CONSTRUCTION OF DIGITAL SURFACE MODEL BY MULTI-SENSOR INTEGRATION FROM AN UNMANNED HELICOPTER

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ABSTRACT:

Three dimensional data is in great demand for the various applications. In order to represent 3D space in details, it is indispensable to acquire 3D shape and texture together efficiently. However, there still lack a reliable, quick, cheap and handy method of acquiring three dimensional data of objects at higher resolution and accuracy in outdoor and moving environments. In this research, we propose a combination of a digital camera and a small (cheap) laser scanner with inexpensive IMU and GPS for an unmanned helicopter. Direct geo-referencing is achieved automatically using all the sensors without any ground control points. After the accurate trajectory of the platform with attitude changes are determined through the direct geo-referencing, 3D shape of objects is determined by laser scanner as 3D point cloud data, while texture is acquired by CCD sensor from the same platform simultaneously. A method of direct geo-referencing of range data and CCD images by integrating multi sensors for constructing digital surface model are focused. While measuring, an unmanned helicopter is continuously changing its position and attitude with respect to time. For direct geo-referencing, IMU measures the movement of the platform. IMU has a rising quality, but it is still affected by systematic errors. Through Kalman filter operation, an optimal estimate of the sensor position and attitude are determined from GPS and IMU. Meanwhile, geo-referencing of CCD image is determined by bundle block adjustment. GPS and IMU allow automatic setting of tie-points and they reduce the number of tie-points and searching time of tie-points by limiting of searching area. The result of bundle block adjustment aids Kalman filter. IMU are initialized for Kalman filter using the result of bundle block adjustment. That is, after every bundle block adjustment, IMU and its error are complemented. Geo-referencing of laser range data is done by using the result of aiding Kalman filter. Therefore, geo-referencing of range data and CCD images is done directly to overlap exactly with high accuracy and high resolution. The method of data acquisition and digital surface modelling is developed by direct geo-referencing of laser range data and CCD images with GPS and IMU. This is the way of rendering objects with rich shape and detailed texture automatically. A new method of direct geo-referencing by the combination of bundle block adjustment and Kalman filter is proposed.

1. INTRODUCTION

Utilization of mobile platform is very important for acquiring data effectively in wide area (Zhao, H., Shibasaki, R., 2000 and Zhao, H., Shibasaki, R., 2001). The mobile mapping has been developed since late 1980's. The development of the mobile mapping system becomes possible due to the availability of GPS and IMU (Manandhr, D., Shibasaki, R., 2002). In this research, a combination of a CCD sensor and a small (cheap) laser scanner with an inexpensive IMU and GPS for mobile platform are proposed. The method to integrate these sensors should develop for the high precision positioning system in moving environment (Nagai, M., Shibasaki, R. et al., 2003). In this research, the way of direct geo-referencing is achieved automatically from mobile platform without any ground control points. Here, direct geo-referencing means geo-referencing which do not require ground control points with accurately measured ground coordinate values. The methods of data acquisition and digital surface modelling are developed with the method of direct geo-referencing of laser range data and CCD images with GPS and IMU from an unmanned helicopter. This leads to rendering objects with rich shape and detailed texture automatically.

2. SYSTEM DESIGN

1.1 Sensors

In this research, laser scanner and digital camera with IMU and GPS are used to construct digital surface model. In order to construct digital surface model automatically, it is necessary to develop the high precision positioning system in all circumstances for determining the movement of sensors. Integration of GPS/IMU is very effective for high accuracy positioning of mobile platform (Kumagai, H., Kubo, Y., 2002 and Kumagai, H., Kindo, T., 2000). 3D shape is acquired by laser scanner as point cloud data, and texture information is acquired by digital camera from the same platform simultaneously. List of sensors which is used in this research is shown in Table 1.

The key points of the system design are to realize “handiness” and “mobility”. “Handiness” means low cost, easy method, and

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so on. Utilization of a small laser scanner, a commercial digital camera, and an inexpensive IMU (fiber optic gyro) are proposed to use in this research and these sensors are low cost in comparison with existing 3D measurement tools. These low cost equipments are easy to find in market. “Mobility” means light weight system, simple system, and so on. Weights of sensors are shown in Table1. That is, this system can be borne by a variety of platforms, not only an unmanned helicopter but also small vehicle, carrying by human, and so on. These sensors do not own excellent specification, but they are light and low cost with enough specification. In this research, these handy sensors are used and make excellent result by integrating of sensors.

