

Development of a vehicle-mounted road surface 3D measurement system

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Abstract: In recent years, automation system based on IT technology becomes very popular not only for manufacturing industries but also for the construction and civil engineering industries. The conventional location survey method in the civil engineering construction site is pinpoint location survey for a broad objective area. The conventional method has severe constraints when it comes to measure the broad objective area as macro or to estimate general distinctive geometrical features. In this study, a unique vehicle-mounted mobile measurement system which can measure dense 3D point-cloud data for wide construction site is presented. The proposed MMS (Mobile Mapping System) is equipped with the carrier phased D-GPS/DR combined navigation system, the GPS gyro, and a laser scanner. The MMS, which measures unlevelled round surface at 40 [km/h] using laser scanner's range data and vehicle attitude stabilization algorithm, can construct continuous dense road surface 3D model. The functional and performance test as a mobile measurement instrument is revealed.

Keywords GPS-Gyro/IMU, Mobile Mapping System, as-built management, 3D measurement

1. Introduction

In recent years, automation system based on IT becomes very popular not only for manufacturing industries but also for the construction and civil engineering industries.

The conventional method like a using tape measure, level, and pictures, has problems, that is inefficient, is low reliability and accuracy. So in recent years, the method of as-built management has moved the traditional method towards the method which using GPS and Total Station (TS). The TS measurement method has advantages on its operational flexibility, reliability and accuracy. But the TS measurement method has severe constraints when it comes to measure the broad objective area as macro or to estimate general distinctive geometrical features.

In this study, a unique vehicle-mounted mobile measurement system which can measure dense 3D point-cloud data for wide construction site is presented. The proposed MMS is equipped with the carrier phased D-GPS/DR combined navigation system, the 3 axes GPS gyro, and a laser scanner. The MMS, which measures unlevelled round surface at 40 [km/h] using laser scanner's range data and vehicle attitude stabilization algorithm, can construct continuous dense road surface 3D model. In short-time measurement, when the number of visible satellites doesn't change, data continuousness is high. So, 3D surface model and can identify change region using GCP (Ground Control Point), which is generally used in aerial survey, according to the construction process progress.

The functional and performance test as a mobile measurement instrument is revealed.

2. System configuration

This mobile mapping system combines an accurate positioning by GPS/DR measurements and attitude/heading referencing by carrier phase based GPS Gyro measurements with three progressive scan cameras and three laser scanners as shown in Fig.1. A hybrid car provides 1500 watt continuously for the sensor and computer's electric power without a supplementary battery. An embedded system guarantees the synchronization of navigation data with imagery. The spatial referencing is provided by PAS (Positioning Augmentation Services) system operated by Mitsubishi Electric Corporation. Two GPS antennas are set parallel to the left side of the vehicle and one antenna is set triangular position to the others. The sensor specifications are listed in Table1.

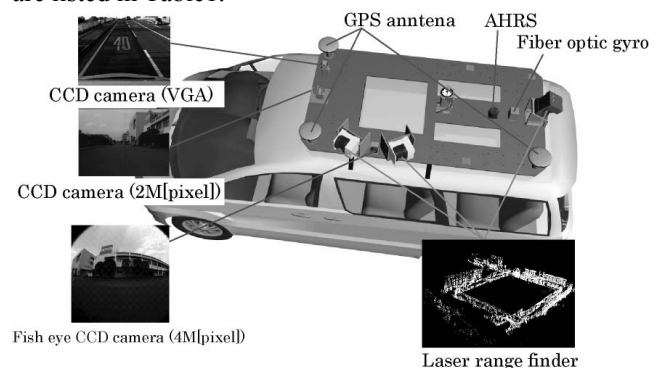


Fig.1. System configuration

All sensors are mounted on the top of a van on a rigid roof-rack.

Table1 Sensor Configuration

Loaded sensor	Sensor name	Manufacturer
GPS	BD950	Trimble
	ANTARIS	u-blox
odometer		Mitsubishi Electric
IMU	AHRS400CC-100	Crossbow
Fiber Optic Gyro	JG-35FD	Japan Aviation Electronics
CCD Camera	VGA-120	IMPERX
	2M30C	
	4M15C	
Laser scanner	LMS 291	SICK
	LMS 200	

3. Precise positioning by GPS/DR measurements and attitude/heading referencing by carrier phase based GPS Gyro/IMU measurements

