19th ITS World Congress
Vienna, Austria
22 to 26 October 2012
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Global 3D Modeling and its Evaluation for Large-Scale Highway Tunnel using Laser Range Sensor

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Abstract

Precise and accurate 3D model of a road structure is basic information that can be utilized for various purposes, such as safety measures, driving simulation, and reference data for autonomous driving. Generally, the 3D model of a tunnel has been constructed using gyro sensor, however, error accumulation becomes a considerable problem in the case of long tunnels. We tried a method to obtain the most optimal structure of a tunnel by geometric processing: (1) Acquire a set of partial structures by static scanning, and align them by 3D matching using edge feature (2) Fix the absolute position of the data at both ends of the tunnel by GPS and align the rest data again. We modeled the Awagatake (Kanaya) Tunnel in Shin-Tomei Expressway, whose length is 4.6 km by this method. The error in lateral direction was up to 0.1% relative to the tunnel length.

Keywords:

Tunnel, Autonomous driving, GPS, 3D modeling, Alignment

1. Introduction

Precise and accurate 3D model of a road structure is basic information which can be utilized for various purposes, such as safety measure and its verification, 3D navigation, driving and noise simulation, and reference data for autonomous driving in the future, etc. Especially a tunnel zone is dark and narrow, and gives psychological suppression to drivers. Once an accident occurs in a tunnel, it tends to take long time for rescue and traffic control, therefore sufficient safety measure is required. Nowadays, 3D modeling of urban structure is actively done generally based on aerial survey and vehicle survey by self positioning and in some cases by matching sensing data with prior information such as maps and landmark databases.

However, things drastically change in the case of tunnels, where GPS and aerial survey is completely unavailable. The most popular solution for this is to obtain the self position by filtering measurement values of on-vehicle gyro sensor and speedometer, and quite a few cases are in practical use as [1]. However, since this kind of method is essentially based on an integral of local measurement, accumulation of error becomes a considerable problem in a tunnel of kilometer-order length. Although other kind method to use on-vehicle camera and apply image processing such as factorization is known [2], it is not easy to stably and precisely extract and track feature points in a dark environment. Another problem is, while using laser range sensor mounted on the survey car, they can only obtain sparse scans with less detail information. Also, using prior information as [4, 5] is not reasonable, since it is essentially difficult to construct prior map and landmark database and to uniquely match a series of quite similar scenes inside a tunnel.

In the case of this paper, we give priority to density and accuracy of the model rather than efficiency, with reasonable quantity of human work. We assume that a set of dense and accurate scans in a tunnel are obtained by static surveys and they are aligned by geometric processing without using external devices as a gyro sensor and a speedometer, and finally they are corrected and geometrically optimized using global information, where the accumulated errors are dispersed. The global corrective information can be given by GPS at both end of the tunnel.

Also, a CAD drawing for the tunnel construction can be considered to give global accuracy to some extent, however, it should be noticed that the actual structure of the tunnel is not assured to be same as the CAD drawing. One reason is that it only shows the most outer part in a cross section of the tunnel and does not show the inner wall area with some thickness, and will differ from the scanned data. Moreover, even at the stage of construction, a tunnel shield machine can not strictly follow the drawing, since the position of the machine digging forward in a tunnel is surveyed by using a total station behind the machine, and the machine can not suddenly change the heading. It can be naturally said that no one knows the true drawing or the 3D model of the tunnel inside.

The modeling and evaluation procedure is shown in Fig. 1. Section 2 aims to build a locally accurate raw model. We firstly extracted geometric edges as features for the alignment, and then aligned each pieces of the acquired structure into a whole one by pair-wise alignment algorithm. Section 3 aims to globally modify the whole structure by dispersing the error accumulated in the previous step, using simultaneous alignment algorithm with GPS constraint. Also, an algorithm to fill deficits on the ground is presented. In section 4, we compare the modeled tunnel with CAD as one of reference, although it is not assured to be accurate.