Table 1 List of Sensors

Sensors	Model	Specification
Digital Camera	Canon EOS 10D	3072×2048 pixels Focus length: 24.0mm Price: $1,500US Weight: 500g
Laser Scanner	SICK LMS-291	Angular resolution: 0.25° Max. Distance: 80m Accuracy (20m) : 10mm Price: $4,000US Weight: 4,000g
IMU	Tamagawa Seiki Co., Ltd TA7544	Fiber Optic Gyro Accuracy Angle: ±0.1° Angle Velocity: ±0.05°/s Acceleration: ±0.002G Price: $20,000US Weight: 1,000g
GPS	Ashtech G12	Accuracy Differential: 40cm Velocity Accuracy: 0.1(95%) Price: $4,000US Weight: 150g

All the sensors are tightly fixed on the unmanned helicopter to have constant geometric relationship in all circumstances. Calibration of digital camera and laser scanner is conducted to estimate relative position and attitude. Also, all sensor are synchronized by 1 pps GPS data to integrate.

1.2 Platform

In this research, all the measurement tools are loaded on the unmanned helicopter, RPH2, which is made by Fuji Heavy Industries Ltd., shown in Figure 1. The size of RPHS is a length of 4.1m, a width of 1.3m, and a height of 1.8m. And Table 2 shows the main specification of RPH2. And all the sensors are tightly fixed under the unmanned helicopter. In the experiment, the unmanned helicopter flies about 1.8m/sec. of speed for acquiring laser point data with sufficiently fine resolution and sequential digital camera images with sufficient overlaps.

Figure 1 RPH2

Table 2. Specification of RPH2

Weight	330 kg
Pay load	100 kg
Motor	83.5 hp
Main Rotor	2 rotors, diameter 4.8m
Tail Rotor	2 rotors, diameter 0.8m
Operational range	3km or over
Endurance	1 hour
Ceiling	2000m

There are several advantages to utilize an unmanned helicopter. One of the most advantageous things is unmanned platform, so it can fly over dangerous zone such as disaster, floating ice, land mines, and so on. Advantage of unmanned helicopter suits the purpose of direct-georeferencing of this research. Direct-georeferencing does not require ground control points with accurately measured ground coordinate value. In dangerous zone, it is impossible to set control points unlike normal aerial surveys. Therefore, combination of this direct-georeferencing method from an unmanned helicopter might be ideal tools for dangerous monitoring purpose.

3. MULTI-SENSOR INTEGRATION

3.1 Overview

Figure 2 shows the overview of data processing. In this research, following data are acquired; base station GPS data, remote station GPS data, IMU data, CCD images, and laser range data. Though the data are acquired in different frequencies, they are synchronized each other. At first, kinematic GPS post processing is conducted by Waypoint’s GrafNav commercial software. Secondly, processed GPS data and IMU data are integrated with Kalman filter operation. Thirdly, bundle block adjustment of CCD image is made with the support of GPS/IMU. Finally, GPS/IMU and bundle block adjustment of CCD images are combined generating high precision and time series position and attitude. Then, this hybrid positioning data is used for coordinate conversion of laser range data and construction of digital surface model.

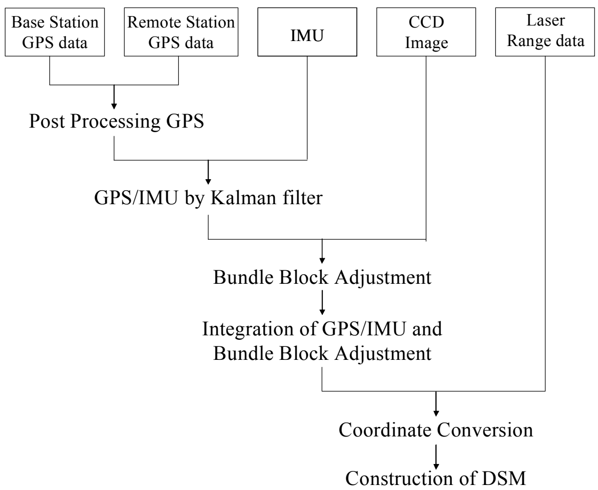

Figure 2 Overview

3.2 GPS/IMU integration by Kalman filter

The integration of GPS and IMU is implemented using Kalman filter. Kalman filter can be used to optimally estimate the system states. In Kalman filter, the final estimation is based on a combination of prediction and actual measurement. Figure 3 shows the pure navigation algorithm for deciding attitude, velocity, and position. IMU has a rising quality, but it is still affected by systematic errors. Here, GPS measurement is applied as actual measurement in order to aid IMU by correcting this huge drift error. Through Kalman filter operation, an optimal estimate of the sensor position and attitude is determined from GPS and IMU. Figure 4 shows Kalman filter circulation diagram for GPS/IMU integration.

