURE 5. Antipolar geometry relationship. There is an antipolar relationship between the diameter d and the vanishing point vp with respect to the ellipse E.

3. Proposed Method

In previous studies, measurements were often achieved in one plane. However, the real world is a three-dimensional world, and there are obvious limitations in the realization of distance measurement only in a single plane. It is necessary to further extend the algorithm to realize the measurement from one plane to another, so as to realize the multiple planes measurement and meet the needs of three-dimensional measurement. As shown in Fig. 6, A, B and C are three intersecting planes, and plane A is the reference plane. Taking the rectangular measurement as an example, plane B intersects plane A, plane C intersects plane B, and plane A does not intersect with plane C directly. Plane A has the measurable conditions (including a rectangle and its two sides), on the basis of plane A, plane B and plane C only need to provide fewer known conditions to realize measurement. When the following conditions are known in plane B an plane C, the measurement of any line in three planes can be realized: a set of parallel lines perpendicular to the intersection line and any segment not parallel to the intersection line with known length, or a rectangle in any direction and a segment not parallel to the intersection line.

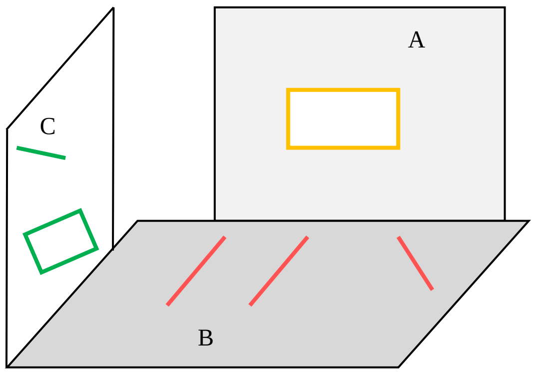

FIGURE6. Spatial relationship and known conditions between multiple planes. A, B and C are three intersecting planes, and only Plane A has the measurable conditions

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The multiple planes measurement of two planes can be achieved by four steps. The algorithm of distance measurement is as follows:

a) According to the known conditions, the measurement in plane A is realized;

b) Extracting the intersection line of two planes to get the intersection line equation, and finding the intersection point of the intersection line and the vanishing line of plane A;

c) According to the parallel condition of plane B, the vanishing line of plane B is obtained, and then a linear equation parallel to the intersection line is determined to construct the rectangle in plane B;

d) The measurement of any line segment in plane B is realized with the known line segment;

e) According to the similar steps, the unknown distance in plane C can be calculated from the known condition of plane B.

Through the above method, the distance measurement from plane A to plane B can be realized. In addition, taking plane B as a transition, the unknown distance measurement from plane A to plane C which does not directly intersect with plane A can also be realized.

