INTERACTIVE ROOF PATCH RECONSTRUCTION BASED ON 3-D LINEAR SEGMENTS

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ABSTRACT

An interactive system for roof patch reconstruction is introduced in this paper. The reconstruction is based on 3-D linear segments. The concept of interactive approach combines the interpretation ability of human operator and the computation ability of the computer together to increase the successfulness of the reconstruction. To increase the successfulness of the automatic finding of roof corners, a specially designed Point Database is used by the system. The interactive approach is accomplished by human intervention in various steps during the process. Experiments show that the system is very practical.

1 INTRODUCTION

The general procedure for roof reconstruction could be thoroughly divided into three subtasks: the geometrical feature extraction, the detection of possible locations of roofs or roof boundaries, and the final roof reconstruction. In all three subtasks intelligent interpretation is needed more or less. Despite the rapid development of the computer technology, it is still a great problem to make the computer deal with the interpretation task correctly. The central point lies on the lack of intact theory to handle this problem. Therefore methods for the fully automatic reconstruction of buildings found in the literatures [Collins et al., 1995;Fischer et al., 1997; Henriccson and Baltsavias, 1997; Lin et al., 1995; McGlone and Shuffel, 1994; Nevatia et al, 1997; Shufelt 1996] can’t meet the general requirements encountered in the practice.

Hence, the reconstruction problem becomes another issue as how to effectively integrate the interpretation ability of operator into the system in order to improve the performance. The development of the so-called semi-automatic system for roof reconstruction [Gruen,1998; Gülch, 1997; Heuel and Nevatia,1995; Hsieh, 1995; Lang and Förstner,1996] is a substantial improvement for the correctness of the building reconstruction. However, semi-automatic approach handles the problem in a simple forward way. Once the interactively provided information from the human operator is fully used, the system prompts a solution. If the solution is wrong, there is hardly any further intervention from the operator possible.

Therefore, in this paper we would like to present an interactive approach for the roof patch reconstruction on the basis of 3-D linear segments. It is called “interactive” because in addition to including the high interpretation ability of the human operators, we have designed a constant interaction between the operator and the computer. Therefore the difference between interactive and semi-automatic systems is that our interactive system draws stronger human intervention in various steps during the reconstruction procedure and that the result of intervention is immediately prompted by the system on the screen for the operator to confirm or deny it. If it is not a correct one, the operator has to interfere immediately. All the interactive actions take place mono-scopically in single image, no precise stereo measurement is needed.

We have specially designed this trial and error approach for handling the very dense buildings in most urban areas in Taiwan. It is very common in Taiwan that people build extra illegal superstructures on the top of the legally constructed buildings. These illegal superstructures are most of the time in the form of gable roofs with very different sizes and heights adjacent to each other (cf. Fig.7 or 8). Since almost no side walls of the buildings could be seen on the image, only roofs can be reconstructed.

Although lines or edges are the most extracted information from aerial images for building reconstruction, they are most of the time incomplete and not reliable. Because they are most of the time merely an accumulation of individual edge pixels without any semantic information in the object space. Therefore in our system the edges are used only as intermediate elements for determining roof corners and a roof patch is actually reconstructed by corners. For better usage of corner points, we have designed the Point Database for managing and searching the corners.

The system first tries to find as much as possible all “meaningful” 2-D and 3-D line segments from the stereo images automatically without any human intervention. By “meaningful” we mean that a line segment, which due to its semantic nature in the object space could be part of a roof edge. Among all the meaningful line segments the system chooses the best one and prompts it on the screen with an initial guess of the possible form of that roof patch. The operator then has to confirm it or deny it interactively on the screen.

If the operator denies it, the computer tries to find another one and prompt it again on the screen. Since human operator is good at the interpretation and the computer is good at the computation, we let the operator do the examination of the results computed by the computer. Immediately after each action of the operator, the computer starts to recalculate the new situation provided by the new information from the operator's action. It prompts new suggestions on the screen. Eventually an initial line segment will be accepted by the operator. In the following we will call this first confirmed 3-D line the initial 3-D line. This line in general is only a segment of a roof edge.