When operating in higher speeds in quickly changing surroundings, any global application of precise trajectography requires high-performance GPS receivers with instantaneous re-acquisition of signals after loss. The dual frequency receiver Trimble BD950 can provide raw data 10 times per second. To ensure a use of the system under a poor GPS coverage, DR system consisting of an odometer and a FOG (Fiber Optics Gyro) provides the linear speed and angular rate at 120 Hz. The carrier phased D-GPS fixed solution provides aiding to the loosely coupled inertial navigator by EKF(Extended Kalman Filter). Further aiding comes in the form of initial heading angle from the GPS Gyro. The GPS/DR combined navigation system is shown in Fig.2 The horizontal positioning accuracy is about 20[mm] (1σ) and the vertical one is about 40[mm] (1σ) when excellent GPS visibility is obtained. The GPS Gyro consists of three pairs of single frequency GPS antennas, three un-synchronized receivers, an AHRS providing three angular rates and EKF. As the GPS Gyro's synchronization of three un-synchronized receivers is achieved by the GPS 's UTC time stamp, any low price receivers with low carrier phase noise can be used. The block diagram is shown in Fig.3.

GPS Gyro's operational theory is shown in Fig.4. Suppose that (a) and (b) are GPS antennas which receive same two GPS satellites signal simultaneously.

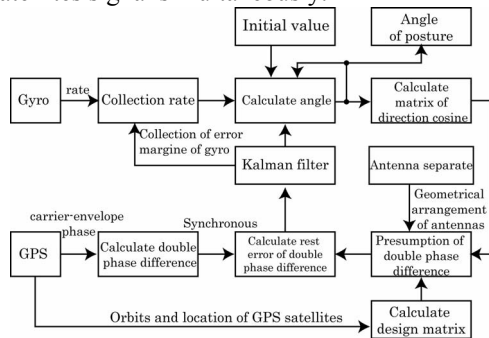


Fig.2. Software synchronized GPS Gyro.

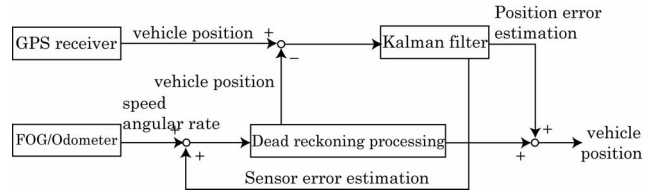


Fig.3. Loosely-Coupled Carrier-Phase D-GPS/DR combined navigation.

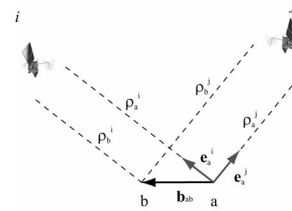


Fig.4. Relation between double difference and baseline vector

The pseudo range ρ_{ab}^{ji} can be expressed as dot product of the baseline vector b_{ab} and its double phase difference as shown in equation (1).

$$\begin{aligned}\rho_{ab}^{ji} &= (\rho_b^j - \rho_a^j) - (\rho_b^i - \rho_a^i) \\ &= -(e_a^j - e_a^i) \cdot b_{ab}\end{aligned}\quad (1)$$

Where, b_{ab} is the baseline vector between antenna a and b, e_a^j is the LOS(Line Of sight) vector from antenna a to satellite j, e_a^i is the LOS vector from antenna a to satellite i, ρ_b^j is the pseudo range from antenna b to satellite j, ρ_a^j is the pseudo range from antenna a to satellite j, ρ_b^i is the pseudo range from antenna b to satellite i, ρ_a^i is the pseudo range from antenna a to satellite i.

Firstly, three independent double phase differences can be obtained by the expansion of the equation (2) to four satellites.

$$\begin{bmatrix} \rho_{ab}^{ji} \\ \rho_{ab}^{ki} \\ \rho_{ab}^{li} \end{bmatrix} = \begin{bmatrix} \lambda(\phi_{ab}^{ji} - N_{ab}^{ji}) \\ \lambda(\phi_{ab}^{ki} - N_{ab}^{ki}) \\ \lambda(\phi_{ab}^{li} - N_{ab}^{li}) \end{bmatrix} = \begin{bmatrix} -(e_a^j - e_a^i) \\ -(e_a^k - e_a^i) \\ -(e_a^l - e_a^i) \end{bmatrix} b_{ba} \quad (2)$$

Where λ is latitude ϕ is longitude, N is ambiguity. Suppose that all LOS vectors from three un-synchronized receivers are synchronized by the GPS time stamp in the data logger. The Equation (3) is simplified as equation (1) using vector W: double phase differences, A: symmetric positive definite matrix and b: baseline vector.

$$w = Ab \quad (3)$$

Secondly, the baseline vector b in ECEF coordinates can be calculated as equation (6) using Cholesky decomposition.

$$(AA^T)^{-1} = U^T U \quad (4)$$

$$b^T b = w^T U^T U w \quad (5)$$

$$b = Uw \quad (6)$$

Finally the baseline can be calculated with every GPS update epoch as equation (7). The ambiguity N can be calculated by the constraints as shown in (8).