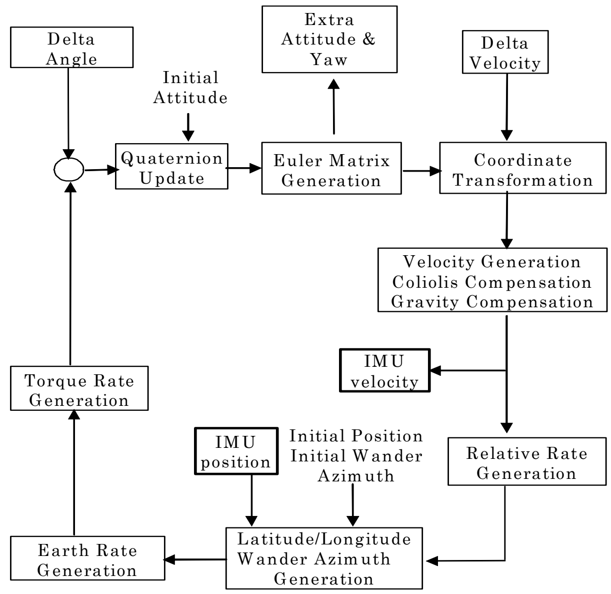

Figure 3 Pure Navigation Algorithm

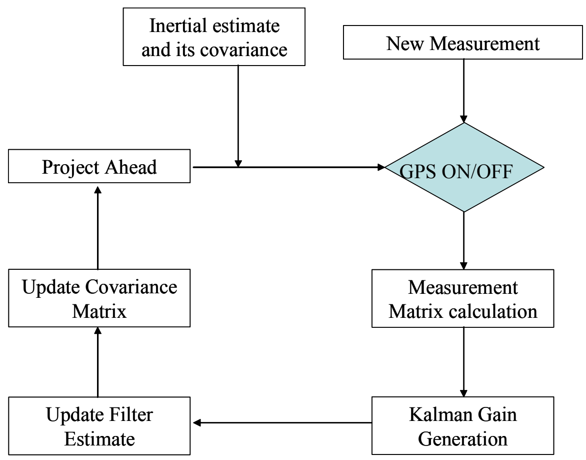

Figure 4 Kalman filter Circulation

In addition, boresight offset must be estimated between GPS antenna and IMU. In Kalman filter circulation, differences of position and velocity between IMU and RTK-GPS are used to estimate amount of errors. If the unmanned helicopter just goes straight, amount of errors is not affected because the relative movement is very constant. However, if the unmanned helicopter makes a turn, amount of errors is not small. Position and velocity of near axis of gyration is small, though its far axis of gyration is big. In this research, boresight offset from GPS antenna to IMU in a platform is obtained by direct measurement.

3.3 Bundle block adjustment of CCD images

Meanwhile, orientation of digital camera is determined by bundle block adjustment. Bundle block adjustment is a non linear least squares optimization method using tie-points of inside block. Bundle block adjustment is used for the determination of the orientation parameters of all CCD images. Bundle block configuration increases both the reliability and the accuracy of object reconstruction. An object point is determined by intersection from more than two images, which provides local redundancy for gross error detection and which makes a better intersection geometry as a result. So, in this research, CCD images are taken for more than 60% overlapping in forward direction, and more than 30% overlapping in side.

Table 3 shows the result of bundle block adjustment. "cp" is the control points which is measure by total station as true values. "ba" is the computation result by bundle adjustment. Accuracy is estimated by comparing 20 control points and the result of bundle adjustment. Average of residual of its plane (X, Y) is approximately 3cm to 6cm. Average of residual of its height (Z) is approximately 10cm. That is, this result is very accurate as compared with RTK-GPS or GPS/IMU integration. Therefore, the result of bundle block adjustment aids Kalman filter by initialization of position and attitude.