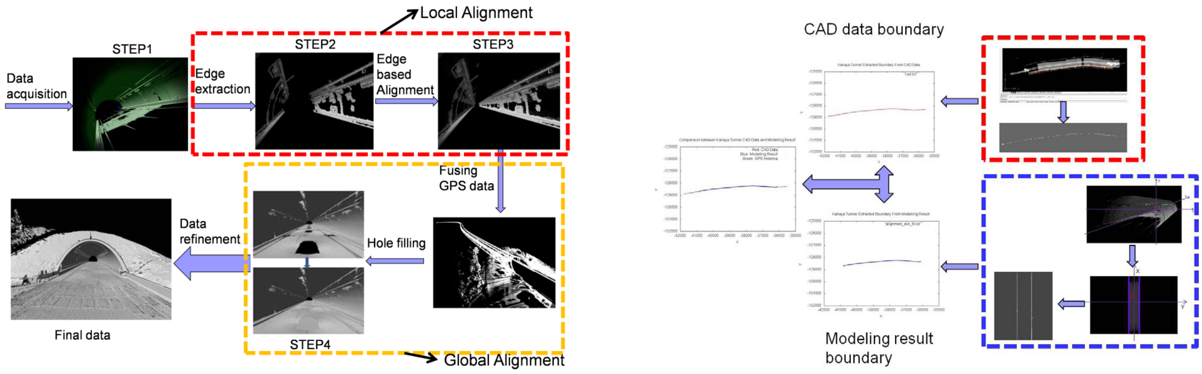


Figure 1 –Modeling and evaluation procedure.

2. Local Alignment

Every piece of the scanned tunnel data are stitched into an integrated one by 3D-3D matching. However, most parts of the tunnel are similar in geometry as a cylinder, which will possibly lead to mismatching. Besides, the point cloud data of a long tunnel tends to be quite huge, which will obviously affect the processing cost. The point of this section is to take advantage of geometric features in the matching, for overcoming the problem.

2.1 Input Data

The input data is a set of dense and accurate 3D point crowds inside a tunnel as Fig. 2. For acquiring the data, we use a survey car with an omnidirectional range sensor mounted as we adopted in [6], and the scan is done with the vehicle stationary. Details on the surveying system are described in the experiment. Moving and scanning is repeated by turns, keeping enough overlap between adjacent scans.

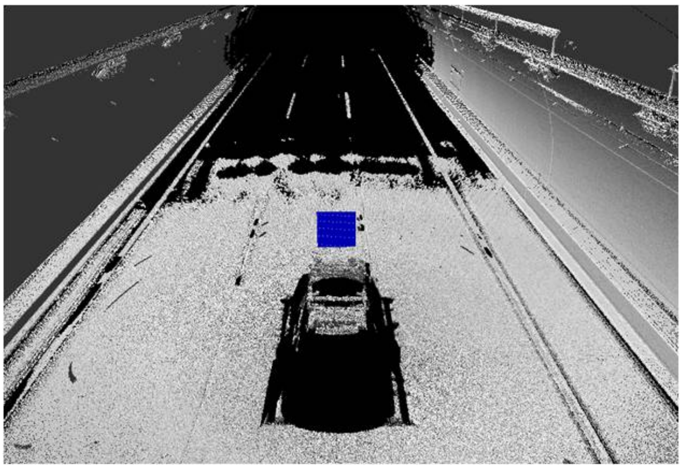


Figure 2 – An example of the input data, a single scan representing a part of the tunnel.

