SURFACE MODELLING OF URBAN 3D OBJECTS FROM VEHICLE-BORNE LASER RANGE DATA

Huijing Zhao, Ryosuke Shibasaki

University of Tokyo

Commission III, WG III/7

KEY WORDS: Laser Range Scanner, Vehicle-borne, Marching Cube, Urban 3D Model, Reconstruction

ABSTRACT:

In this paper, a method is presented to generate surface model of urban out-door environment using vehicle-borne laser range scanners, which have been developed in Konno *et al.*[11]. A classification is conducted first, where range points are divided into the groups of vertical building surface, road surface, other surface, window, tree and others, unknown objects. Erroneous measurement are corrected, e.g. window data or discarded, e.g. irregular data. Volumetric modelling and marching cube method are exploited in this research to model both surface-structured objects, e.g. building and road surface, and volume-structured objects, e.g. tree. Estimates for signed distance are proposed. Through an experiment, it is demonstrated that urban out-door environment can be reconstructed with high automation and efficiency using our method.

1. INTRODUCTION

Up to now, many research groups in photogrammetry community have been devoted to the analysis of aerial based imageries for the reconstruction of 3D urban object (e.g. [5,10]). Normally, aerial survey can cover relatively wide area, but fail in capturing details of urban objects such as sidewall (façade) of buildings. On the other hand, most of the existing systems in computer vision field have been demonstrated at small scales, using simple objects, under controlled light condition. (e.g. [1,6,15]). With the development of automobile navigation system, 3D GIS (Geographic Information System), and applications using virtual and augmented reality, details of urban out-door objects are found to be of importance, as user viewpoints are involved on the ground, not in the air. An efficient reconstruction method exploiting ground-based survey technique at large scale, for complicated and unexpected object geometries, under uncontrolled light condition is required.

Several systems aiming at generating 3D model of real world have been developed during the last few years. According to the major data source being used for reconstructing object geometry, the systems can be broadly divided into two groups. One is called image-based approach. Another is called range-based approach.

In the first group, 3D model of urban scene is reconstructed using still or moving images. Image-based approach is also called in-direct approach since object geometry has to be automatically or human-assistedly extracted using stereo or motion techniques. Debevec, *et al.* [3] presented an interactive method of modelling and rendering architectural scenes from sparse sets of still photographs, where large architectural environment can be modelled with far fewer photographs than using other full-automated image-based approaches. MIT City Scanning Project [9] developed a prototype system of automatically reconstructing textured geometric CAD model of urban environment using spherical mosaic images, where camera's position and orientation of each spherical image is first initialised using positioning sensors, then refined through image matching. Geometric representation is extracted either using feature correspondence or by identifying vertical facades. Uehara and Zen [12] proposed a method of creating textured 3D map from existing 2D map using motion technique, where a video camera is mounted on a calibrated vehicle and the image streams that captured are geo-referenced to the existing 2D map using GPS data. Through the above research efforts, it is demonstrated that image-based approach can be used in reconstructing 3D model of urban out-door environment. Whereas, the difficulties in reliable stereo matching, distortion from limited resolution and unstable geometry of CCD cameras are the major obstacles to reconstruct a 3D model of complicated environment with necessary accuracy and robustness.

In the second group, 3D model of urban scene is reconstructed using range image. Range-based approach is also called direct approach since object geometry can be directed measured using range scanner. In recent years, as the development of laser technique, range scanners using eye-safe laser with high accuracy, large range distance and high measurement frequency are being used for the modelling of urban environment. Sequeira *et al.*[14] and El-Hakim *et al.*[4] developed systems on reconstructing indoor environment of rather large scale. Stamos and Allen [17], Zhao and Shibasaki [20] aimed at generating 3D model of urban out-door objects. In these systems, range scanners are mounted on stationary platforms (called stationary system). Range images produced by the systems are typically rectangular grids of range distances (or 3D coordinates after conversion) from the sensor to the objects being scanned. Objects are measured from a number of viewpoints to reduce occlusions, where location and direction of viewpoints are unknown or roughly obtained using GPS, Gyro sensors and/or other navigation systems. Range data obtained in different viewpoints are registered and integrated, and a completed model of urban environment is reconstructed.

