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Building DSMs Generation Integrating Three Line Scanner (TLS) and LiDAR

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Abstract : Photogrammetry is a current method of GIS data acquisition. However, as a matter of fact, a large manpower and expenditure for making detailed 3D spatial information is required especially in urban areas where various buildings exist. There are no photogrammetric systems which can automate a process of spatial information acquisition completely. On the other hand, LiDAR has high potential of automating 3D spatial data acquisition because it can directly measure 3D coordinates of objects, but it is rather difficult to recognize the object with only LiDAR data, for its low resolution at this moment.

With this background, we believe that it is very advantageous to integrate LiDAR data and stereo CCD images for more efficient and automated acquisition of the 3D spatial data with higher resolution. In this research, the automatic urban object recognition methodology was proposed by integrating ultra high-resolution stereo images and LiDAR data. Moreover, a method to enable more reliable and detailed stereo matching method for CCD images was examined by using LiDAR data as an initial 3D data to determine the search range and to detect possibility of occlusions. Finally, intellectual DSMs, which were identified urban features with high resolution, were generated with high speed processing.

Key Words : 3D urban model construction, Data fusion, Three Line Sensor, LiDAR, Stereo matching, Image segmentation, Ultra high-resolution image.

1. Introduction

1) Background

Recently, in GIS field, vigorous demand for detailed simulations and analyses, especially, in urban areas are observed. Examples are a propagation analysis of electric wave for wireless communication, a flood analysis, an analysis of wind caused with high-rise building and landscape simulation. 3D spatial urban data faithful to the real world is needed for such simulations.

Now, we have two main techniques to reconstruct 3D spatial urban data. The first of them is photogrammetry, and another is using LiDAR. Photogrammetry is a current method of the 3D spatial data acquisition. Various features such as urban objects can be extracted from image due to high resolution. However, as a matter of fact, a large manpower and expenditure for making detailed 3D spatial information is required especially in urban areas where various buildings exist. There are no photogrammetric systems which can automate a process

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of spatial information acquisition completely. On the other hand, LiDAR has high potential of automating 3D spatial data acquisition because it can directly measure 3D coordinate of objects, though the resolution is so limited at this moment.

2) Three Line Scanner (TLS)

STARIMAGER / Three Line Scanner (TLS) is an optical passive sensor for aerial survey. TLS is composed of three linear CCD arranged in parallel, and it can acquire three images of each direction (forward, nadir and backward) at the same time. Orienting it on an aircraft perpendicularly to flight direction, and scanning a ground plane, a treble stereo image of a ground object can be acquired (See, Fig. 1). As a result, occlusion area can be extremely reduced. Using two images of the three, it is also possible to get 3D coordinates by stereo matching. As one of advantages of a linear CCD sensor, more pixels can be arranged in a single scene compared with an area CCD sensor. This means that a linear CCD sensor can achieve a resolution comparable with that of an air photo. Though a linear CCD sensor can acquire data only by one line at a time (The ground resolution of TLS data in this research is 3 cm approximately). However, time of acquiring each line image is different. Since position and direction of each line when acquiring image is also different, orientation cannot be done by an existing method of photogrammetry. Moreover, the image is greatly influenced by fluctuation of an airplane position and attitude because TLS is air-borne. But setting up a stabilizer between an airplane and TLS, the fluctuation's influences can be reduced.

3) LiDAR

LiDAR is an optical active sensor, which irradiates laser to an object and measure a distance to the object by measuring returning-time as the laser reflects. If the position of sensor and the angle of irradiating laser beam are known, 3D coordinates of a place, where laser hits, can be acquired easily. And, an automation of measurement with LiDAR is simply processed too, because 3D coordinates of a measurement point can be acquired directly. However, it is difficult to know what the object is, because LiDAR data provides only information about object's coordinates and reflection strength. And, in general, by the restriction of LiDAR output, a ground resolution of airborne LiDAR is 2 m. It is not high resolution to make use of the laser data as 3D urban data. To extract a building in a urban area from LiDAR data, auxiliary data is required.

4) Objective

We believe that it is very advantageous to integrate LiDAR data and stereo CCD images for more efficient and automated acquisition of the 3D spatial data with higher resolution (Masafumi *et al.*, 2003; Yoshiaki,

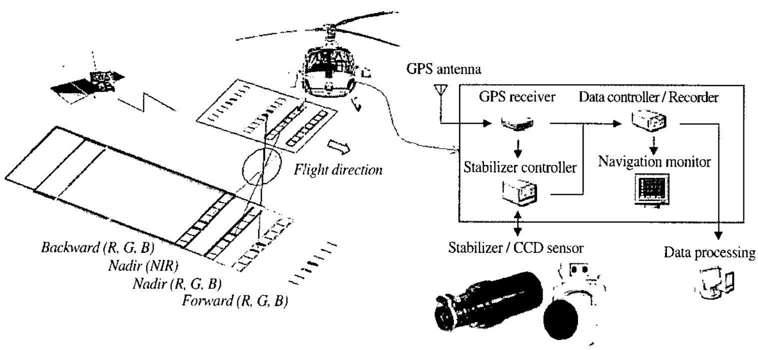

Fig. 1. Method of TLS data acquisition.

2001). LiDAR can measure coordinate values of an object directly, but it is rather difficult to recognize the object with only LiDAR data, due to its low resolution. On the other hand, CCD image represent detailed texture information on the object's surface and has potential of detailed 3D data generation as long as careful manual operation is applied. In this research, by using LiDAR data as an initial 3D data to determine the search range and to detect possibility of occlusions, a method to enable more reliable and detailed stereo matching method for CCD images is examined.