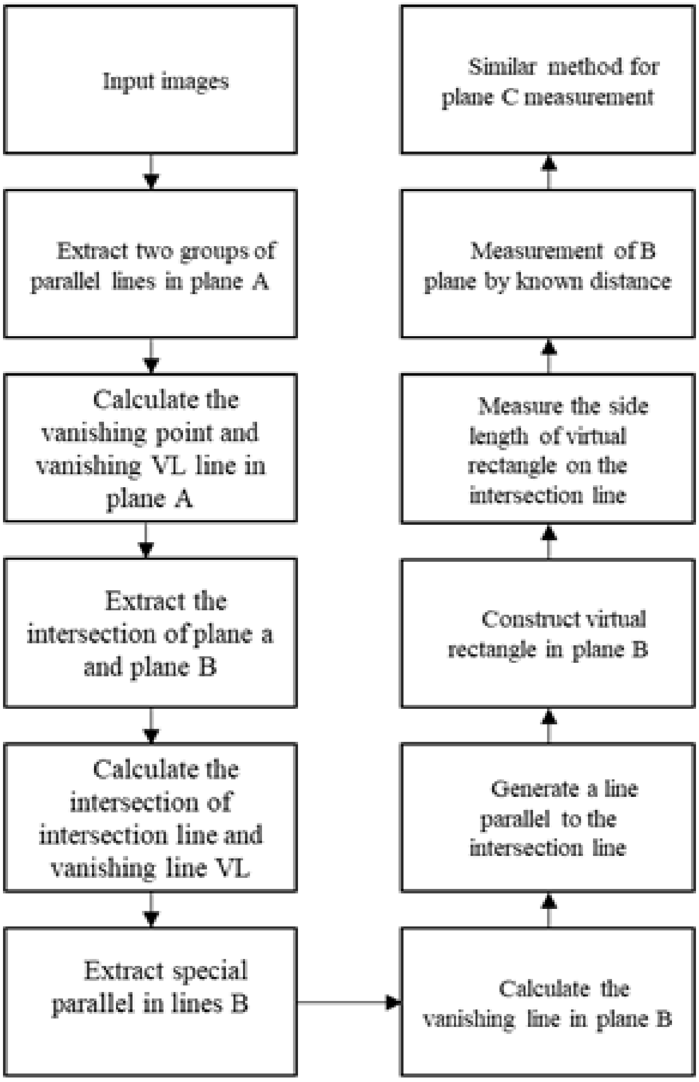

FIGURE7. Algorithm flow of multiple planes measurement.

The algorithm flow of measurement experiment is shown in Fig. 7. As shown in Fig.6, two groups of parallel lines are extracted in plane A and the corresponding vanishing points are calculated respectively, and then the vanishing line VL1 of the plane could be determined. The intersection line

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JL of plane A and plane B is extracted and the intersection point VP1 between JL and VL1 is calculated. This point is the vanishing point of a set of lines parallel to the intersection line. After extracting another group of parallel lines perpendicular to the intersection line of plane B and calculate the vanishing point VP2, then the vanishing line VL2 of plane B can be determined by VP1 and VP2, and any line parallel to the intersection line can be calculated by the intersection line JL and the vanishing line VL2. After selecting one of them to determine the linear equation, then the intersection can be obtained from two groups of perpendicular parallel lines, and then a virtual rectangle in plane B can be constructed. One side of the virtual rectangle is a line segment on the intersection line, and the length of the line segment can be measured by plane A. If the length of any segment of plane B is not parallel to the intersection line, the measurable conditions in plane B are all satisfied, and the distance measurement of any segment of plane B can be realized. By using the similar principle, the measurement of plane C can be realized by plane B. When plane A, plane B and plane C belong to different objects, the distance measurement can be realized not only across plane but also across the object.

4. Experimental Results

Two experimental scenes are designed to measure the distances across the plane. The first is the indoor experimental scene, which is composed of three planes, i.e. the bookcase placed in different positions and the ground, to measure the distance across the plane and objects. The second experiment is the outdoor experiment scene of multiple planes measurement. Taking the regular building as the experiment scene, the distance measurement across different building surfaces and building bodies in the larger scene are realized, and the detailed distance of the building are measured.

4.1 Indoor Multiple Planes Experiment

As shown in Fig. 8, the indoor office scene includes two separate bookcases, floor tiles and other multiple planes, which are respectively represented by plane A, plane B and plane C. Plane A is set as the reference plane, which contains a rectangle (bookcase door) with known side length. The goal is to determine the length of the line to be measured on plane C. In this figure, the red line segments represent the known distance, the yellow line segments represent the distance to be measured, and the required data are measured on site with meter scale.

FIGURE 8. Known lines and lines to be measured in each indoor plane. The red line segments represent the known distance, the yellow line segments represent the distance to be measured.

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Measuring each line according to the proposed measurement method of multiple planes based on rectangle, and the results are shown in Table 1. From the Table 1, it can be concluded that the relative error of each line segment in plane A is between 0.7% and 2.2%, and that in plane B is between 1.3% and 2.3%, and that in plane C is between 1.0% and 2.6%. Due to the influence of error propagation and imaging position, the distance error on the plane C is large, but the overall accuracy is less than 3%, and good results are still obtained.

4.2 Outdoor Multiple Planes Experiment

Indoor scenes are usually more regular and smaller in scope. However, there are many problems in recording outdoor scenes with photos, such as large building volume, more content in the scene, far sight distance, large imaging deformation, and non-obvious plane intersection line etc. Selecting an outdoor building scene as shown in Fig. 9, the scene includes two buildings that one is the student dormitory and the other is the student canteen. Now, based on the plane where the front door of the student canteen is located, the two segments marked in red are known lengths. Through the proposed multiple planes measurement method, the dimensions of the south wall and any details on the west wall of the student dormitory building within the visible range on the image can be determined. Among them the red line segment represents the known distance, the blue line segment represents the distance to be measured, and the results of each line segment to be measured are compared with the field measurement results according to the rectangular multiple planes measurement method as shown in Table 2.