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} u_{11} & u_{12} & u_{13} \\ 0 & u_{22} & u_{23} \\ 0 & 0 & u_{33} \end{bmatrix} \begin{bmatrix} \lambda(\phi_{ab}^{ji} - N_{ab}^{ji}) \\ \lambda(\phi_{ab}^{ki} - N_{ab}^{ki}) \\ \lambda(\phi_{ab}^{li} - N_{ab}^{li}) \end{bmatrix} \quad (7)$$

$$\begin{aligned} -B &< b_3 < B \\ -\sqrt{B^2 - b_3^2} &< b_2 < \sqrt{B^2 - b_3^2} \\ -\sqrt{B^2 - (b_3^2 + b_2^2)} &< b_1 < \sqrt{B^2 - (b_3^2 + b_2^2)} \end{aligned} \quad (8)$$

The coordinates transformation from ECEF to NED is obtained as equation (9), where C_e^n is coordinates conversion matrix. Fig.5. shows three antenna placement and its corresponding two baseline vectors: b_2^n and b_3^n .

$$b^n = C_e^n b \quad (9)$$

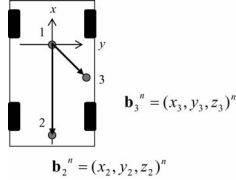


Fig.5. Three antenna placement

Then the vehicle heading and pitching angle is obtained as (10), (11) respectively, and rolling angle is obtained as (12). EKF is used so that an IMU's angle measurement result at 120 Hz is compensated by the GPS Gyro's observation angle.

$$\psi = -\tan^{-1}\left(\frac{x_2}{y_2}\right) \quad (10)$$

$$\theta = \tan^{-1}\left(\frac{z_2}{\sqrt{x_2^2 + y_2^2}}\right) \quad (11)$$

$$\phi = -\tan^{-1}\left(\frac{z_3''}{x_3''}\right) \quad (12)$$

$$\begin{bmatrix} x_3'' \\ y_3'' \\ z_3'' \end{bmatrix} = \begin{bmatrix} \cos \theta \cos \psi & \cos \theta \sin \psi & -\sin \theta \\ -\sin \psi & \cos \psi & 0 \\ \sin \theta \cos \psi & \sin \theta \sin \psi & \cos \theta \end{bmatrix} \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} \quad (13)$$

Fig.6 shows the proposed GPS Gyro's angle resolution in a condition that GPS signal which is corresponding to 0 degrees is offered from a GPS simulator(Spirent,GSS7700).

Fig.7 shows the GPS stationary positioning result. Fig.8 shows the proposed Loosely-Coupled Carrier-Phase GPS/DR combined navigation system positioning result.

The jerk on the data is caused by the tracked satellite's change. The angle resolution, which is decided by the antenna baseline pitch as well as GPS's L-1 band frequency, is 0.1[deg] for heading and rolling and 0.2[deg] for pitching.

The precise posture estimation can contribute to the road sign accuracy improvement as a van tends to cause pitching and rolling movement at larger than 2[deg] in a normal

cruise speed. The GPS-Gyro/IMU's measurement angle data which is corresponding to Fig.9's.

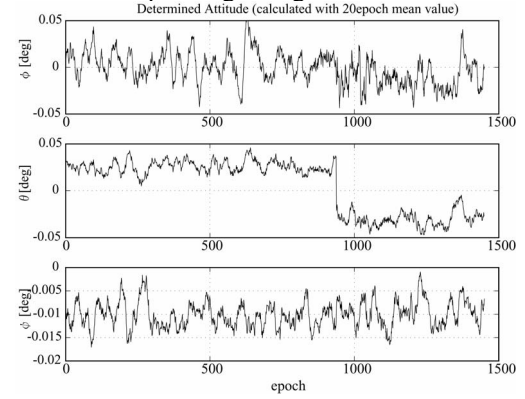


Fig.6. GPS Gyro stationary test result.