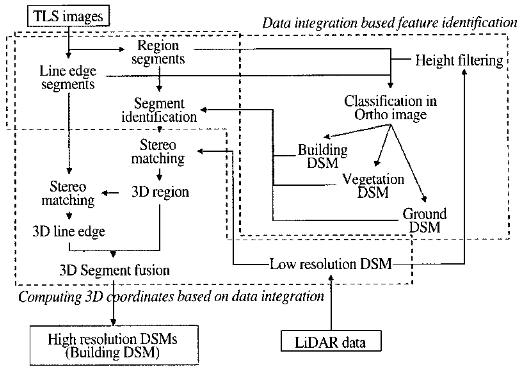

Fig. 2. The outline of our approach.

2. Methodology of Integrating TLS Image and LiDAR Data

It is easy to acquire 3D coordinate values of an object by corresponding features in stereo images in photogrammetric approach (Gruen *et al.*, 2001; George *et al.*, 2000). However, it is very difficult to acquire 3D coordinate values of the object in urban dense area due to some problems such as occlusion. Moreover, even if ultra high resolution stereo images are prepared to extract some information, it is also very difficult to detect building features from images. Therefore, in this research, we propose data fusion based building modeling approach, which is integrated ultra high resolution stereo images and LiDAR data, to solve these problems. The data fusion based building modeling is conducted with the following approach (See Fig. 2). This processing consists of 'Data integration based feature identification section' and 'Computing 3D coordinates based on data integration section'. First of all, TLS images are input as ultra high-resolution images, and LiDAR data are input as a low resolution DSM. In the first section (Data integration based feature identification), TLS images are segmented into regions, line-edges. And, LiDAR data are by a height filter algorithm to divide higher areas and lower areas. These segments are classified into building DSM, vegetation DSM and ground DSM. In this research, only building DSM is used to generate 3D building models. In the second section (Computing 3D coordinates based on data integration), 3D segments are generated through an image matching processing using the nadir image and a forward image or a backward image. A high-speed processing algorithm, which is integrated ultra high-resolution images and LiDAR data, is applied in the image matching algorithm in this step. And more, 3D segments are generated through a course to fine approach. Firstly, 3D region segments are generated to obtain approximate 3D building objects. Then, the approximate 3D objects are refined using 3D line segments. Finally, 3D segments are clustered to acquire a high resolution DSM in a 3D segment fusion processing. Details of each processing section are described in the following sections.

1) Data Integration Based Feature Identification

It is possible to presume that regions, which exist on higher level, are buildings or trees by use of LiDAR data as height information. And it is also possible to presume that regions, which exist on lower level, are ground surfaces. Moreover, buildings and trees can be classified by an edge classification in TLS images, because not only building edges but also branches and leaves of trees can be seen in ultra high resolution images. Therefore, the following assumptions can be applied to detect buildings in images.

- Building roofs and tops of trees exist in higher position than surrounded ground surface.
- Building's edges are long straight line.
- When a roof's color is uniform, building roof can be represented as a region segment.
- A region segment has similar information in stereo images.
- A straight line segment has similar information in stereo images.
- Feature points of a building exist on corners and edges of building.

Here, based on these assumptions, buildings, trees and ground surfaces are classified by integration of TLS nadir image and LiDAR data as shown Fig. 3.

(1) Segmentation

As a preprocessing for feature identification, three image segmentation algorithms are applied to LiDAR data and TLS nadir image as follows.

- Region segmentation on LiDAR data by using normal vectors
- Region glowing on TLS nadir image
- Canny based line edge extraction on TLS nadir image

Region segments are extracted from LiDAR data to classify buildings or trees and ground surfaces. If a terrain is flat, these features can be detected by a simple slicing in a horizontal plane of a certain height. However, if the terrain is not flat, buildings or trees and ground surfaces can not be detected by the simple slicing, because they may exist in same horizontal level. Here, vertical surfaces are detected as breaklines in height direction by calculation of a normal vector of each grid in DSMs. After that buildings or trees and ground surfaces are separated. Region segments in nadir image are extracted to generate approximate 3D positions of features. Here, region glowing algorithm is applied to a filtered nadir image from which high frequency noises are removed by using median filtering algorithm. As a result, region features are extracted approximately. Line edge segments are extracted for building or trees extraction and a fine matching processing. Here, straight lines are extracted after an edge extraction. In the edge extraction, essential edges can be extracted from an image with the canny filter, even if the image has shadow area. Moreover, a line extraction is achieved by applying the line tracking algorithm with a template of 3×3 pixels. As a result, line segments that its lengths are labeled are generated.

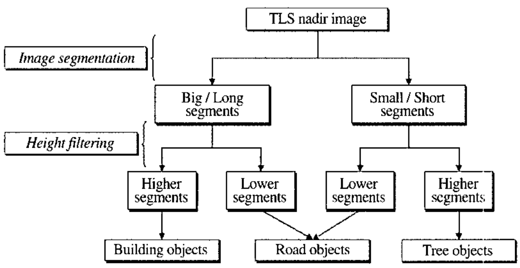

Fig. 3. Feature identification.