After confirming the initial 3-D line, the operator then has to select relevant line segments (mostly also only broken fragments) associated with the initial 3-D line. By association we mean that they, together with the initial 3-D line, seem to form a roof patch. In the following we will call these relevant line segments the associated lines. The associated lines could be 2-D or 3-D, depending on how they are linked and matched in the first stage of finding meaningful lines. The selection is done mono-scopically in one image, therefore it can not be hundred percent correct. If the new information is enough, the system tries to reconstruct the entire roof patch. Otherwise the system will ask the operator to point the cursor to the approximate location of the roof corners. The system will find the best point from the Point Database for that corner. After that, the system starts to compute the 3-D coordinates of all the corners. The roof patch is then reconstructed from the corners. The result is displayed either in perspective view on the screen or stereoscopically in two images. The operator can examine the result. If the operator is not satisfied with the result, he can modify it interactively. If for any roof patch the finding of the initial 3-D line failed at the very beginning, that roof patch must be reconstructed manually by the operator by indicating the corners and assigning a roof patch model to it.

Thus, the verification of the initial 3-D linear segment, the selection of relevant 2-D or 3-D line segments, the pointing to the missing corner(s) and the modification of results are the main interactive components, which characterize the whole system.

2 SYSTEM DESIGN AND ILLUSTRATION

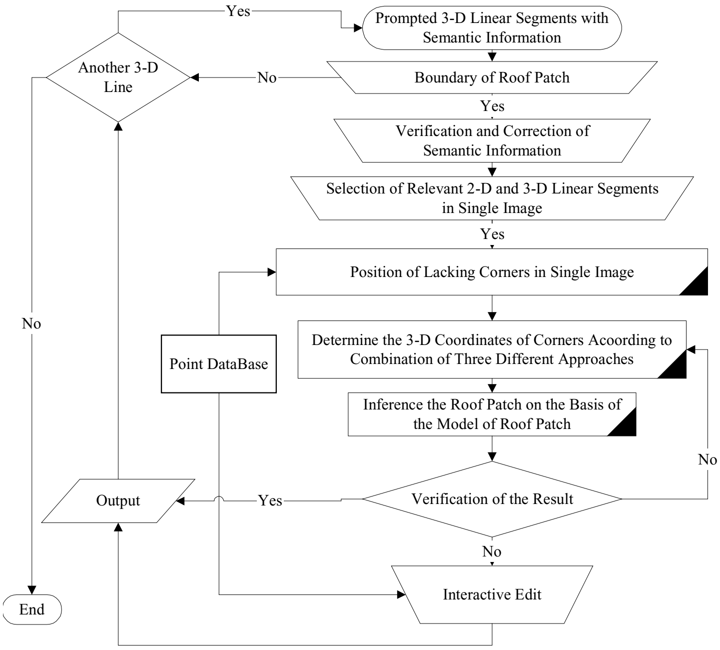


Fig.1: Diagram for roof patch reconstruction

Fig. 1 shows the diagram of this interactive system for roof patch reconstruction. All the necessary lines, no matter 2-D or 3-D, are all prepared in a forgoing program. In that program straight lines are constructed by simultaneously linking and matching of consecutive single edge pixels in the two stereo images under the consideration of the general knowledge about roof edges in the object space. Here, the general knowledge we assumed is that a roof edge is limited to a straight line in the space. It is either horizontal or oblique. Thus, curvilinear roof edges are not considered here. With this knowledge in mind, we can link and match edge pixels, extracted by low-level feature extraction methods, more effectively into meaningful line segments. Details about the method are described in a previous publications [Chio et al., 1999].

At the beginning of the roof patch reconstruction, the system will display all successfully linked and matched 2-D and 3-D lines in both images of the stereo pair. For each roof patch, one of the 3-D lines will be chosen by the system as the initial 3-D line for starting the reconstruction process. That line will be prompted on the screen with different color. The system will then select a roof patch model associated to this line and prompt the semantic information of that roof patch model on the screen.

Only two kinds of roof patch models shown in Fig.2 are assumed in this research. They represent the most encountered cases in Taiwan. Here we suppose that a roof patch is either quadrangular slope or flat plane in the object space. Note that one complete roof might consist of more than one roof patch. For example, a gable roof with one single ridge is composed of two slope roof patches. The selection of the roof patch model depends firstly on the building construction and secondly on the generalization by the operator. By assuming only these two simple models, the semantic information of 3-D linear segments becomes very simple: namely for slope roof patch either oblique or horizontal straight lines, for horizontal roof patch only horizontal lines. The semantic information of a line segment is composed of the height information of the two endpoints of a 3-D line segment and the average height of that segment.