There are several drawbacks of stationary systems. First, in data acquisition, successive range views have to keep a degree of overlay, so that location and direction of viewpoints can be traced (or refined) by registering range data. Planning for viewpoints and directions in data acquisition becomes difficult when measuring large and complicated scene, since a balance between the degree of overlay and the number of viewpoints has to be decided according to both target objects and registration method. Secondly, there is still no registration method that could succeed in automatically registering range data of all kinds. When the number of range views increases, registration while keeping necessary accuracy becomes difficult. Updating stationary systems to moving platform ones (called vehicle-borne system) for reconstructing 3D model of large real scene is very important.

Konno *et al.*[11] developed a sensor system by mounting three single-row laser range scanners on a vehicle with a high accurate navigation system. In this research, we propose a prototype of reconstructing the urban outdoor environment from the output of the vehicle-borne sensor system.

2. OUTLINE OF THE RESEARCH

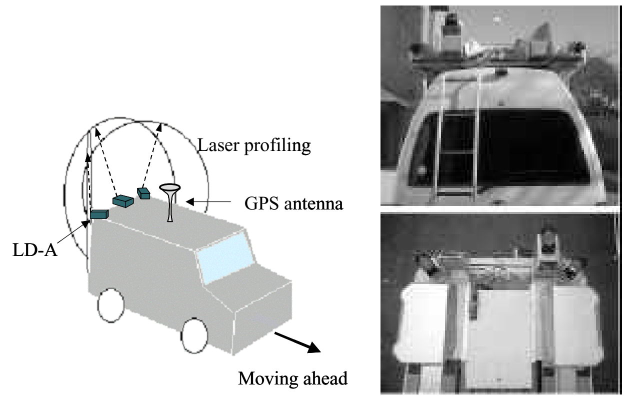
In this chapter, we first briefly introduce the sensor system, and its data output, then state the problems, and finally outline the concept of the research.

2.1 Sensor system

In the sensor system developed by Konno *et al.*[11], three laser range scanners (LD-As) are mounted on a measure vehicle (GeoMaster), which has been equipped with a GPS/INS/Odometer based navigation unit (see Figure 1). LD-A, produced by IBEO Lasertechnik, is a single-row laser range scanner. It has a profiling rate of 10Hz, a maximal range distance of 100 meters, and a measurement error of 3cm. In each profiling (scan line), 1200 range distances are measured equally in 300 degrees, where 60 degrees of blind area exists due to hardware configuration. Reason for using three LD-As is to reduce occlusions by trees and other obstacles. As the vehicle moves ahead, LD-As keep profiling the surroundings on three different vertical planes (cross-section). Meanwhile, the navigation unit outputs the vehicle's location coordinates (x, y, z) and orientation angles (, ,) in world coordinate system at the moment of each laser scanning, so that all range distances (range points) in LD-A's local coordinate system at the moment of measurement can be geo-referenced to the world coordinate system. Range points of different LD-As are recorded in different output files (views) in the order of measurement sequence.

2.2 Problem statement

This research focus on generating a surface representation of urban out-door environment using the range outputs of the above sensor system. Surface reconstruction from dense range data has been studied for decades. Soucy and Laurendeau, [16] and Turk and Levoy, [18] exploited the connectivity of structured range points. Hoppe, *et al* [8] proposed a method of generating an implicit surface from unorganized points using volumetric representation and marching cube algorithm. Curless and Levoy [2], Wheeler *et al.*[19] are the hybrids of the above two methods, where implicit surface method is exploited to integrate structured range views. Most of the researches assume that all the range points are on or near an implicit surface, and they are clear or only have a systematic error. However this is not always true in urban out-door environment.



(a) Sensors' alignment (b) Pictures of the vehicle

Figure 1. Sensor System

Except the irregular points that reflected by passing cars and pedestrians, window glasses and trees are two major difficulties in the modelling of urban out-door environment by laser scanning. Some window glasses are penetrative to laser beam, subsequently yields range measurement of unknown indoor objects, which are beyond our interest. While some window glasses give mirror reflection, so that yields black holes (no data) on building surface. Trees are of complicated shape and plenty of occlusions. Laser scanning of a tree yields a cloud of scatter points, which are not implying a surface but a volume. It is obvious that modelling a surface-structured object, such as building and road surfaces, should be conducted in a different level with that of a volume-structured object, such as trees. However trees are always near to and block the measurement of building, borderline between them is always confusing.