(2) Feature Extraction

Features are extracted from images by integrating segments, which are generated in the previous processing. Firstly, buildings / trees and ground surfaces are separated by using region segments in LiDAR data. A region segmentation based integration of height information in LiDAR data and breaklines, which are generated in the normal vector processing, separates them approximately. Next, these approximate features are projected into region segments in nadir image. There are some gaps between projected segments and segments in the nadir image in point level, because LiDAR data is lower resolution than TLS images. However, corresponded region segments are overlapped approximately though they don't exist same position

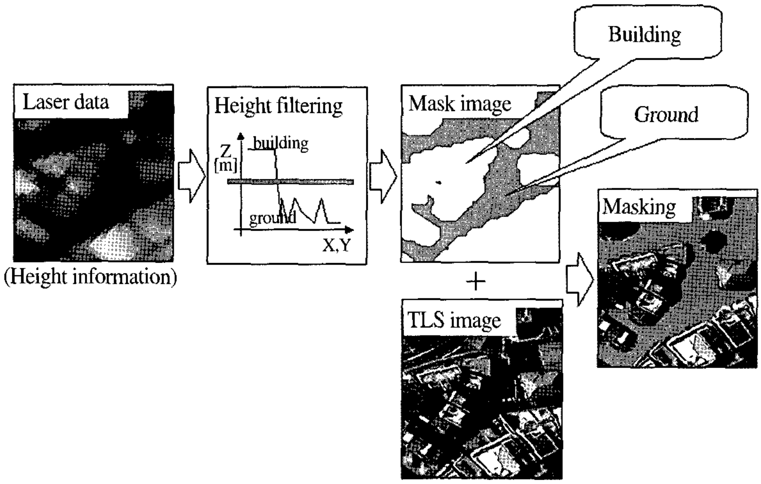

Fig. 4. Ground surface removal.

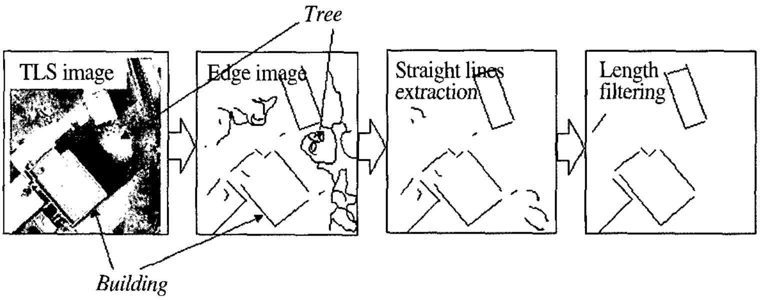

Fig. 5. Tree removal.

accurately. Here, results of the feature classification are applied to each region segment in nadir image by regional correspondence between region segments in the nadir image and features in LiDAR data approximately. After that, each region segment can be flagged as buildings / trees or ground surfaces. As a result, ground surface features are extracted from region segments in the nadir image in this step. Then, after removing ground surfaces from nadir image, buildings and trees are separated by using edge segments in the nadir image. TLS has so ultra high spatial resolution that branches and leaves of trees can be seen. So, trees can be defined as an object that composed by short lines, and also buildings can be defined as an object that composed by long lines. Therefore, building features can be detected by extracting long lines from the nadir image. Here, buildings and trees are separated by classification of the edge length. Based on these processing, identified features including buildings, trees and ground surfaces are extracted.

2) Computing 3D Coordinates Based on Data Integration

Epipolar line makes a range of a search in image matching processing reduced, because two-dimensional search can be changed to one-dimensional search. In the case of an area sensor, the epipolar line is generated as a straight line by a calculation using both ends of ray vectors in a matching range. However, in the case of a line sensor, it is necessary to calculate ray vectors line by line (scan by scan) to generate the epipolar line artificially. As a matter of course, this pseudo epipolar line is winding, and a curvature of this line depends on a flight trajectory of sensor. But, in the case of TLS, almost non-distorted images can be obtained due to mounted stabilizer. Therefore, it is possible to process this pseudo epipolar line as an approximate straight line, if the range of the search is short. In this paper, segments obtained through the image segmentation algorithm are used for matching-templates in the computing 3D coordinates methodology. An identity frequency of region segments and overlapped ratio of edges in stereo images are used for parameters of matching processing. Correlation coefficient values are calculated by some functions corresponding to each segment, and a matching point is taken from a peak of these correlation coefficient values. As a result, prepared region segments and line edge segments are corresponded in stereo images (See, Fig. 6). And more, TLS images are triplet images. Hence, two matching results can be acquired by stereo matching using a combination of the nadir image and the forward image and that of the nadir image and the backward image, separately. And then, higher correlation coefficient value can be selected as a reliable result. Therefore, accurate 3D measurement with an occlusion evasion can be conducted. Though this matching algorithm is more reliable than existing stereo matching algorithm using aerial photos, there are some mismatched results and it takes a lot of time for the processing in many cases. As a solution of these problems, we propose the high speed and reliable stereo matching algorithm by stereo matching with LiDAR data as an initial 3D model. Here, the algorithm provides two kinds of benefits such as 'Narrowing down search range in stereo matching' and 'Automatic anticipation of occlusion', as described in the section of 'High speed and high accurate stereo matching'.

(1) Region Matching

Region matching is conducted to extract outlines of building objects. After a selection of a region on the nadir image, the region is cut out as a template with