2.1 Edge Extraction

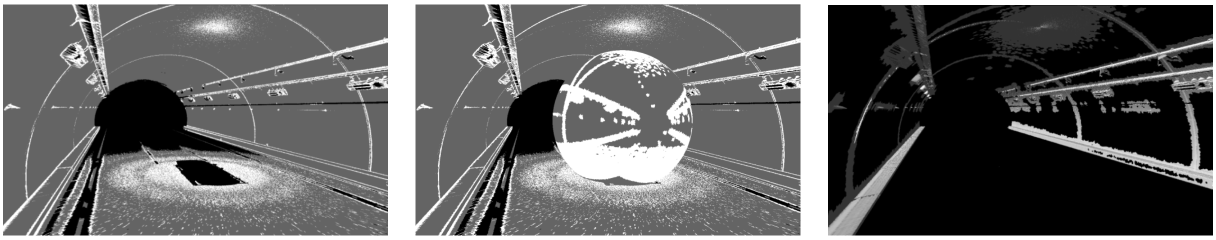
In order to avoid mismatch in the alignment, we extracted edges as features. Only the points around the 3D edges will be used for the alignment. After this step, the matching point pair for alignment will be reduced obviously, so the alignment can also become more efficient. The extraction procedure is shown below:

1. Extract 3D edges from the scanned data.
2. Map the 3D edges onto a virtual sphere whose center is at the sensor position.
3. Re-map the expanded edge back to the original place and extract the surrounding area of edges.

The output data of range sensor are the collection of 3D points of the object surface, these continuous points can be considered as many small meshes. If the angular difference of normal vectors of two nearby meshes is larger than a threshold (20 degree in our case), the two meshes can be considered as 3D edges (Fig. 3 (a)).

Some portions on the ground are also mis-extracted as edges, and some edges on the wall can not be recognized easily since they are too thin or too sparse to discriminate. In order to correctly extract edges, the edge expansion process is done as Fig. 3 (b). We do not expand the edges on the surface of meshes directly. In the first step, we mapped the edges onto a sphere surface to equalize the point density. Then we split the surface of the sphere into a regular icosahedron, recursively subdivide them into 5242880 triangle patches, and find the nearby pair patches mapped with edges. Lastly, the expanded surrounding patches of edge should be re-mapped back to the original data. This processing is done by the rendering function of OpenGL, which can be finished in a high speed. Note that the data directly under the sensor has high density and just small difference in scanning will lead the direction of normal vector to be changed and the edge detection to be erroneous. In order to avoid this, we calculated the distance to roads and eliminated the points if it is under a certain threshold.

After these steps only edges are extracted and the data size also can be reduced to around 10 % of the original data. Fig. 3 (c) shows the result feature after the edge extraction.



(a) (b) (c)

Figure 3 – Edge extraction schema. (a) Highlighted edges. (b) Edges mapped onto a sphere and expanded. (c) Expanded edges displayed in the original position, with the road surface eliminated.

2.2 Edge-based Alignment

The range image taken by range sensor contains the distance information between object and laser sensor, so the origin of coordinate is at the sensor position. In order to express the aligned multiple data, the coordinate relationship must be calculated and all the data coordinate should be transformed into a same coordinate system.

To express all of the data into a same coordinate system, it is necessary to know the position of range sensor. We use the fast simultaneous 3D-3D matching algorithm for the alignment that we have ever proposed in [7, 8]. Certainly we can find same features and corresponding points in the adjacent data for alignment feature. By doing this alignment work repetitively, we can get a whole tunnel in the same coordinate system. The concrete procedure of the matching method is to minimize the equation below by iterative numeric calculation,

$$\min_{R,\vec{T}} \sum_i \left| R\vec{x}_i + \vec{T} - \vec{y}_i \right| \qquad (1)$$

where $\vec{x}_i$ is a point on a range image, $\vec{y}_i$ the corresponding point to $\vec{x}_i$, which is the closest point in this case. R, $\vec{T}$ are rotation matrix and translation vector respectively. Fig. 4 shows the schema of edge based alignment.

Figure 4 – Schema of edge-based alignment.

3. Global Optimization

3.1 Simultaneous Alignment with Fixed-position Constraint

After the edge-based alignment the "locally accurate" raw tunnel model can be obtained, including the accumulated errors in global. Although [7, 8] can originally provide solution for the global optimization, the simultaneous alignment, it requires so-called loop-closure constraint to work properly, i.e. the model data at one side and the other side should have overlap and can be aligned as a pair, which is not the case of a tunnel. One idea for this problem is to give absolute position and posture to the data at both ends, and then apply the simultaneous alignment method.