TABLE 1. Statistics of multiple planes measurement results of indoor scene (unit: cm)

Plane	Segment number	Segment type	Measurement results	Field measurement results	Absolute error	Relative error (%)
A	A1A2	Known	108.235	109	-0.765	0.7
	A2A3	Known	38.312	37.5	0.812	2.2
	A4A5	Unknown	101.243	100	1.243	1.2
	A6A7	Unknown	78.106	78.9	-0.794	1.0
B	B1B2	Known	49.167	50	-0.833	1.7
	B2B3	Unknown	71.423	70.5	0.923	1.3
	B4B5	Unknown	36.531	35.7	0.831	2.3
C	C1B5	Known	69.586	68.9	0.686	1.0
	C2C3	Unknown	30.768	30	0.768	2.6
	C1C4	Unknown	40.809	40	0.809	2.0

TABLE 2. Statistics of multiple planes measurement results of outdoor scene (unit: cm)

Plane	Segment number	Segment type	Measurement results	Field measurement results	Absolute error	Relative error (%)
A	A1A2	Known	470.92	470.3	0.62	0.13
	A2A3	Known	317.45	317.0	0.45	0.14
	A4A5	Unknown	80.12	82.5	-2.38	2.9
	A6A7	Unknown	230.08	232.4	-2.32	1.0
	A8A9	Unknown	369.21	381.8	-12.59	3.3
B	B1B2	Known	336.82	335.0	1.82	0.54
	B2B3	Known	238.08	235.8	2.28	0.97
	B4B5	Unknown	269.62	277.0	-7.38	2.7
C	C1C2	Known	813.50	816.0	-2.5	0.31
	C2C3	Unknown	274.16	273.1	1.06	0.39
	C3C4	Unknown	233.18	235.8	-2.62	1.11

From Table 2, it can be concluded that the relative error of each line segment in plane A is between 0.13% and 3.3%, that in plane B is between 0.31% and 2.7%, and that in plane C is between 0.31%

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and 1.1%. Although the outdoor scene range is large, the building is irregular, and the absolute error is large, the overall relative error still reaches a high accuracy of the line to be measured.

FIGURE9. Known lines and lines to be measured in each plane of outdoor scene. Among them the red line segments represent the known distance, the blue line segments represent the distance to be measured.

5. Conclusion

With the popularization of the digital cameras, the whole people are participating in the production of photos, among which there are a lot of geographic information. If we can make full use of these information, we will greatly expand the source of geographic data, improve the participation of the public in geographic information, and promote the socialization of geographic information.

In this paper, single uncalibrated image is taken as the research object, and a set of algorithm model based on single image measurement is established. The algorithm needs a certain number of known conditions, including parallel lines, rectangles or circles, lines with known distance, etc. Under the constraints of known conditions, it can realize the distance measurement of the same line with the known line and the same plane with the known line. At the same time, the real world is a three-dimensional world, and the in-plane measurement based on a single image is still limited. In this paper, a single image cross plane distance measurement algorithm based on cross ratio is proposed to realize the cross from one plane to another, so as to realize the multiple planes three-dimensional measurement, which reduces the number of known conditions in a single plane, and expands the theoretical method of single image measurement.

The information needed in the algorithm is usually easy to obtain in the structured scene, which is useful for users' on-demand measurement, and the measurement can be repeated many times, which reduces the workload of field measurement. Based on the research of theory and method, several experiments are carried out. The results show that the relative errors of indoor and outdoor distance measurement are almost both better than 3%.

Based on the spatial information recovery of a single image, to some extent, this paper solves the application problem with only a single image. However, due to the complexity of single view scene in real life, there are still a lot of problems remained to be further studied in order to fully realize the automatic analysis of single image without any manual intervention. In particular, the existing research still has certain requirements for the structure and content of the scene, such as the number of known conditions, the composition relationship of the scene, etc. In the future, it is necessary to develop more universal geometry measurement method for single image, so as to reduce the dependence of the algorithm on the existing conditions. In addition, it is necessary to further study the influence of parameter selection on the accuracy of measurement results, so as to make more reasonable inversion strategies to meet the needs of application for geometric information extraction.

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