GPS/IMU allows automatic setting of tie-points and it reduces the number of tie-points and searching time of tie-points by the limitation of searching area. Many researches have done for bundle block adjustment, but it is very difficult to set accurate tie-points automatically. This is the reason of difficulty of real-time processing of bundle block adjustment. GPS/IMU helps to set tie-points with enough accuracy,

Table 3 Accuracy of Bundle block adjustment

Num	X (cp:m)	Y (cp:m)	Z (cp:m)	X (ba:m)	Y (ba:m)	Z (ba:m)	residual: X	residual: Y	residual: Z
1	0	0	-12.584	0.094	-0.059	-12.311	0.094	0.059	0.273
2	11.3105	0	-12.3825	11.293	-0.062	-12.48	0.0175	0.062	0.0975
3	20.8395	0.168	-12.4065	20.79	0.111	-12.515	0.0495	0.057	0.1085
4	32.588	0.2885	-12.441	32.527	0.229	-12.564	0.061	0.0595	0.123
5	46.196	0.5035	-12.5105	46.103	0.447	-12.518	0.093	0.0565	0.0075
6	0.074	-8.1735	-12.515	0.173	-8.145	-12.336	0.099	0.0285	0.179
7	11.3245	-7.905	-12.428	11.346	-7.891	-12.458	0.0215	0.014	0.03
8	20.5425	-7.703	-12.4345	20.525	-7.72	-12.499	0.0175	0.017	0.0645
9	30.677	-7.315	-12.406	30.622	-7.341	-12.575	0.055	0.026	0.169
10	46.7025	-7.81	-12.566	46.608	-7.849	-12.459	0.0945	0.039	0.107
11	0.4485	-14.9755	-12.473	0.551	-14.917	-12.376	0.1025	0.0585	0.097
12	11.6895	-15.058	-12.4075	11.734	-15.019	-12.483	0.0445	0.039	0.0755
13	20.3605	-14.902	-12.419	20.361	-14.891	-12.518	0.0005	0.011	0.099
14	30.447	-15.3555	-12.47	30.424	-15.347	-12.503	0.023	0.0085	0.033
15	46.3735	-15.455	-12.5715	46.289	-15.456	-12.401	0.0845	0.001	0.1705
16	0.3535	-24.139	-12.443	0.453	-24.072	-12.522	0.0995	0.067	0.079
17	11.911	-23.7855	-12.455	11.987	-23.721	-12.466	0.076	0.0645	0.011
18	20.594	-23.461	-12.453	20.623	-23.421	-12.507	0.029	0.04	0.054
19	30.176	-23.1665	-12.4505	30.165	-23.13	-12.491	0.011	0.0365	0.0405
20	46.258	-22.5005	-12.5545	46.2	-22.493	-12.39	0.058	0.0075	0.1645
						ave	0.05655	0.0376	0.09915

cp: control points ba: bundle adjustment

3.4 Multi-sensor integration

The positioning and attitude of sensors are decided by integration of GPS/IMU, as well as CCD images. One of the main purposes of this research is to integrate sensors for

developing the high precision positioning system in all circumstances. Integration of GPS, 1Hz, and IMU, 200Hz, has to be made with Kalman filter for geo-referencing of laser range data with the frequency of 18Hz. Positioning accuracy of GPS/IMU is around 10-30 cm, because it is limited by the accuracy of RTK-GPS. On the other hand, position and attitude can be estimated very high accurately with bundle block adjustment of CCD images, though the images are taken every 10 seconds.
Therefore, the combination of bundle block adjustment and GPS/IMU by Kalman filter is conducted to achieve higher accuracy. The results of bundle block adjustment are assumed to be true position values. IMU/GPS are initialized for Kalman filter using the result of bundle block adjustment. Namely, after every computation of bundle block adjustment, GPS/IMU and its error are corrected. Figure 3 is the strapdown navigation algorithm for integrating GPS/IMU with the result of bundle block adjustment. The combination of GPS/IMU and bundle block adjustment can be called “hybrid IMU”.