2.3 Outline of the research

Reconstructing a surface representation of urban out-door objects is conducted in two procedures. First, range points are classified into six groups, i.e. the measurement of vertical (building) surface, false window area, road surface, other kinds of surface, tree and unknown objects. False window area (briefly referred to "window area" in the following sections) implies the penetrative or mirror-like window area, of which range values are corrected and interpolated using the measurement on surrounding vertical building surfaces. In this research, window area that does not yield erroneous or false reflections is not our research interest. They are regarded as a part of vertical building surface. Secondly, volumetric representation and marching cube algorithm are exploited since it is easy in generating a model of desired level of detail, which is required in many 3D GIS applications. The scheme for generating volumetric representation and the algorithm for computing signed distance are defined differently, where iso-surfaces are computed for surface-structured objects, i.e.

vertical (building) surfaces, windows, road surfaces and other surfaces, while surrounding surfaces are generated to enclose volume-structured objects, i.e. trees.

In the followings, we discuss each procedure in details. An experiment and discussion is followed, where a real urban outdoor environment is reconstructed, and the efficiency of the method is proved.

3. CLASSIFICATION OF RANGE POINTS

As the vehicle moves ahead, LD-As take the cross-sections of urban objects by scan lines (1200 range points per scan line). Since LD-A has a circular scanning resolution of 0.25 , spatial resolution of range points in one scan line (vertical spatial resolution) depends on the distance from LD-A to target object. If the target object is 20m (r) far from LD-A, range points are sampled at a vertical spatial resolution of about 0.087m (r*tan0.25). On the other hand, when the vehicle moves straight at a speed of 10~20km/h, scanning planes are almost parallel with an interval of about 0.1m. Subsequently, horizontal spatial resolution of range points at the same sequential number is about 0.1m. However, it alters as the vehicle's moving direction changes. Classification is conducted by examining the local connectivity between the range points of the same and neighbouring scan lines.

3.1 Segmentation of scan lines

Scan lines are first segmented into linear patches, where successive range points are extracted, which are linearly distributed with a variance lower than a given threshold. Linear patches are then compared with the extraction of neighbouring scan lines. Isolated linear patches are discarded, which cannot find a linear patch of nearby sequential number and of similar direction in the extraction of neighbouring scan lines. It means that the range points have only vertical but no horizontal linear continuity, so that they are not the measurement of surface object. Finally, range points in one scan line are divided into four groups as follows.

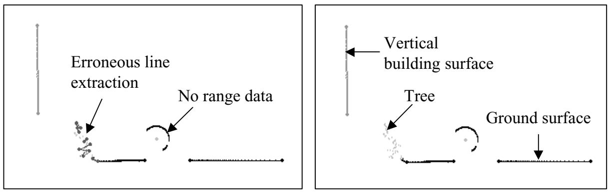
1) Range points belonging to vertical linear patches are the measurement of vertical building surface.
2) Range points belonging to horizontal linear patches and at ground elevation are the measurement of road surface. Relative elevation from the origin of LD-A to the nearest ground surface is almost constant. It can be measured previously in calibration stage.
3) Range points belonging to other linear patches are the measurement of other surface.
4) Range points do not belong to any of the above groups are scatter points.

3.2 Correction of window area

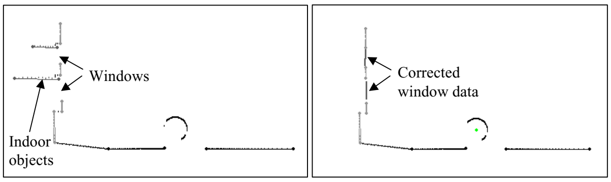
In this research, we assume that the building surface between windows of different floor is vertical as a whole, is range sampled enough that can be extracted, and its material is neither penetrative nor mirror reflective to laser beam. In each scan line, penetrative measurement on window area has the following characteristics.

1) They are behind the building surface from the viewpoints of LD-A.
2) Their sequential numbers are between two pieces of vertical linear patches, which are on a common vertical line.