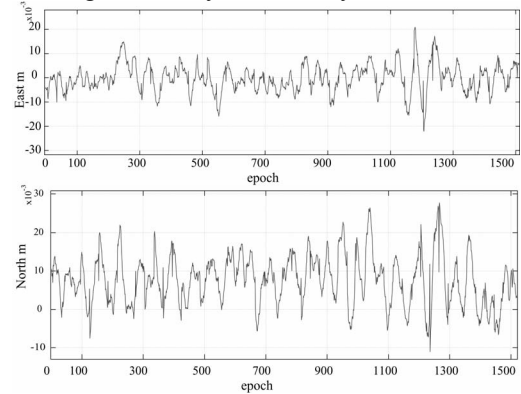


Fig.7. GPS stationary test result.

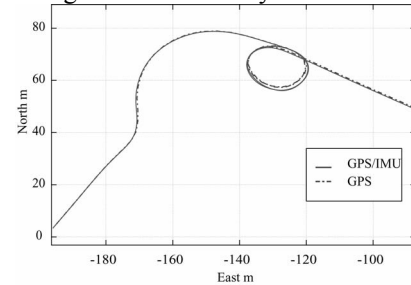


Fig.8. GPS stationary test result.

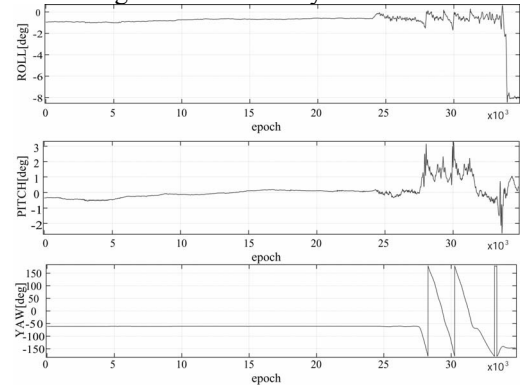


Fig.9. GPS-Gyro/IMU angular measurement result.

4. 3D Reconstruction using point cloud model

Laser measurement result based on the mobile platform is transformed into point cloud data in ENU coordinates. Fig.10 shows an example of the fore slope model. Comparing with corresponding picture, it can be said that

precise terrain feature can be modeled by the GPS mobile measurement. Fig.11 shows a tunnel and Fig.12 shows the corresponding measurement result. As the two sets of LRF are equipped on the left side of the MMS, two ways measurement results are merged into one model. In precise GPS measurement like RTK GPS, height precision ($0.04[m], 1\sigma$) is inferior to that of horizontal precision ($0.02[m], 1\sigma$) and is influenced by the satellite arrangement. Thus, without considering GPS satellite arrangement, long term height error deteriorates 3D reconstruction quality. Fig.10 b) shows the manual coordinate translation result. Comparing with Fig.10 a), it can be said that the internal wall surface was successfully smoothed and was precisely well modeled. If GCP (Ground Control Point), which is measured by the conventional static GPS measurement, can be used to identify tie-point or matching point, GPS mobile measurement quality will be improved.

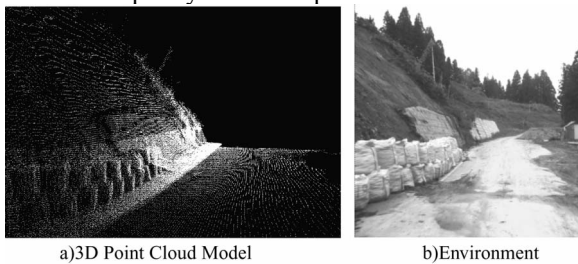
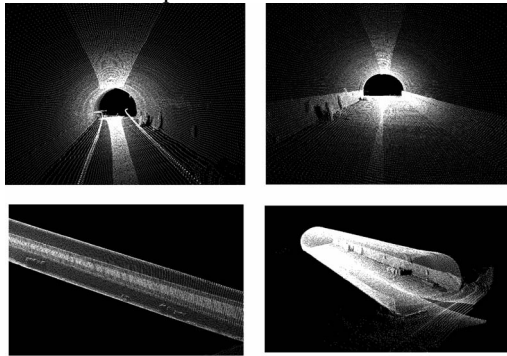


Fig.10. Fore slope 3D point cloud model



Experimental environment



nonaligned model

aligned model

Fig.11. 3D Tunnel Model

5. Pavement depth measurement experiment by the MMS

MMS was applied to the asphalt pavement construction to measure each course depth.

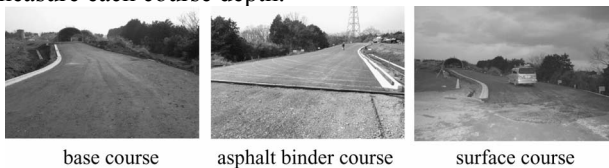


Fig.12. Experiment environment.