Then, the operator verifies whether this semantic information is correct or not and whether this 3-D line represents the border of a roof patch or not. In case that this 3-D line is denied by the operator, the system will prompt the next one. Only if the initial guess of the roof patch model (the semantic information) is wrong, the operator can change it. Otherwise, the operator will confirm it and the system guides the operator to the next step. In the next step, the operator has to select relevant line segments associated to the initial 3-D line to form the roof patch. The selection is done mono-scopically by clicking the cursor onto the lines. Without losing the generality, we will assume that in the subsequent interactive procedure all the selection and confirmation are done in the left image of the stereo pair. Note that although the selection is done in one image, but the selected associated line segments could be labeled as 2-D or 3-D lines depending on the results from the previous stage of linking and matching in object space

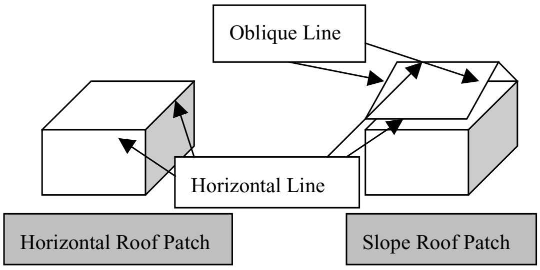


Fig.2. Plane Model for Roof Patch Reconstruction and Semantic Information of 3-D Line

Since no feature-extraction method can guarantee a complete extraction of linear features, the associated line segments are in general only piecewise and represent only fragments of roof edges. Sometimes there is even no line for selection at all. If the system finds out that the information aggregated up to now is still not enough for the reconstruction of that roof patch after the selection of the associated line segments, it will request the operator to position those corner(s) which is (are) necessary for the reconstruction of that roof patch. In subsequence we will call these corners the "lacking corners". The locating of these lacking corners is done mono-scopically in the left image by clicking the cursor on the corner position. The system then search in the Point Database of the left image to find a point which is probably a corner point at that location. If in the vicinity of the cursor position there is no point in the Database, the system simply takes the current cursor position as the corner point.

Depending on how many lines and lacking corners are selected and how much information is inhered in the lines and corners, different situations could arise. Fig.3 illustrates 8 possible cases after the selection of associated lines and positioning of the lacking corners. Assuming that for all cases the lower side edge (displayed in thick lines in Fig.3) is the initially confirmed 3-D edge segment of a roof patch. The associated lines selected by the operator are displayed as thin lines. The dotted lines mean missing lines (either there is no line at all for selection or can not be confirmed by the operator). An unmarked corner means it is determinable at least in 2-D image space by the system itself. A double circle represents the lacking corner.

The aim here is to obtain the 3-D coordinates of all four corners of the roof patch. But since there are so many different situations, there is no unique way to obtain them. In the following we will see that for each different case the solution is also different.

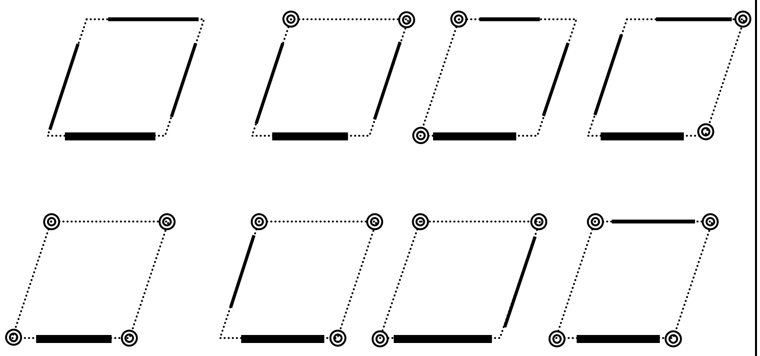


Fig.3. The Relation of Selected Lines, lacking Corner(s) within One Complete Roof Patch
Thick Line in Every Quadrangle: First Prompted 3-D Line
Thin Lines: Selected Lines
Double Circles: The Lacking Corners

The most ideal and simplest case would be the upper left one shown in Fig.3. In that case, for all four edges, some segments of the roof edges have been confirmed by the operator. If all segments are 3-D lines, 3-D coordinates of all corners can be calculated directly through intersection of two adjacent line segments pointing to the corner. For all other cases the 3-D coordinates of the corners have to be determined indirectly through information provided by the geometrical structure shown in Fig.3 and the semantic information associated with the selected lines and the roof patch model.