Discrimination of window area is conducted using all other range points besides those belong to vertical building and road surface. To the range points that satisfying both conditions, their range values are corrected to fit the common vertical line. To the false points (no range value) that satisfying the second condition, their range values are interpolated.



(a) Linear patches that extracted from a scan line, (b) erroneous extractions are discarded by comparing the horizontal linear continuity with the extractions of neighbouring scan lines



(c) Some window glasses are penetrative to laser beam, so that indoor objects are measured, (d) Range points at window area are corrected using the data of surrounding vertical building surface.

Figure 2. Classification and correction of range points

3.3 Trees and others

Range measurement of volume-structured objects, e.g. trees, has the following characteristics.

1) They are in front of the building surface from the viewpoint of LD-A.
2) They have higher elevation values than the ground surface.
3) The cloud of range points implies not a surface but a volume.

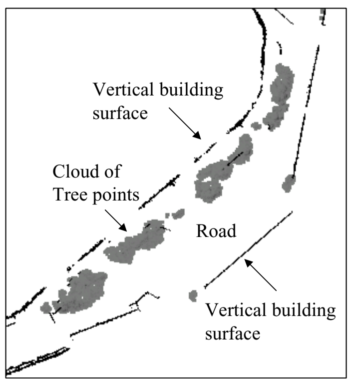


Figure 3. Extraction of tree and other volume-structured objects

Volume-structured objects are discriminated as followed. All scatter points that satisfying the first two conditions are projected onto a regularly tessellated horizontal plane. For each grid pixel i, three values are recorded. They are the maximal elevation value $\bar{z}_i$, the minimal elevation value $\underline{z}_i$, the number of range points c_i. The grid pixels are regarded as having vertical volume if they satisfy the following conditions.

$$(\bar{z}_i - \underline{z}_i) > T_z \text{ and } c_i > T_c \qquad (1)$$

Where T_z and T_c are experience values. In addition, grid pixels are segmented by region growing, where each pixel is assigned to one of two states, i.e. 0 if c_i=0 and 1 if c_i>0. The grid pixels belonging to a region that larger than a given threshold are regarded as having horizontal volume. The scatter points that belonging to a grid pixel of both horizontal and vertical volume are extracted as the measurement of volume-structured objects.

4. VOLUMETRIC MODELING AND MARCHING CUBE

One of the key issues of generating an implicit surface using volumetric modelling and marching cube method is to calculate the signed distance d_c from the centre point of each voxel V_c to the isosurface. The sign of d_c indicates the state of V_c, i.e. it is invisible from all viewpoints if $d_c>0$, it is visible from one of the viewpoints if d_c<0, and it is on the iso-surface if d_c=0. Hoppe, *et al* 1992 performed a search for the closet point to a voxel's centre, while Wheeler *et al.*1996 generated triangular meshes using the connectivity of structured data, and calculated the signed distance from the centre of each voxel to the closest triangular surface. Curless and Levoy 1994 calculated the weighted signed distance of each voxel to the nearest range surface of a single range view along the line of sight. The weighted average of all these measures is exploited as the signed distance estimate to the integrated iso-surface.

The surfaces of urban outdoor objects are always not continuous ones. There might be window frames, rain pipes, cables on a planar building surface. There might be pavement, road guild on a road surface. The local surface normal calculated using the neighbouring range points might not really reflect the implicit surface that are of interest. In this research, range points are treated as independent and unorganized points. Extraction of iso-surface is conducted for surface-structured objects, i.e. vertical (building) surfaces, windows, road surfaces and other surfaces, and volume-structured objects, e.g. trees separately.

4.1 Iso-surface of surface-structured objects

A range measurement *x* from viewpoint *o(x)* tells that there is nothing in the extent of laser beam between *o(x)* and *x*, there are something at *x*, and the extent far from x is unknown. On the other hand, a point *c* is visible from *o(x)*, if and only if it is in the extent of laser beam between *o(x)* and *x*. It is invisible from *o(x)* if and only if it is in the extent far from *x*. As the range measurement in our research is a point sampling of the surroundings with a vertical angular resolution (v*res*=0.25) and a horizontal spatial resolution (*hres* 0.1m), measurement extent of a laser beam is considered as a compound of a circular cone and a cylinder as shown in Figure 4, where radius of any circular section of the compound structure is defined as follows.

$$R = \max(r*\tan(vres), hres) \qquad (2)$$

Where, *r* is the range distance from *o(x)* to the circular section.