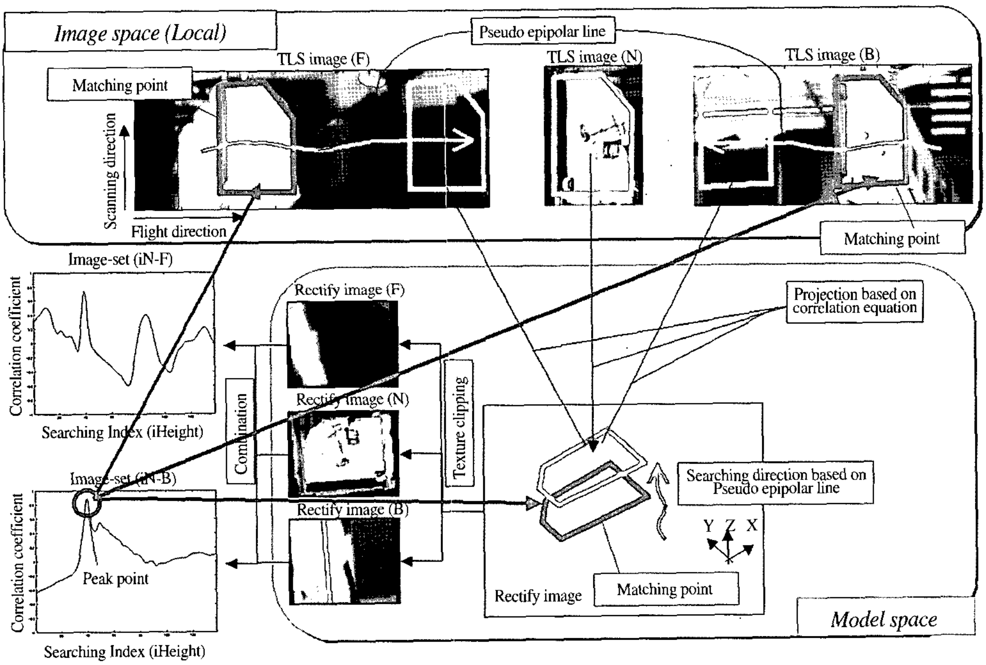

Fig. 6. Outline of stereo matching.

region information such as a texture. Then, the template is projected in the forward / backward image, and corresponded region is searched along the epipolar line. Following definitions are applied in the region matching, and regions are corresponded each other with two steps; 'Region matching based on feature's shapes and sizes' and 'Region matching based on the area correlation algorithm'.

- Shapes and sizes of features are resembled.
- Feature's color is resembled.

The region matching based on feature's shapes and sizes is applied to detect corresponded features roughly as the first step. At first, all features on the epipolar line are taken from the forward / backward image. Next, R-value, which is a reference value of each feature in the region matching, is calculated by eq.1. Then, R vector is generated as a result. Finally, an approximate matching point is taken from a peak of the R vector.

$$R = (N / Nt) * (N / Nf) \qquad \text{(eq.1)}$$

where N = pixel number of overlapped area
Nt = pixel number of a template
Nf = pixel number of a corresponding feature

The region matching based on the area correlation algorithm is applied to obtain approximate 3D coordinate values of region as the second step. As a consequence, corresponded region feature is selected exactly. At this time, the range of the search can be narrowed using the obtained result in the first step as an initial value. Finally, 3D region is generated with stereo matching. The height information obtained here becomes an initial value in the next stage (Line edge matching). Moreover, using the LiDAR data, rough corresponding features can be done instead of the first step, because the LiDAR data can be used as an initial height value for the region matching. Therefore, substantially, region matching becomes one step only of the use of the area correlation method in the region matching processing.

(2) Line Edge Matching

In this stage, straight edge matching is done for breakline extraction of building objects. Straight edges around a region segment in the nadir image are selected, and the edges are projected into the forward / backward image. Also, a corresponding straight edge is searched on the epipolar line. Moreover, edges are corresponded with similar information of edges as clues in the matching. The clues are a direction of the edge, a length of the edge and the average intensity on both sides of edge. However, the matching parameters are changed according to the direction of edge segments in images when TLS images are used. For instance, if a vector of an edge segment is parallel to the CCD scan direction approximately, only edge geometries are referred to correspond features. And if a vector of an edge segment is parallel to the flight direction approximately, the matching function refers not only edge geometries but also intensities on both sides of the edge (See, Fig. 7). Finally, 3D lines are generated with stereo matching.

(3) High Speed and High Accurate Stereo Matching

Though the previous matching algorithm can do 3D measurement of features, there are some mismatching and it takes a lot of time for the processing in many cases. As a solution to it, we propose the high speed and high accurate stereo matching algorithm by stereo matching with LiDAR data as an initial 3D model. Here, the algorithm provides two kinds of benefits as follows.

1) Narrowing down search range in stereo matching: In stereo matching, the range of the search for feature point is relatively very wide, because there is no information on approximate height of features such as buildings. But, using LiDAR data, there are good estimates of height, which allow us to narrow down the range of the search (See, Fig. 8). At first, after calculation of a ray vector from feature point in the nadir image, an intersection between LiDAR data and the ray vector is

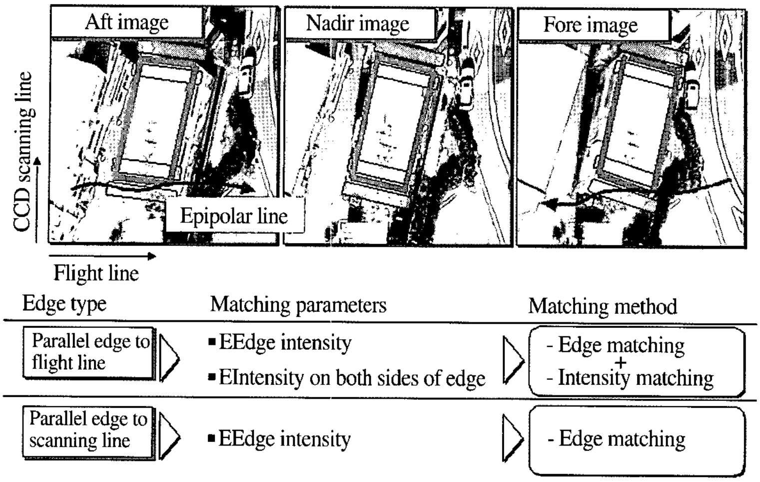

Fig. 7. Parameters for line edge matching.