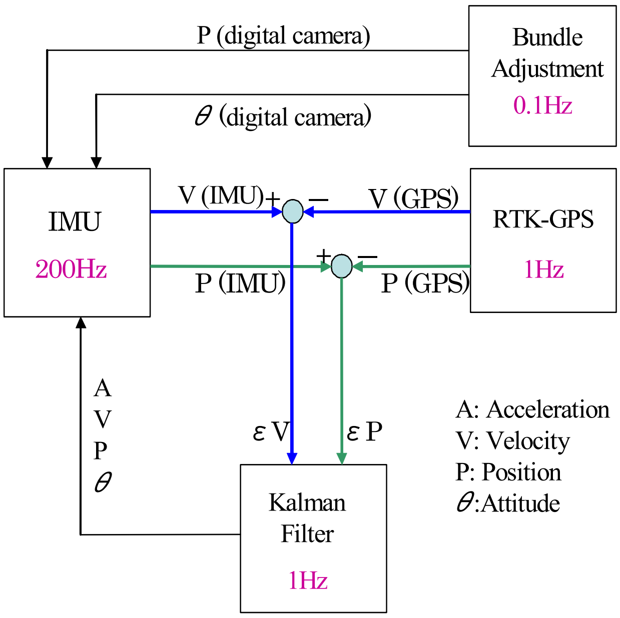

Figure 5 Strapdown navigation algorithm

As the result of GPS/IMU is corrected with bundle block adjustment, trajectory of hybrid IMU can assure good geo-referencing accuracy for the CCD images. That is, the trajectory of a platform is trajectory of digital camera. This is one of the advantages of this system. GPS/IMU coordinate is fitted to digital camera coordinate. Figure 6 shows the trajectory of the unmanned helicopter in this experiment. Hybrid IMU is computed by aiding of GPS/IMU and bundle block adjustment. The square dots are the timing of bundle block adjustment, GPS/IMU by Kalman filter is initialized by these points. The circle dots are the trajectory of RTK-GPS. The line is the Hybrid IMU, which is combined GPS/IMU and results of bundle block adjustment.

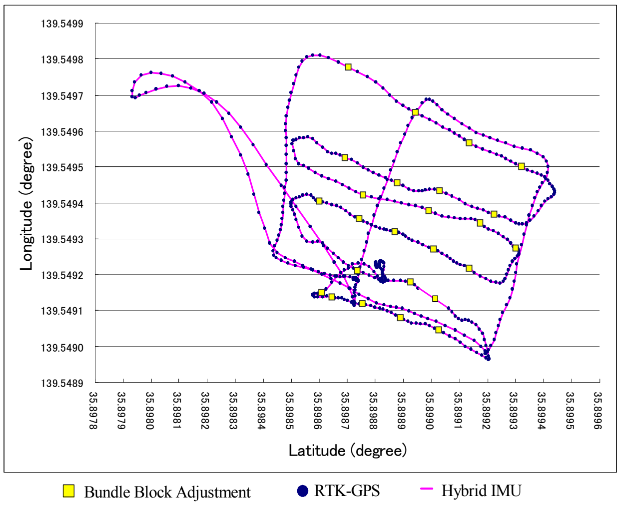

Figure 6 Trajectory of the unmanned helicopter

4. DIGITAL SURFACE MODEL

4.1 Direct geo-referencing

While the measuring, the platform including all sensors is continuously changing its position and attitude with respect to time. For direct geo-referencing of laser range data and CCD images, hybrid IMU, position and attitude, which are integrated by GPS/IMU and bundle block adjustment is used. There are only two coordinate systems, laser scanner coordinate system and the common world coordinate system, are existing. Thus GPS/IMU and bundle block adjustment of CCD images have the common world coordinate system. That is, just laser scanner coordinate system must be converted to the common world coordinate system by geo-referencing. Geo-referencing of range data is determined by 3D Helmert’s transformation which is computing rotation matrix and shift vector with hybrid IMU data and calibration parameters as offset. Offset from laser scanner to digital camera in body frame is already obtained by sensor calibration.

All the points scanned by the laser scanner (x) are converted to the common world coordinate system (X_w) which is the same as digital camera coordinate system as given by Eq.(1). Rotation matrix (R_h) and shift vector (S_h) from hybrid IMU which is corrected drift error are used with respect to time. Offset values ($R_{l\text{-}d}$ and $S_{l\text{-}d}$) are already estimated in sensor calibration.

$$X_w = (R_h * R_{l\text{-}d})\, x + (S_h + S_{l\text{-}d}) \qquad (1)$$

where R_h, S_h : hybrid IMU, Rotation and Shift
$R_{l\text{-}d}$, $S_{l\text{-}d}$: offset by calibration

Geo-referencing of laser range data and CCD images is done directly to overlap exactly with high accuracy, which is accuracy of CCD image. In this research, the world coordinate system of CCD images by bundle block adjustment is used as the base coordinate system. IMU/GPS is adapted to this common coordinate system by initialization of Kalman filter. Finally, laser range data are converted to this common coordinate system by using hybrid IMU and results of calibration.