According to marching cube algorithm, an edge is intersected by the implicit iso-surface, if and only if the two terminal points (centre points of neighbour voxels) of the edge are in different states. Thus, instead of the signed distance estimate, in this research, we first calculate the state of all voxel centres, then calculated the intersection points on the edge that bridging different states.

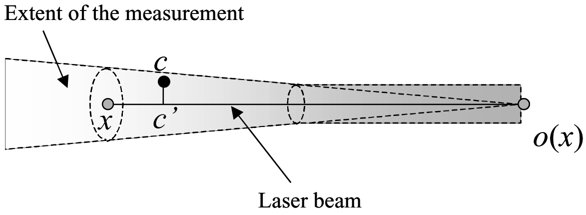


Figure 4. Laser beam and its measurement extent

Computation of point state: Theoretically, if *c* is visible from one of the viewpoint, it is outside of the surface. If *c* is invisible from all of the viewpoints, it is inside of the surface. Let S_c be the sign of *c*, where, S_c=-1,1,0 indicates *c* inside, outside, and on the object surface. S_c is computed as follows, where E_r is a predefined value indicating the order of range error.

Algorithm ComputeState
Input: *c*
Input: the set of all range points $X = \{x\}$
Output: S_c
    $S_c \leftarrow -1$
    For $x \in X$
        $\vec{v}_c \leftarrow c - o(x), \vec{v}_x \leftarrow x - o(x), r_c(x) \leftarrow \vec{v}_c \cdot \vec{v}_x$
        $d_c(x) \leftarrow \sqrt{\|\vec{v}_c\|^2 - r_c(x)}$,
        $R_c(x) \leftarrow \max(r_c(x) \times \tan(vres), hres)$
        If $d_c(x) \geq R_c(x)$
            If $\| r_c(x) - r(x) \| < E_r$ then $S_c \leftarrow 0$
            Else if $r_c(x) < r(x)$ then $S_c \leftarrow 1$
    Return S_c

Computation of edge intersection point: Suppose the centre points c_i of voxel V_i and c_j of V_j are of different states. The intersection point p_{ij} on edge $E(c_i, c_j)$ by the implicit iso-surface is calculated as follows, where $d_{ij}(x)$ is the orthogonal distance from range point *x* to edge $E(c_i, c_j)$, $p_{ij}(x)$ is the corresponding orthogonal point.

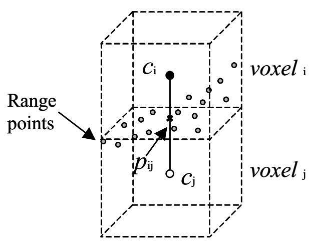


Figure 5. Edge intersection point

Algorithm ComputeEdgeIntersectionPoint
Input: $E(c_i, c_j)$
Input: range points $X = \{x\}$ falling into V_i and V_j
Output: p_{ij}
For $x \in X$
calculate $d_{ij}(x)$ and $p_{ij}(x)$

$$\omega \leftarrow \sum_{x \in X} \frac{1}{d_{ij}(x)}, \quad p_{ij} \leftarrow \frac{1}{\omega} \sum_{x \in X} \frac{p_{ij}(x)}{d_{ij}(x)}$$

4.2 Iso-surface of volume-structured objects

A surrounding surface is generated between filled and empty voxels, so that enclosing the volume-structured objects. Each voxel might have one of two states, S_c=-1,1 for filled and empty respectively. Generation of surrounding surface is also break down into two steps, i.e. compute the state of each voxel, and calculate the intersection points on the edges that bridging different states.

Computation of point state: Let $n_{i,j,k}$ be the number of range points falling into the voxel of index (*i,j,k*). After smoothing operation of

$$n_{i,j,k}' = \frac{1}{27} \sum_{ii=i-1}^{i+1} \sum_{jj=j-1}^{j+1} \sum_{kk=k-1}^{k+1} n_{ii,jj,kk} \qquad (3)$$

state $S_{i,j,k}$ is assigned by

$$S_{i,j,k} = \begin{cases} -1 & if\ n_{i,j,k}' \geq T_n \\ 1 & otherwise \end{cases} \qquad (4)$$

Computation of edge intersection point: Suppose the center points c_i of V_i and c_j of V_j are of different states. We define the intersection point p_{ij} on edge $E(c_i, c_j)$ as the middle point of $p_{ij} = (c_i + c_j)/2$.