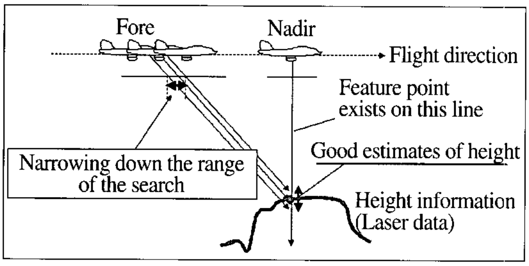

Fig. 8. Narrowing down search range in stereo matching.

detected. With this result, a height value can be calculated approximately. Next, a matching point is searched along a vector of a vertical direction, because an accuracy of LiDAR data is not high. This search also means an image matching processing in a forward image or a backward image. However, the searching range in stereo matching with LiDAR data can be narrower than that in stereo matching without LiDAR data, drastically.

2) Automatic anticipation of occlusion: In TLS image, if a feature point cannot be seen from one direction (e.g. in a forward image), the same feature point may be likely seen from the opposite direction (in a backward image). If occlusions are anticipated, appropriate image pairs (in this case, nadir image and backward image) can be selected. For anticipating the occlusion, the LiDAR data are used as the height information (See, Fig. 9). Firstly, a

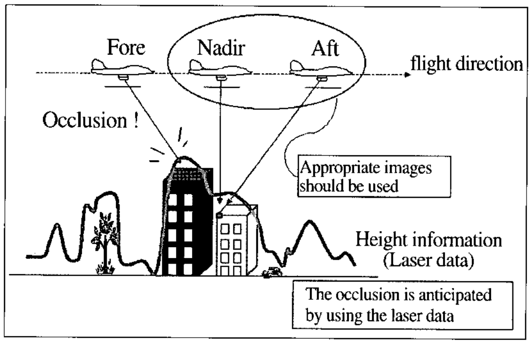

Fig. 9. Anticipating of occlusion.

3D feature point, which is calculated by a combination of a feature point in the nadir image and height value in LiDAR data, is back projected into the forward image or the backward image. In this time, a presence of an intersection of a ray vector of the back projection and LiDAR data as an initial 3D model is checked. If the intersection doesn't exist along the ray vector, an occlusion doesn't exist in a model space and an image. On the other hand, if the intersection exists along that, the occlusion exists. Moreover, if the occlusion exists in the forward image and the backward image, the feature should have a flag that cannot be measured. With these methods, and it is possible to decrease mismatching and processing-time drastically.

3. Experiment

The following experiments are done. As a result, how using the laser data is effective is considered.

1) *Building extraction using DSMs and TLS images*: An extraction rate is evaluated by comparing with existing GIS data.

2) *Evaluate performance of matching*: The processing with LiDAR data and the processing without LiDAR data are done respectively. A matching accuracy is evaluated by comparing processed data and existing GIS data. In case of the processing without LiDAR data, region segments, which are selected by manual in the nadir image, are used.

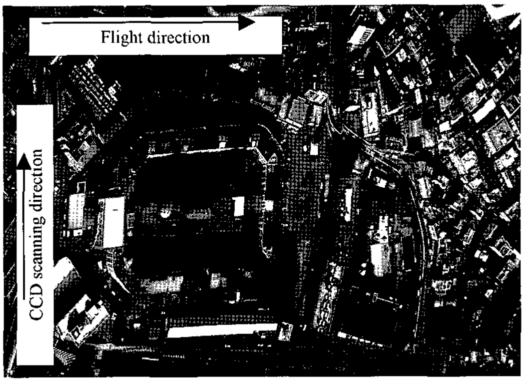

Fig. 10. TLS image (Fore).

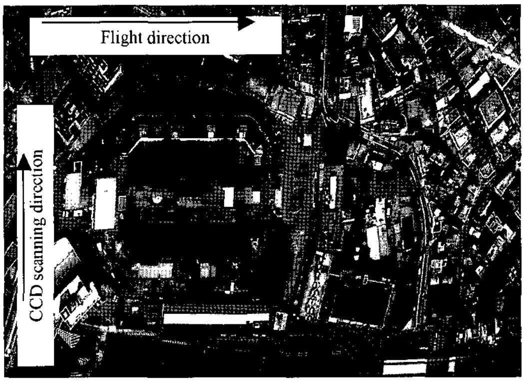

Fig. 11. TLS image (Nadir).

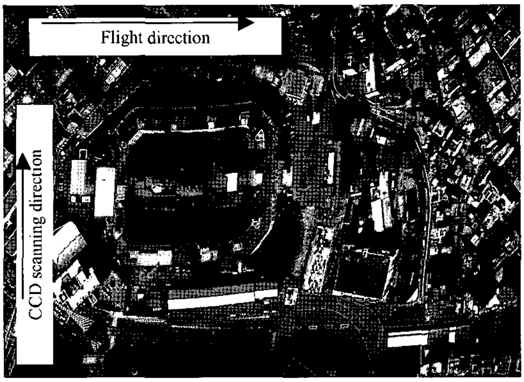

Fig. 12. TLS images (Backward).

1) Study Area

The study area is Tokyo in Japan. Buildings with various shapes exist in this area. If buildings are classified by sizes, there are various building such as houses and multistory buildings. If buildings are classified by roof's shapes, there are various building such as gable roofs and flat roofs. Besides there are roads, trees and parking lots, etc. The terrain of this area is full of ups and downs.

2) Data

1) *TLS images*: TLS images used in this experiment are shown in Fig. 10, 11 and 12. The original spatial resolution is 3cm approximately. The images are reduced to half resolution for a performance of a processing in this research. 2) *DSMs*: The spatial resolution is 2m in consideration of a general resolution in Tokyo area. The data are simulation data, which are generated from airborne LiDAR data with 50cm spatial resolution.