4.2 Digital surface model

The DSM, digital surface model, is a 3D model of the object surface that is manipulated using a computer. It is comprised of 3D measurements that are laid out on colored points cloud. These measurements are the 3D point cloud data, which are derived from laser scanner, and texture data, which is derived from CCD sensor.

The point cloud data acquired by laser scanner is geo-referenced by hybrid IMU data. This hybrid IMU data is based on the common world coordinate system, which is the same as the coordinate of CCD images and GPS. Texture data are overlaid on geo-referenced point cloud data. The integrated point cloud data shows a good matching with image data because hybrid IMU data is initialized by the result of bundle block adjustment of sequential image data. Figure 7 shows the concept of construction of DSM (Digital Surface Model). Each point of geo-referenced laser point data corresponds to a pixel of geo-referenced CCD image in the same coordinate system. In this research, 3D point cloud data takes on a color from the corresponding image pixels for textured digital surface model.

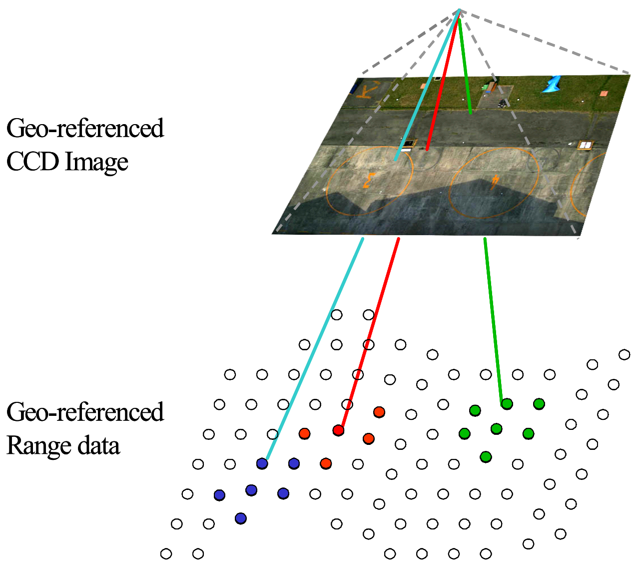

Figure 7 DSM

5. CONCLUSION

In conclusion, all the sensors, laser scanner, digital camera, IMU, and RTK-GPS are integrated for constructing DSM. In this research, a new method of direct geo-referencing by the combination of bundle block adjustment and GPS/IMU by Kalman filter is proposed. Because of the aiding Kalman filter by bundle block adjustment, geo-referenced laser range data and CCD images are overlapped correctly in the common world coordinate system. All the sensors and equipments are assembled and loaded on an unmanned helicopter as a experiment. This paper focus on how integrate these sensors with mobile platform. Finally, accurate trajectory of sensor is computed as hybrid IMU and it is used for direct geo-referencing for laser range data and CCD images to construct digital surface model.

6. REFERENCES

Nagai, M., Shibasaki, R., Zhao, H., Manandhar D., 2003. Development of Digital Surface Model and Feature Extraction by Integrating Laser Scanner and CCD sensor, Proceedings of the 24th Asian Conference on Remote Sensing, Busan, Korea.

Kumagai, H., Kubo, Y., Kihara, M., and Sugimoto, S., 2002. DGPS/INS/VMS Integration for High Accuracy Land-Vehicle Positioning, Journal of the Japan Society of Photogrammetry and Remote Sensing, vol.41, no.4 pp.77-84.

Kuamgai, H., Kindo, T., Kubo, Y., Sugimoto, S., 2000. DGPS/INS/VMS Integration for High Accuracy Land-Vehicle Positioning, Proceedings of the Institute of Navigation, ION, GPS-2000, Salt Lake.

Manandhar, D., Shibasaki, R., 2002. Auto-Extraction of Urban Features from Vehicle-Borne Laser Data, ISPRS, "GeoSpatial Theory, Processing and Application", Ottawa.

Zhao, H., Shibasaki, R., 2000. Reconstruction of Textured Urban 3D Model by Ground-Based Laser Range and CCD Images, IEICE Trans. Inf.&Syst., vol.E83-D, No.7.

Zhao, H., Shibasaki, R., 2001. High Accurate Positioning and Mapping in Urban Area using Laser Range Scanner, Proceedings of IEEE, Intelligent Vehicles Symposium, Tokyo.

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