5. EXPERIMENTS AND DISCUSSIONS

An experiment is conducted in a real outdoor environment, *Roppongi* Campus of the Univ. of Tokyo. A map of the testing site and vehicle trajectory is shown in Figure 6. The measurement vehicle ran at a speed of about 10km/h, and 500 scan lines were measured by each LD-A. In Figure 7, range data from different LD-As are shown in different colours, while red, green, blue represents the centre, right, left LD-A respectively. Range data measured by each LD-A are showed in Figure 8 (left column) in intensity values. From both Figure 7 and 8, it can be found that the objects are measured simultaneously from three different directions to reduce occlusions efficiently. All the range points are geo-referenced into a world coordinate system using to the navigation data. The result is shown in Figure 9. It can be found that there are many windows on the building surface, some, not all, of the laser beams penetrate window glasses and the sensor got the reflections of unknown indoor objects. In addition, it can be found that there are many irregular points in sky, which might be caused by direct sunlight and sensor's systematic error. Range points from different LD-As are classified in separate procedures into vertical building surface, road surface, other surface, window, tree and others. Classification result is shown in Figure 8 (right column). There are totally 319743 valid range points, where 35.4% are discriminated as the measurement of vertical building surface, 42.61% are road surface, 3.16% are other surface, 4.57% are window, 9.7% are trees. Other points that do not belong to any of the above groups, which hold about 4.51%, are classified to the group of unknown objects. Irregular points as shown in Figure 9 are also classified to this group. They are discarded in our system. A surface model is generated using volumetric modelling and marching cube method as shown in Figure 10. Voxel sizes of surface-structured and volume-structured objects are assigned 0.3m. As we generate a surrounding surface to enclose volume-structured objects, the surface swells with voxel size. On the other hand, if the voxel size for surface-structured objects is set too small, not only black holes, but also distorted surfaces might be generated in the area of windows, rain pipes and corners, so that manual modifications are required.

6. CONCLUSIONS AND FUTURE WORK

In this paper, a method is presented to generate surface model of urban out-door environment using vehicle-borne laser range scanners. Range points are classified into six groups, so that erroneous measurement are corrected or discarded, and surface-structured and volume-structured objects are modelled in different strategies. Volumetric modelling and marching cube method are exploited in this research, where an estimate for signed distance is proposed. Through an experiment, it is demonstrated that urban out-door environment can be reconstructed with high automation and efficiency using our method. Future study will be addressed on improving the accuracy of classification, and extracting and modelling other urban features like parking cars, telegram poles, traffic signals, and so on.

REFERENCE

[1] Chen,Y., G.Medioni, Object Modelling by Registration of Multiple Range Images, Image and Vision Computing,Vol. 10, No. 3, Apr. pp.145-155, 1992.

[2] Curless, B., M.Levoy, A volumetric method for building complex models from range images, Proc. of SIGGRAPH, pp.303-312, ACM, 1996.

[3] Debevec, P.E., C.J.Taylor, J.Malik, Modeling and Rendering Architecture from Photographs: A hybrid geometry- and image-based approach, SIGGRAPH1996.

[4] El-Hakim, S.F., C.Brenner, G.Roth, A Multi-sensor Approach to Creating Accurate Virtual Environments, JSPRS Journal of Photogrammetry &Remote Sensing, vol.53, pp.379-391, 1998.

[5] Gruen, A., TOBAGO – a semi-automated approach for the generation of 3-D building models, ISPRS Journal of Photogrammetry and Remote Sensing, vol.53, issue 2, pp.108-118, 1998.

[6] Higuchi, K., M.Hebert, and K.Ikeuchi, Building 3-D Models from Unregistered Range Images, Graphical Models and Image Processing, vol.57, No.4, pp.315-333, 1995.