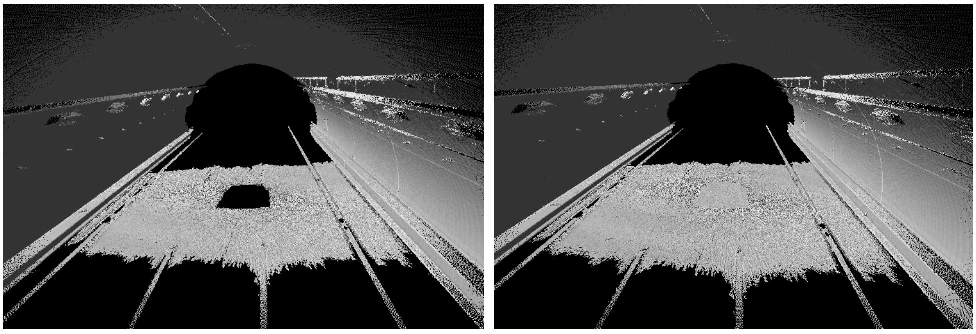
For the absolute localization, we use high-accuracy GPS in this case. We put the GPS antenna at multiple places in both ends of the tunnel by turns, and record the positional information. At this point, the both ends of the model are fixed in absolute positions. Keeping this constraint, we applied the simultaneous alignment and can get the model that can be considered as geometrically optimal in global.

3.2 Filling the Deficient Regions

The output data of range sensor always have deficiency parts because of these two reasons: (1) Road directly under the vehicle can not scanned by laser sensor, (2) Some parts of the road surface do not reflect laser enough. The deficient regions mostly correspond to road, not just regular plane. So the regions around the deficient region also need to be considered, gradient and curvature should also be interpolated smoothly. For filling the region, we resample the scanned data so that we can assume a top-view depth image $\Omega(u,v)$ above the deficient area, where each pixel contains the distance to the surface, $z(u,v)$. This depth image can be speedily generated by rendering function of OpenGL. In order to fill the deficiency in the whole image, we calculate z that minimize the cost function

$$\int_{\Omega}\left(\alpha(z-D)^2+(1-\alpha)\left(\frac{\partial^2 z}{\partial u^2}+\frac{\partial^2 z}{\partial v^2}\right)\right)d\Omega \qquad (2).$$

$D(u,v)$ is the actual depth value by the scanning, and α is a binary parameter representing that the scanned data exist (1) or not (0). The first term in the integral let z be near to the scanned data when it exists, and the second term of the integral let z be connected with surrounding data smoothly. The cost function is calculated repeatedly to minimize the value. Fig. 5 shows the result of the filling.



(a) (b)

Figure 5 – Filling the deficiency. (a) Before. (b) After.

4. Experiment and Evaluation

4.1 Data Acquisition

For the target of 3D modeling, we selected Awagatake (formerly Kanaya) Tunnel in Shin-Tomei Expressway, whose length is 4.6 km. Under the permission of the road administrator, Central Nippon Expressway Co. Ltd., we could have a chance to make the experiment without other vehicles since the Shin-Tomei Expressway is not opened to public at the present moment. For on-vehicle laser range scanner, we used an omnidirectional laser sensor, Z+F Imager 5003 [9], which can make a scan for all directions using phase difference detection method to measure the distance. Fig. 6 shows the actual system.

In the surveying activity we repeated scanning and moving 20 meters to keep overlap between adjacent scans, and it took about 6 hours/km. We obtained 240 range images with the total size in about 100 GB in the Stanford PLY format [10]. Fig. 2 shows the example. Here the survey car is also considered as noise, which can be simply eliminated by thresholding the distance from the laser sensor.

Figure 6 – The survey vehicle in Awagatake (Kanaya) Tunnel, Shin-Tomei Expressway.