In the analytical Photogrammetry we know that a point in space can be determined in two ways. The first way is using stereo Photogrammetry by forward intersection of two rays from two stereo images. The second way is using the analytic of single image by knowing at least one of the space coordinates, usually the height Z, of that point. Both methods will be used here depending on the available information. If the height information could be derived through any way, we will use the second method. Otherwise we will use the first method. The requisite for using the first method is that the stereo correspondence of the corner in both the left and the right image must be known. Therefore after the associated lines and corners have been selected or positioned by the operator in the left image, the first question is whether the roof corners can be defined in the left image. The second question is how to find the stereo correspondences in the right image.

In principle, if two adjacent edges of a corner have been confirmed in the left image, that corner can be determined by the intersection of these two edges (unmarked corners in Fig.3). Moreover, if at least one of the two edges is a 3-D line segment, then 3-D coordinates of the corner can be directly calculated without the need to find its stereo correspondence in the right image. The calculation is based on simultaneous solving of Eq.1 and Eq.2, which will be explained later again. If none of the two intersecting lines is 3-D lines, then that corner is only determined in the left image. Its stereo correspondence needs to be determined in the right image.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \lambda \begin{bmatrix} a1 & b1 & c1 \\ a2 & b2 & c2 \\ a3 & b3 & c3 \end{bmatrix} \begin{bmatrix} x \\ y \\ -f \end{bmatrix} + \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} \qquad \text{Eq.(1)}$$

f : The Focal Length of Camera

X_s,Y_s,Z_s : The 3-D Coordinates of the Projection Center

X , Y, Z : The 3-D Coordinates of the Point in Object Space

a1,a2,a3,b1,b2,b3,c1,c2,c3: The 9 direction cosines consists of the 3 angular elements

λ : The Scale Factor

$$Y = aX + b \qquad \text{Eq.(2)}$$

X,Y: The Plane Coordinates of the Point in Object Space

a,b : Coefficient for Linear Equation in X-Y Plane

Only if one of the two adjacent edges to a corner is selected and the other one is missing (dotted lines in Fig.3), that corner must be a lacking one (double circle in Fig.3). Of course, if both edges to a corner are missing, that corner is also a lacking one. Due to the nature of the applied low-level feature extraction method [Förstner, 1994] and the simultaneous linking and matching of linear features in our system, lines and points are simultaneous extracted. The presence of lines is independent of the presence of points. That is even though a line is missing there could be still points existed at the lacking corner position. The points are stored in the Point Database. Therefore, even though no line is available we still can go into the Point Database and look for points which might be roof corners.

For each lacking corner, the system will try to assign a point from the Point Database to that corner. If the operator is not satisfied with the assignment, he can deny it. The system will assign another one. If there is no one available in the Database, the current cursor position will be used directly as the corner. In Fig.3 all corners, which can not be determined by the system itself, are marked as lacking corners

After all the corners have been determined in the left image, the system now examines the corners one by one to see if the 3-D object coordinates of them could be solved from the information obtained so far. For example, all corners related to the bottom edge in Fig.3 are solvable because the bottom edge is a 3-D line. Since the corner is requested to locate on that line, the condition provides a height constraint. Therefore according to the second method mentioned above, the 3-D object coordinates can be solved. Since the 3-D line segment might be only a portion of the entire roof edge and the corner might not locate directly on the line, no direct height of the corner is used in solving the problem. Instead, we will solve the 3-D coordinates of that corner by an indirect way. Two equations, Eq.1 and 2, are used for solving the coordinates. Equation 1 states that all known pixels of the 3-D line segments together with the corner pixel must satisfy the basic linearity equation. The difference is that for pixels of the 3-D line segment all 3 object coordinates X, Y, Z are known, for the corner pixel its object coordinates are unknowns waiting to be solved. Equation 2 describes the projection of this 3-D line on the X-Y plane of the object coordinate system. It says that the projection of the 3-D line on the X-Y plane must be a straight line and the projection of the corner pixel must also on this straight line. For each pixel including the corner pixel, one pair of Eq.1 and 2 can be listed. No matter how many pixels are included for the computation there are always five unknowns, the two parameters a and b in Eq.2 and the X, Y, Z coordinates of the corner pixel. Theoretically two pixels of the 3-D line and one corner pixel will give 6 equations which are enough for solving the unknowns. But in general we have a lot more and the least squares adjustment must be applied. We can see that any corner located on a 3-D line can be solved for it object coordinates in this way. But for all other cases the stereo correspondence in the right image must be found first and the space forward intersection is used to calculate the 3-D coordinates of the corner.