4. Result of Experiment

1) Building Extraction

The following Figures show clips of original image and results in the segmentation processing. Fig. 14 is a clip image of an original nadir image. This image consists of buildings, trees and roads. Fig. 15 shows region segments obtained through the region growing processing. This result shows that buildings and ground

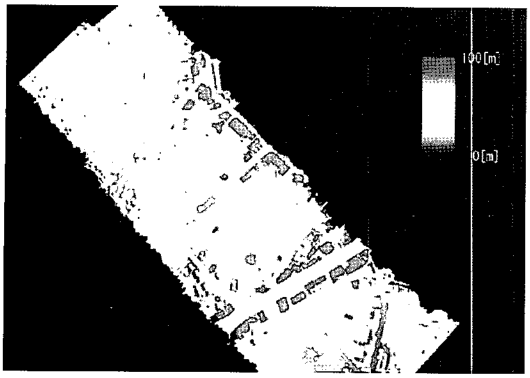

Fig. 13. LiDAR data.

surfaces are extracted as big segments, and trees are extracted as small segments. And, Fig. 17 shows line edge segments extracted from edge image in Fig. 16. Fig. 16 and Fig. 17 show that tree segments are deleted through the line extraction processing. Figures 18 to 21 show results of building extraction processing. Overlapped area of TLS images and DSM are shown as yellow or red frames in each Figure. Fig. 20 shows segmented ortho image overlaid the result of the ground surface removal processing shown in Fig. 19. Though some building segments are not extracted due to low roofs, these Figures show that ground surfaces are deleted from TLS image effectively. Fig. 21 shows an overall result in the building extraction processing. The result is overlaid with an existing 2D map for a clear evaluation of building extraction. Filled polygons show extracted area successfully. The success rate of the buildings extraction by the integration of DSMs and TLS images is 84 % [125/149].

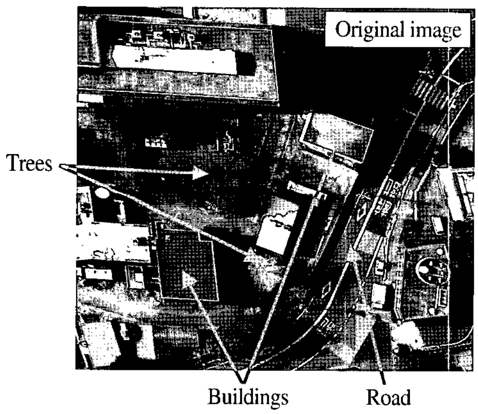

Fig. 14. Original image.

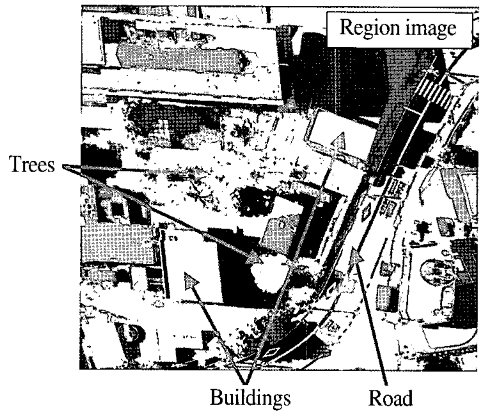

Fig. 15. Region image.

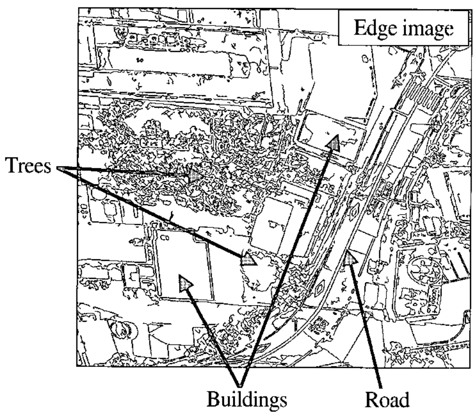

Fig. 16. Edge image.

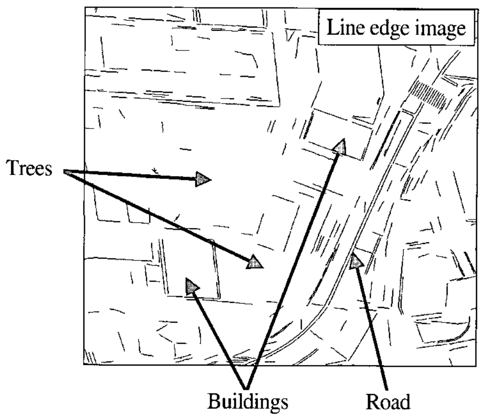

Fig. 17. Line edge image.

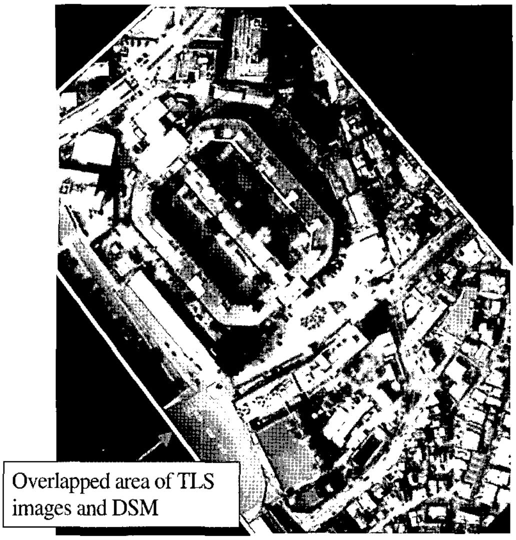

Fig. 18. Ortho image.