4.2 Modeling

In the edge extraction step, we used 20 degree for the angle threshold value. After noise elimination and edge extraction, the data size reduced to about 10 GB.

For fusing GPS data with locally aligned data, we used Nikon Trimble GPS5700 [13]. We put the disc-shaped antenna at 14 places around both ends of the tunnel. In parallel with this, we scanned the scene geometry including the antenna by the Z+F Imager, and align the existing local-aligned data to the scanned data. Here, in order to find the position of GPS antenna in the range image which can not be clearly extracted because of the scanning resolution, we matched a simple 3D model of the antenna created by scanning the antenna with another precise sensor, VIVID 9i [14], in advance.

The modeling result is shown in Fig. 7.

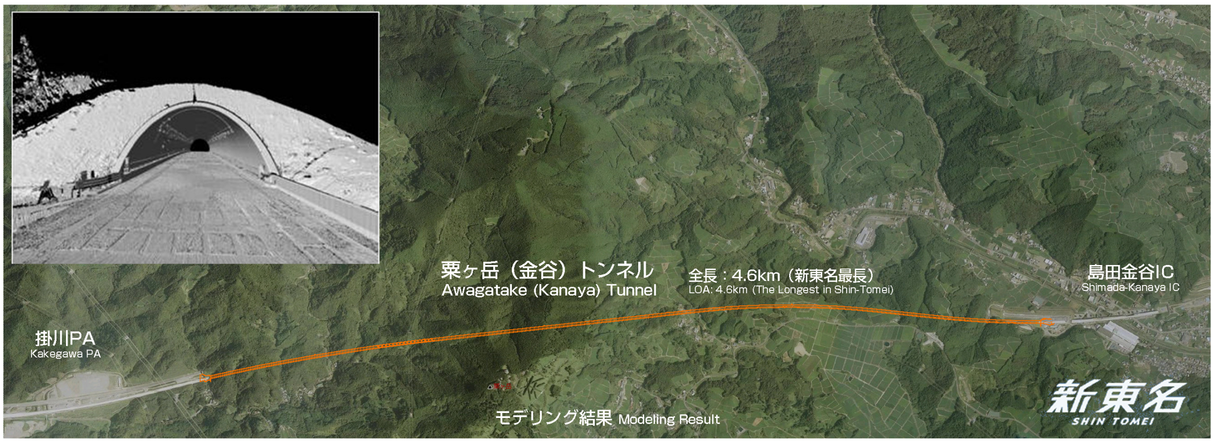


Figure 7 – Awagatake (Kanaya) Tunnel modeling result.

4.3 Evaluation

For evaluating the modeling result, we compared it with 2D CAD blueprint. The coordinate system of the CAD data is based on the *Japan Planar Rectangular Coordinate System No. VIII*, the national standard defined by GSI (Geographical Survey Institute, Ministry of Land, Infrastructure, Transport, and Tourism). The axes (X, Y) correspond to (east, north) in meter unit and it has one-to-one correspondence to latitude and longitude. Since the CAD data is structured as a set of layers, outer boundaries can be easily separated as Fig. 8.

As for the 3D model, inner walls can be extracted by height thresholding. The origin in Fig. 9 represents the range sensor mounted on the survey car. For the extraction, we searched the range along the z axis in which the points representing the inner walls have maximum distance from the z axis. Actually the range was determined as (-1.65, -1.60). Plotting both of them is shown in Fig. 10 (a).

For quantitative evaluation we figured out midlines from the each, a set of midpoints of the shortest lines connecting the northern and southern outer boundaries or the inner walls. And then, we estimated amount of the difference as the closest distance between the midlines in CAD data and our scanned data, which result into Fig. 10 (b).

It shows the largest difference exists around the central zone. It is no wonder since in the central the alignment error accumulates the most and uncertainty becomes the largest. The amount is about 4.5 m, which is just 0.1% of the tunnel length in ratio.

The second largest difference exist around x = -38000 to -37700, which roughly correspond to the sharpest curve zone in a tunnel.