For the search of stereo correspondences in the right image the Point Database of the right image will be used. The search for correspondence shall of course take place along the epipolar direction on the right image. But the question is how to define the search range. Although there is no direct height information of the corner available, but from the semantic information of the roof patch model and the semantic information of the initial 3-D line segment, we can estimate the possible maximum and minimum height of that corner. This height range can be transformed into parallax range along the epipolar line.

If there are more than one point in this range, the one which is nearest to a horizontal line in the object space will be chosen as the correct one and displayed on the screen for confirmation. The finding of the horizontal line will be explained in the next section. If no corresponding point can be found in the Point Database, that corner will be declared as a failure one. This can happen very often for the urban area due to occlusions

After getting the 3-D coordinates of at least three corners, the roof patch can be inferred from the object knowledge of the roof patch model. That is the form of roof patch in the X-Y plane should be parallelism when only 3 corners are available. The height of the missing corner can be deduced according to the semantic information verified by the operator at the beginning of processing.

After the reconstruction is finished, there is still the possibility for the operator to modify it interactively. The operator could modify the roof corners by choosing the optimal corner equivalent from one of the three different types of points in the Point Database or he can simply choose to modify the corner manually.

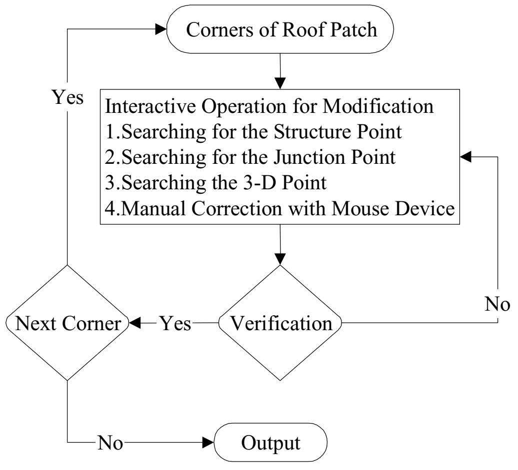


Fig.4. Diagram of Interactive Modification for Roof Corners

From the above descriptions we can see that the advantage of the interactive approach in our system is that the operator can control and modify the result at any time and in any processing step using his high capability of interpretation. Yet the operator needs not to “plot” any thing very accurately.

In case that the modified result is still not acceptable to the operator, there is the last possibility for the operator to reconstruct the roof patch manually, i.e. to “plot” individual corner points by dragging mouse cursor. The diagram of interactive approach for the modification of the corners is illustrated in Fig.4. The workflow in Fig.4 is not only used in the final stage but also used in all stages through out the whole reconstruction process.

3 POINT DATABASE AND POSITION OF CORNERS IN IMAGE SPACE

The Point Database consists of three different types of points. They are the extracted junction points, the intersection points of linear segments (structure points) and the 3-D points. Among them only 3-D points have known 3-D coordinates in object space. A 3-D point is obtained by matching of the extracted 2-D lines in the early stage of finding “meaningful” lines. Their location in the left and the right images are obtained by back projection of the object point into the image space. There are two Point Databases in our system: one for left image and the other for the right image.

There are two major motivations for construction the Point Database. One motivation is that the roof corner usually appears as point feature in image. It will be easier for us to search and locate the corners if there is a database of points. The other reason is that not only point type but also other useful information can be transferred and embodied in this database. For example, the relation of a point to adjacent lines can be included in this database. If some attributes of the points can be obtained and stored in the database, e.g. structure points from the intersection of L type lines or from the T type lines etc, to the search will be more effectively.