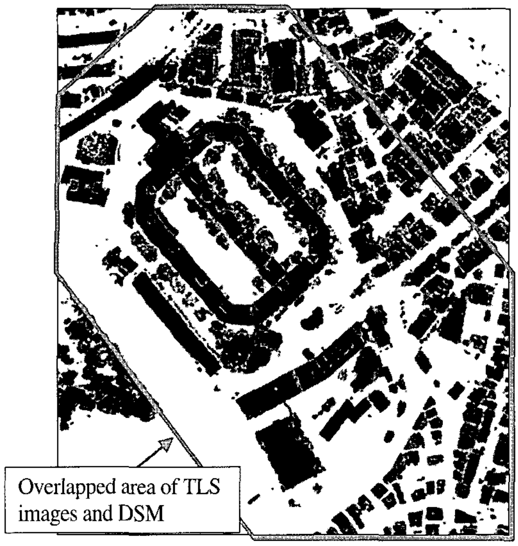

Fig. 19. Result of ground surface deletion.

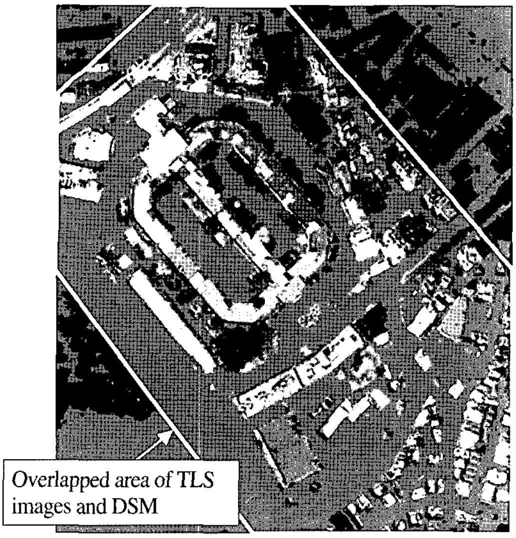

Fig. 20. Segmented Ortho image with road mask.

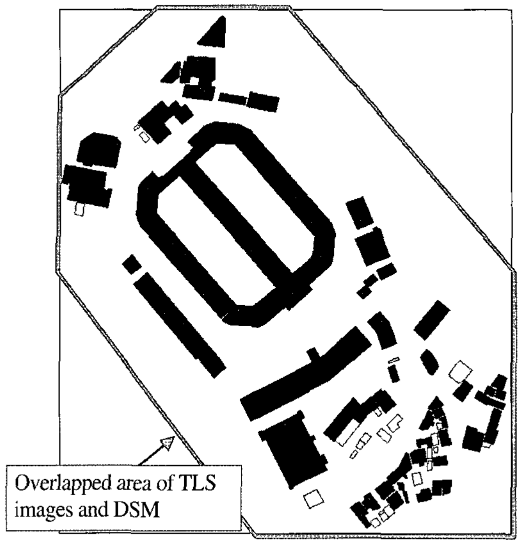

Fig. 21. Evaluation of building extraction.

2) Building DSM Generation

Results of building DSM generation are shown as follows. Errors of these results are recovered by semi-manual building extraction operation (Katsuyuki *et al.*, 2002) for a representation. Fig. 22 shows a surface model, which are height information with nadir image coordinates values. Though this model supports only horizontal roof faces, buildings are identified in this model. Fig. 22 shows a textured building DSM with nadir image (A resolution of this result is reduced to less than half, due to a limitation of video memory).

3) Accuracy of Matching

The matching result is evaluated by measurement of height value gaps (vertical distances in the object space) of features. Fig. 24 shows the accuracy of matching

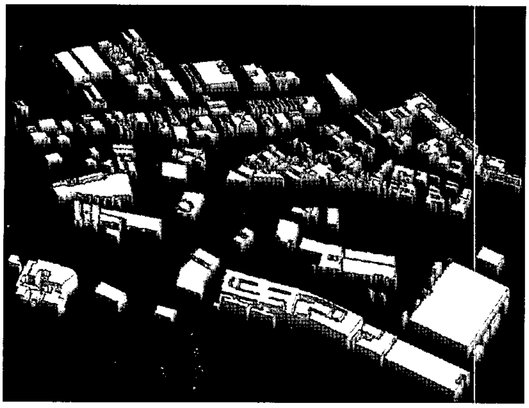

Fig. 22. Generated building DSM.

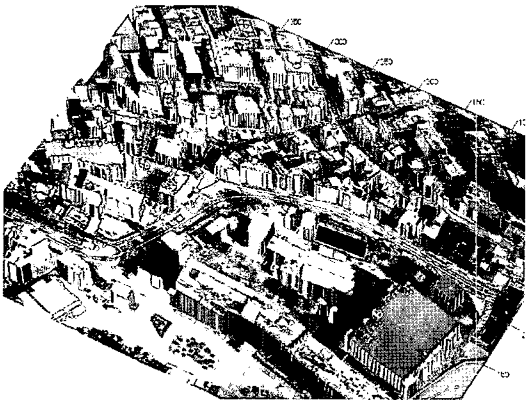

Fig. 23. Textured building DSM.