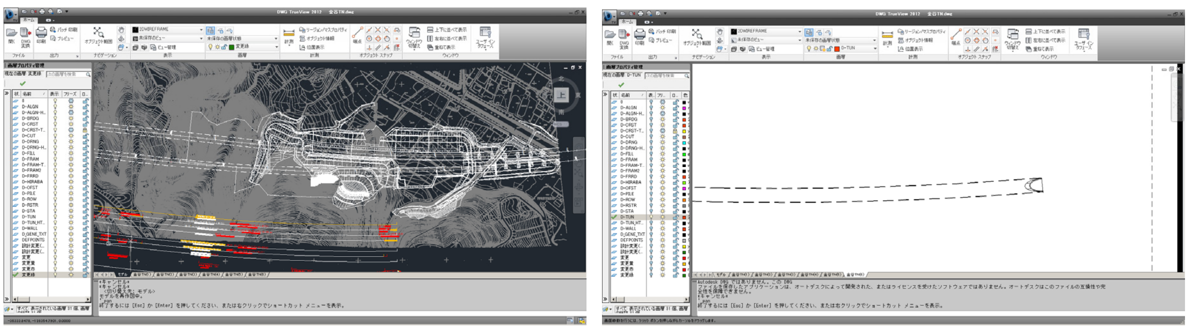


Figure 8 – Separating outer boundaries from 2D CAD blueprint.

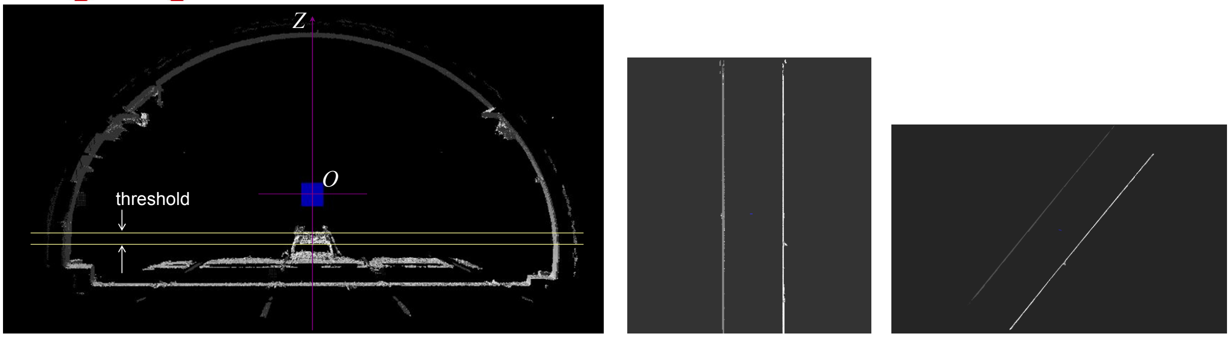


Figure 9 – Extracting inner walls from 3D model.