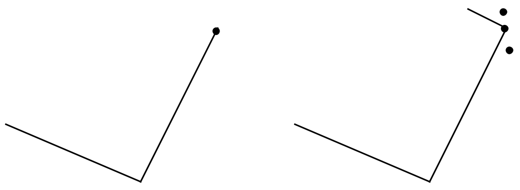

Locked Point on the Line Locked Points nearby the Line

Fig.5. The Illustration of Positioned Location

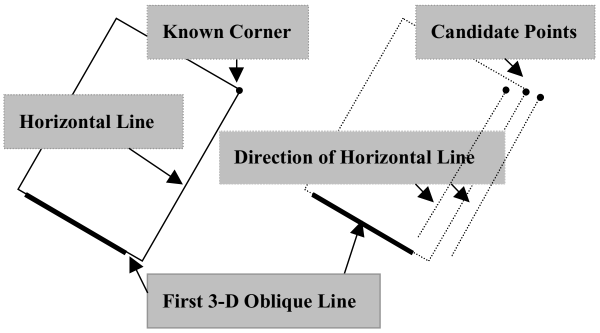
Left : Locked Point is the Positioned Position

Right: Location with the shortest distance to the Line is the positioned Location

Our interactive system will employ this Point Database in three processing stages. The first application of this database is to locate the lacking corners of quadrangular roof patch in single images. After the operator drags the cursor to point to those corners, the system will automatically try to lock a point of the type of the structure point or the type of the extracted junction point within certain range from the current cursor position. If more than one points are available, the system will choose the one which is nearest to the interactively selected 2-D line on the condition that the corner must locate along the direction of that line. If the point is just on this selected line, then it is locked by the system. If no point is exactly on this 2-D selected line, then the system will find the one with the shortest distance to this 2-D line as the locked point. Fig. 5

illustrates these two situations.

Suppose that several points are on the 2-D line, a structure point is preferable than a junction point. Of course, the automatically locked corners might not be accepted by the operator. In that case, it can be unlocked by pressing one key.



Roof Patch in the Left Image **Roof Patch in the Right Image**

Fig.6. Diagram of Searching for the Corresponding Corner

When the roof patch has been formed in the left image, the Point Database of the right image is then used to find the stereo correspondence of the corners defined in the left image. As mentioned in the previous section, when the system can't obtain the 3-D coordinates of the corners from the information supplied by interactive selection and confirmation of lines and corners in the left image alone, it must search for the corresponding corner points in the right image in order to be able to use the forward intersection to calculate the object coordinates. Since we have confirmed the roof patch in the left image and the stereo images are normalized images [Cho and Shenk, 1992], it is easily to determine the search range in the right image based on the epipolar geometry. Possible correspondences can be collected along the epipolar line.

Under our model assumption in Fig.2, at least one of the two adjacent edges of a corner must be horizontal in the object space. Based on the semantic information of the initial 3-D linear segment at least which one of these two edges must be a horizontal one can be determined. The direction of horizontal line from this corner to the neighboring corner is then determined. Since the direction of the corresponding horizontal line in the right image must be parallel to its stereo mate in the left image, its direction in the right image is also known. But the location of that line is of course still not known. If several candidate points near the endpoint of this horizontal line are available for a corner (cf. Fig.6), we have to determine which one shall be chosen. The decision is made on the condition whether a line parallel to that horizontal can be drawn from that point. Thus, from each candidate we can draw a line parallel to that direction. For each pixel along the line the gradient change across this line can be calculated. The line with the maximum gradient change has the greatest probability to be an edge. Therefore the point related to this line will be chosen as the corresponding corner.

Point Database could also employed in the third case of interactive modification of the roof patch corners after a roof patch is reconstructed but the operator is not satisfied with the result. The operator drags the cursor near the corner which should be modified. By pressing a special key, the system will try to modify this corner by changing the corresponding point, similar to the procedure of finding the corresponding corner (cf. Fig.4). The operator examines interactively each result and decides whether the change is acceptable or not.

4 EXPERIMENTS AND RESULTS

Fig. 7 and Fig.8 illustrates the test stereo images and the results of the tests before and after the final interactive modification. The images cover an urban area very typical in Taiwan. They are scanned with 25 μm resolution. The original photos were taken by the normal angle camera with 60% overlap and their image scale is about 1: 6,000. Table 1 lists the difference between the result from our system and the reference data measured carefully by an experienced operator on the Leica-Helava SOCET SET workstation. The number of complete roof patches without occlusion in these test stereo images is 21. 13 of them have been reconstructed by our system. Because of the failure of linear feature extraction due to weak contrast, five roof patches were unable to be reconstructed by our system. We compare our results to the reference on the location, the orientation and the dimension of the roof patches. From Table 1we can see that no matter whether the reconstructed results are interactively modified by the operator or not in the final stage, the difference of plane position are less than 0.5m(3.3 pixels). Additionally, the difference of height is almost also below 0.5m except at one location which is 0.60m(4 pixels). Although it shows the 3.3 pixels in position difference and 4 pixels in height difference respectively, however, the differences could be negligible for the 3-D applications. As for the difference of orientation of roof patch, most of them are less than 6 degrees. Only three patches are larger. The last two columns show the difference of areas. No matter if the area could be a judging factor, we can see that the average percentage of the difference in areas is below 10 %.