[7] Hoover, A., et.al., An Experimental Comparison of Range Image Segmentation Algorithms, in IEEE Trans. on Pattern Analysis & Machine Intelligence, vol. 18(7), pp. 1-17, July 1996.

[8] Hoppe, H., *et al.*, Surface reconstruction from unorganized points. Proc. of SIGGRAPH, 26(2):71-78, 1992.

[9] http://city.lcs.mit.edu//city.html, MIT City Scanning Project: Fully Automated Model Acquisition in Urban Areas.

[10] http://vis-www.cs.umass.edu/projects/radius/radius.html, The U. Mass RADIUS Project.

[11] Konno, T, *et al.*, A New Approach to Mobile Mapping for Automated Reconstruction of Urban 3D Model, proc. of Int. Workshop on Urban Multi-Media/3D Mapping, 2000.

[12] Uehara, M., H. Zen, From Digital Map to 3D Map: Creating 3D Map by Motion Stereo Utilizing 2D Map, IAPR Workshop on Machine Vision Applications, pp.592-595, 2000.

[13] Rosin, P.L., G.A.W.West, Nonparametric Segmentation of Curves into Various Representations, IEEE PAMI, vol.17, no.12, 1995.
[14] Sequeira, V., *et al.*, Automated Reconstruction of 3D Models from Real Environments, ISPRS Journal of Photogrammetry & Remote Sensing, vol.54, pp.1-22, 1999
[15] Shum, H., K.Ikeuchi, and R.Reddy, Virtual Reality Modeling from a Sequence of Range Images, Proc. IEEE/RSJ Int. Conf on Intelligent Robots and Systems, pp.703-710, 1994.
[16] Soucy, M., D.Laurendeau, A general surface approach to the integration of a set of range views, IEEE Trans. PAMI, 17(4):344-358, April, 1995.
[17] Stamos, I., P.K.Allen, 3-D Model Construction Using Range and Image Data, CVPR 2000.
[18] Turk, G., M.Levoy, Zippered polygon meshes from range images, Proc. of SIGGRAPH, pp.311-318, ACM, 1994.
[19] Wheeler, M.D., Y.Sato, K.Ikeuchi, Consensus surfaces for modeling 3D objects from multiple range images, Proc. of ICCV '98, January 1998.
[20] Zhao, H., R.Shibasaki, Reconstruction of Textured Urban 3D Model by Ground-Based Laser Range and CCD Images, IEICE Trans. Inf.&Syst., vol.E83-D, No.7, July, pp.1429-1440, 2000.