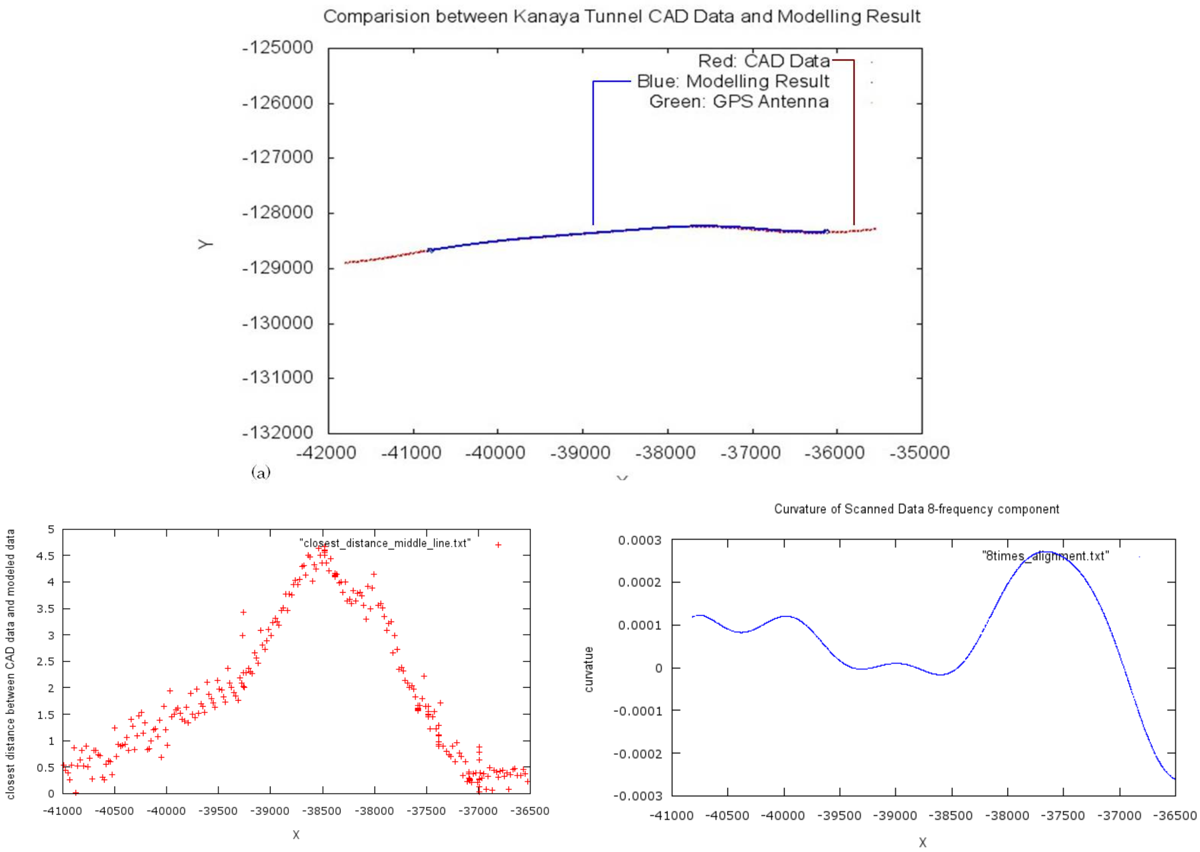


Figure 10 – (a) Outer boundaries in CAD data and Inner walls in the 3D scanned model. (b) Difference between 3D model and 2D CAD data. (c) Curvature of the tunnel.

4.4 Discussion

For examining the second largest difference, we analyzed a curvature of the midline in the

CAD data. In order to focus attention onto general tendency and skip the details, low-pass filter up to 8-frequency component is applied, i.e. a Fourier-series curve is fitted, which directly provides curvature values. The result is shown in Fig. 10 (c). In comparison with Fig. 11, it is surmised that minute rotation error in the alignment process occurred around large curve.

Another factor to be considered is GPS error. In the global alignment process this time we fully fixed the scanned 3D data directly associated with the GPS, however, they should have possibility to move to be matched better with other data, within the limit of GPS precision. s

5. Conclusion

In this paper, we proposed a method for dense 3D modeling of large-scale tunnel, and created the actual 3D model of Awagatake Tunnel in Shin-Tomei Expressway with 4.6 km length. We first acquire a set of partial structures by static laser scanning and align them by 3D matching using edge feature, and then fix the absolute position of the data for both ends of the tunnel by GPS and align the rest data again.

After comparing it with the 2D CAD data, the difference mainly appeared in the central zone and curved zone. The amount was 0.1% of the tunnel length in ratio, which is considered to be caused by minute alignment error and GPS error.

Although this method is not efficient enough for modeling every road in Japan and in the world, it may be reasonable enough for modeling especially long and complex tunnels, or the tunnels with quite a few traffic accidents..

Acknowledgement

This work was, in part, supported by Development of Energy-saving ITS Technology in New Energy and Industrial Technology Development Organization (NEDO).

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