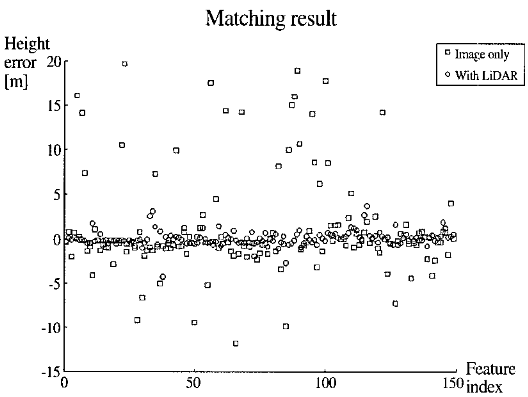

Fig. 24. Matching results (Region matching).

processing in this experiment. Error values of height are plotted against feature indexes. Red squares are results of the matching without initial height values. And, blue circles are results of the matching with initial height values. This Figure shows that the integration of TLS

Table 1. Matching result.

	Image only	With LiDAR data
Mean value [m]	3.23	0.54
Standard deviation [m]	4.62	0.66

images and LiDAR data makes the result better. Moreover, Table 1 shows mean values and standard deviations of height errors in this result. The matching result without initial height values is shown in a row of 'Image only', and that with initial height values is shown in a row of 'With LiDAR data'.

5. Discussion

Fig. 25 shows a relationship between height errors and horizontal areas (object sizes). Height information of small objects cannot be extracted through image matching successfully, as this Figure shows. It is conjectured that small buildings in TLS images do not have enough information to be detected matching points successfully through the image matching processing. Therefore, the integration of TLS images and LiDAR data is effective methodology for a height extraction of small buildings. Additionally, large features in TLS images can keep accuracy even if initial height information doesn't exist, because the features have

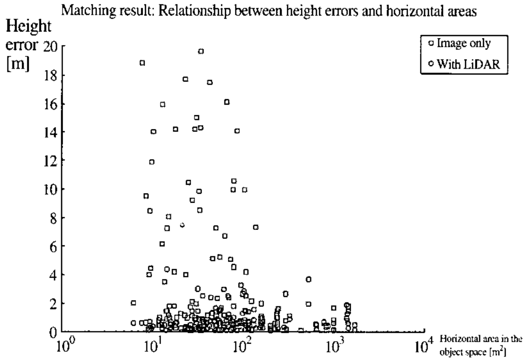

Fig. 25. Relationship between height errors and horizontal areas.

Table 2. Success rate of matching.

	Image only	With LiDAR data
Success rate (Threshold: ±2m)	68% (101 / 149 objects)	96% (143 / 149 objects)
CPU time (1.5GHz, 149objects)	5958[sec] (Search range: 25-60[m]) (Sampling step: 20[cm])	635[sec] (Search range: DSM±2[m]) (Sampling step: 20[cm])

plenty of information for the image matching processing. However, initial height information is needed for stereo matching of small features. This kind of the fact may be remained the object identification from TLS image. When a threshold of success / failure is defined as 2m, the results can be given in the following table (See, Table 2). This threshold value is given from complexness of roof shapes. True values are taken from building edges manually. Actually, average height values of buildings are extracted through the matching processing. This average height values includes not only average heights of slanted roofs, but also noises of some features such as steel fences or antennae. However, it is difficult to measure the average height values manually. Therefore, we define the threshold value as 2m in this experiment. Table 2 shows that using LiDAR data makes the success rate of the matching almost 100%. Moreover, Table 2 shows that using LiDAR data makes calculating-time 1/10 approximately. This is just an effect of the integration of TLS image and LiDAR data. Results are shown in the previous section. Moreover, the success rate and the processing time in the processing are discussed in this section. Based on these facts, we can mention that data integration approach is effectiveness methodology in ultra high-resolution stereo images processing. But, in fact, the performance of data integration depends on the resolution of coarser data, which are LiDAR data in this research.

6. Further Result

Fig. 26 and Fig. 27 show further results, which are converted building DSM from a raster format to a vector format. In this conversion processing, boundaries of building DSM are used as initial values to fit detailed building edges dynamically with a triplet active contour model algorithm. Moreover, textures are also mapped to vertical faces with forward image and backward image full-automatically (Masafumi *et al.*, 2003; Gerke *et al.*, 2001).

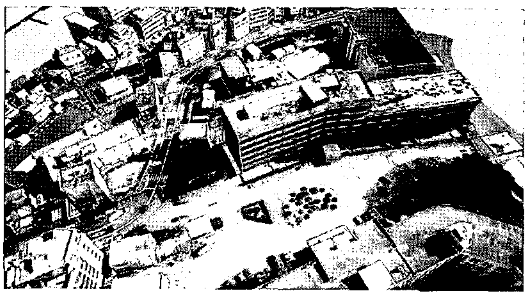

Fig. 26. Further result(1).

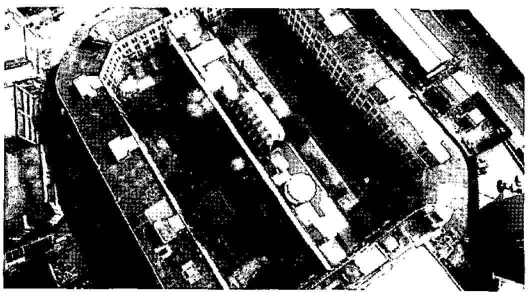

Fig. 27. Further result(2).

7. Summary

In this research, we examined a more efficient method of generating 3D spatial information with higher resolutions by integrating TLS images with LiDAR data. It can be concluded that basic shapes of buildings can be possible to generate full-automatically by integrating TLS images and the LiDAR data. Moreover, the automation level improves dramatically compared with the method using only images. And a more detailed modeling can be done compared with the method using only laser data. As effects of fusing the stereo image and the LiDAR data, we can enumerate the improvement of the matching accuracy (improving it from 68% to 96%) and shortening of calculating-time (Approximately, 10%) for the matching processing. The data obtained here becomes a basic 3D spatial data for city modeling, and we believe that it becomes a big support to digital mapping.

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