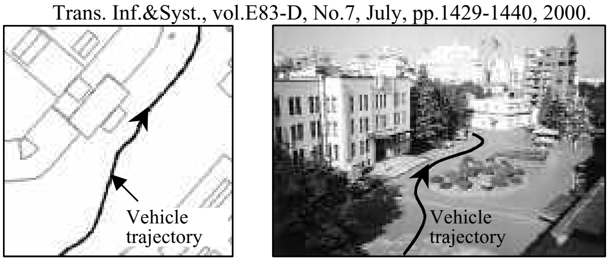


Figure 6. Testing site – *Roppongi* Campus of the Univ. of Tokyo

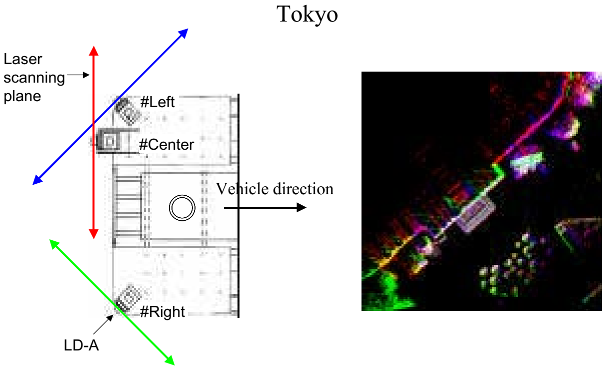


Figure 7. Occlusions are reduced by using three LD-As

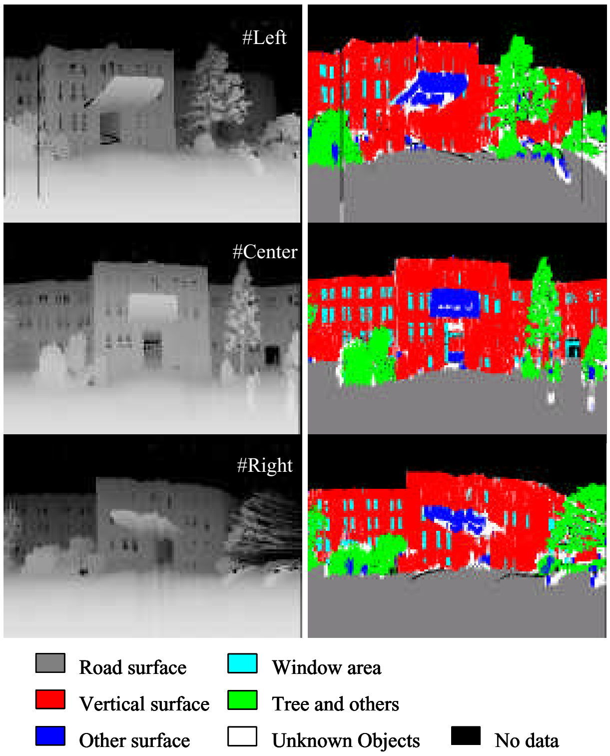


Figure 8. Range Images of three LD-As

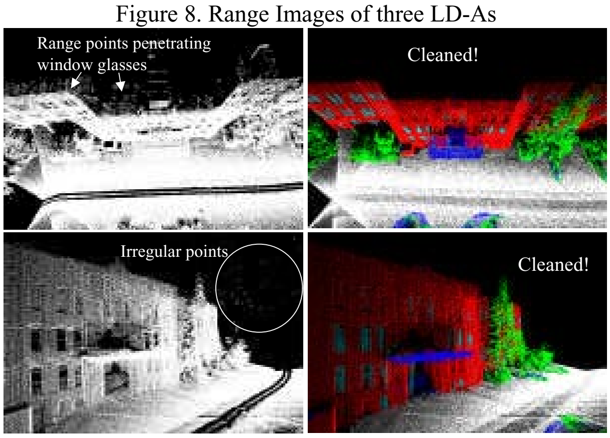


Figure 9. Range correction in classification procedure

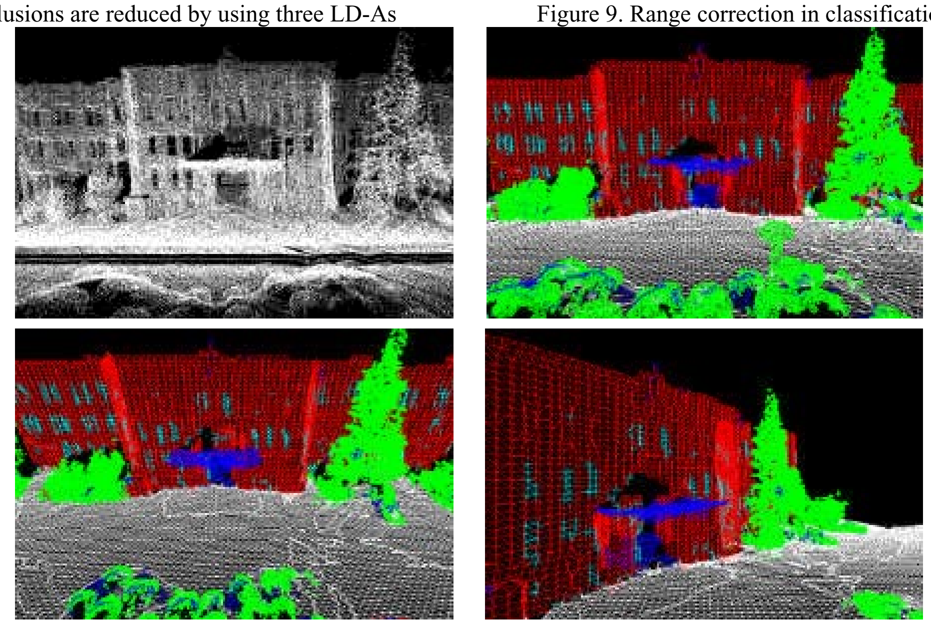


Figure 10. Final results (road surfaces under the measurement vehicle are interpolated)