Fig.12 shows the experimental field which consists of the base course, asphalt binder course and the surface course.

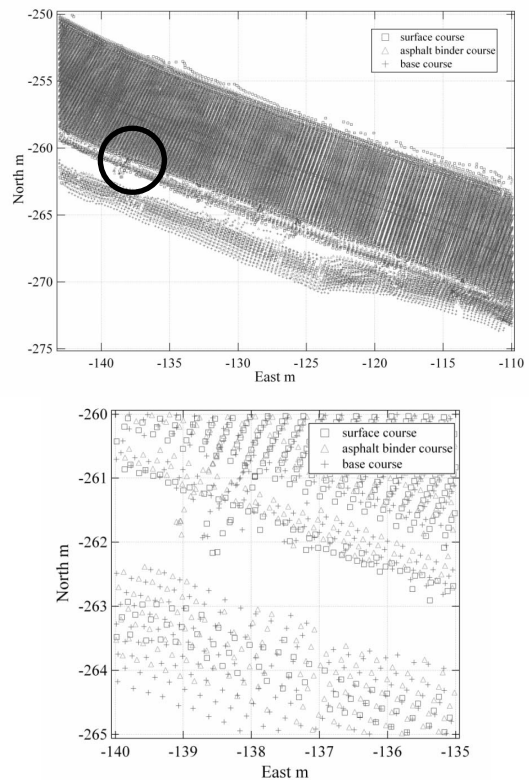


Fig.13. Road Surface Model (nonaligned)

MMS was applied to each construction stage to obtain 3D surface model at about 10[Km/h] speed. These three surface models were simply merged into one road surface model in ENU coordinate as shown in Fig.13.

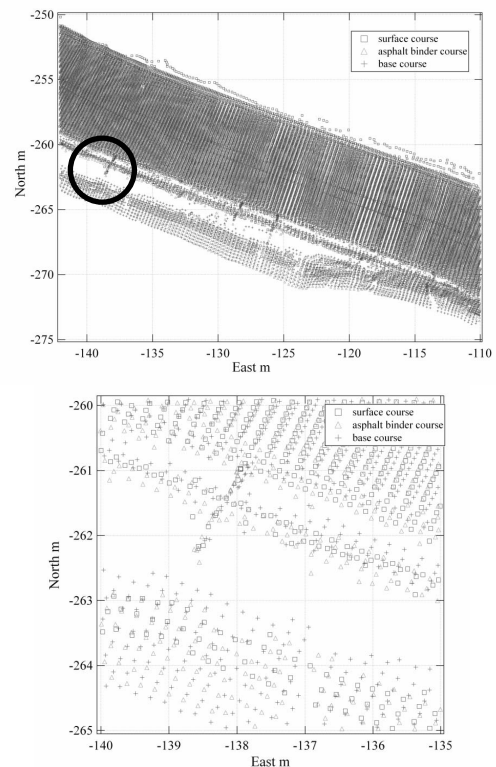


Fig.14. Road Surface Model (aligned)

The lower figure is the enlarged figure which is corresponding to the red circle in the upper figure. The measurement points of each construction stage are supposed to be coincided, but they are definitely shifted.

On the other hand, Fig.14 shows the manual coordinate transformed surface model on the hypothesis that GCP is used to identify the tie point of each surface models. The lower figure of Fig.14 is the enlarged figure which is corresponding points of each construction stage is successfully coincided with all measurement points. It can be said that the obtained each 3D surface model measured by MMS has sufficient continuity and precision. But when it comes to evaluate differential height, i.e. course depth, the tie point of each surface model like the GCP is needed for coordinates adjustment.

6. Conclusion

In this paper, precise GPS mobile measurement by a vehicle-mounted road surface 3D measurement system for the asphalt pavement construction is addressed. The proposed MMS which is equipped with a carrier-phased D-GPS, an IMU, an odometry, the GPS Gyro and three pairs of laser range finder can generate 3D surface model by point cloud data in ENU coordinates. MMS was applied to the asphalt pavement construction to measure each course depth. The measurement points of three construction stage are successfully coincided with all measurement points by manual coordinate transformation. It can be said that the obtained each 3D surface model measured by MMS has sufficient continuity and precision.

7. Future Work

In this paper coordinate transformation of three construction stage's 3D surface model is manually executed. In near future, GCP will be used to identify the tie-point of each stage and the coordinate transformation will be automatically executed. Furthermore, each course depth will be reported analytically.

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