We believe that the accuracy of the result is more than enough for some applications like city planning, telecommunication and so on. Although it is hard to see the fine differences after interactive modification in the final stage from this test, we still believe that the interactive approach will give better results to some extend.

5 CONCLUSIONS

This paper presented an interactive system for roof patch reconstruction based on 3-D linear segments by integration of the interpretation ability of the operator. The reconstruction results are very promising. Our paper also introduces and discusses the concept of Point Database and the concept of the interactive approach. From the results of our tests, we believe that this system is highly practical.

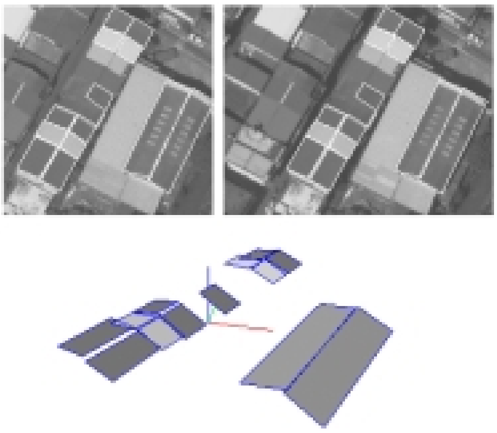


Fig.7 The results without interactive modification

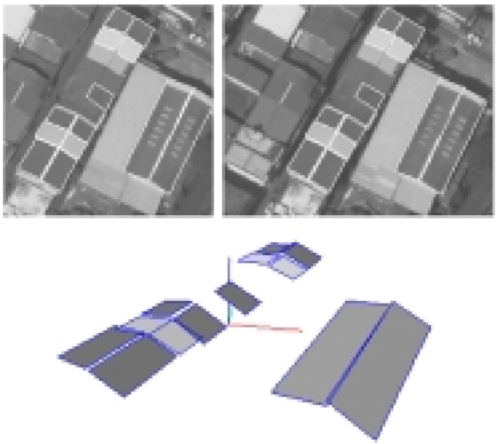


Fig.8 The results after interactive modification

TABLE 1: DIFFERENCE OF THE RECONSTRUCTED RESULTS AND THE REFERENCE DATA										
	Original results	Modified results	Original results	Modified results	Original results	Modified results	Original results	Modified results	Original results	Modified results
NO.	Difference of Plane Position (m)		Difference of Height (m)		Difference of Plane Orientation (°)		Difference of Areas (m^2)		Percentage of Area Difference (%)	
1	0.34	0.36	0.22	0.27	2.85	10.48	-0.40	-1.51	1.65	6.23
2	0.39	0.39	-0.17	-0.17	1.09	1.09	0.91	0.91	3.90	3.90
3	0.42	0.38	0.06	0.36	12.43	5.85	-2.23	-3.59	4.61	7.42
4	0.11	0.14	0.00	0.09	3.88	2.83	0.74	0.64	2.93	2.54
5	0.10	0.11	0.34	0.29	5.86	3.97	2.77	-2.00	5.44	3.93
6	0.27	0.26	0.06	0.20	2.65	5.39	1.13	1.93	4.37	7.45
7	0.19	0.18	-0.28	-0.38	1.24	0.70	-1.17	-2.27	4.63	8.96
8	0.36	0.36	-0.30	-0.48	5.79	1.83	-1.12	-1.48	4.82	6.36
9	0.24	0.16	-0.39	-0.22	6.04	4.19	1.31	-0.35	4.97	1.32
10	0.38	0.44	-0.33	-0.27	3.65	5.37	0.78	-1.69	0.53	1.14
11	0.35	0.35	-0.46	-0.46	1.67	1.67	1.60	1.60	5.92	5.92
12	0.22	0.22	0.33	0.33	0.89	0.89	-1.19	-1.19	5.06	5.06
13	0.23	0.35	-0.19	-0.60	1.73	5.88	4.47	9.82	3.01	6.62

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