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3D Map Generation Algorithm for Energy Management System on Electric Vehicles

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Abstract

This paper proposes a three-dimensional (3D) map generation algorithm for energy management systems on electric vehicles (EV) or hybrid electric vehicles (HEV). The 3D road geometry of the predefined driving path can be crucial information for energy management systems to design an optimal driving strategy. A single GPS receiver can provide the 3D position of a road profile; however, it is not accurate and reliable enough to use for an energy management system. An information fusion algorithm based on the optimal smoother is applied for map generation to improve the accuracy and integrity of the 3D map database. The algorithm developed in this study is verified and evaluated through experimentation using a probe vehicle equipped with GPS and several on-board sensors. The experimental results show that the map generation algorithm performance is sufficiently accurate and reliable for an energy management system.

Keywords: 3D map, optimal smoother, information fusion, GPS, vehicle on-board sensors

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1 Introduction

Many current EV and HEV energy management systems use information technology services (including road geometry and real-time traffic information) from intelligent transportation systems (ITS) to improve energy consumption efficiency. Road geometry information (such as road height and slope) is crucial information to design efficient driving strategies because the road slope resistance force is a major factor in energy consumption [1-6]. An energy management system can obtain road geometry data from a 3D map database; however, an essential prerequisite for the 3D map is accurate and adequate road profile data to apply to an energy management system.

This paper presents a 3D map generation algorithm for and EV and HEV energy management system. A probe vehicle equipped with a GPS receiver, an inertial sensor, and wheel speed sensors was used as a measurement system [7]. Data from the equipped sensors was integrated with an optimal smoother-based information fusion algorithm to improve the accuracy, continuity, and integrity of the position data from 3D road geometry.

2 System Overview

Figure 1 shows the overall system architecture of a 3D map generation algorithm. The 3D map generation algorithm is composed of two steps of data acquisition and data processing. A probe vehicle acquired position data of the road geometry during the data acquisition step.

A GPS receiver is widely used for the position acquisition system since it provides the global position of vehicles. However, (especially in urban

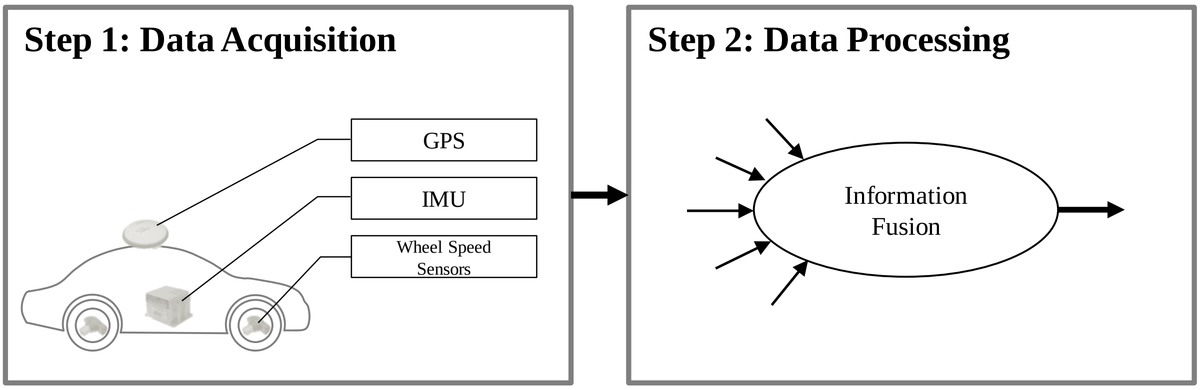


Figure 1: System architecture of a 3D map generation algorithm.

areas) an acquisition system based on a stand-alone GPS receiver can suffer from signal outages and multipath. Therefore, the acquisition system requires additional sensors such as an inertial measurement unit (IMU) and wheel speed sensors that represent vehicle dynamics. At the data processing step, the accuracy, continuity, and integrity of the position data for 3D map generation are improved based on an information fusion algorithm. The information fusion algorithm integrates the acquired vehicle position and dynamic information from the GPS and on-board sensors based on uncertainty characteristics of each sensor using the optimal smoother.

Table 1: List of sensor measurements

Sensor	Measurement	Unit
GPS	Latitude	degree
	Longitude	degree
	Height	meter
	East velocity	meter / second
	North velocity	meter / second
	Up velocity (Climb rate)	meter / second
IMU	3-Axis turn rate	degree / second
	3-Axis acceleration	meter / sencond2
Wheel sensors	Wheel speed	meter / second

3 Data Acquisition of Road Profile

Table 1 describes the list of sensors installed in the probe vehicle. The GPS receiver provides 3D positions that consist of latitude, longitude, and height as well as three-dimensional velocity. The accuracy of the three-dimensional velocity of a single GPS receiver is about 2-5 centimeters per second in the horizontal axis and 4-10 centimeters per second in the vertical axis with a one sigma standard deviation for the stochastic error. Based on the velocity information, the states of the ego-vehicle and road (such as a heading angle of the vehicle and the slope of the road) can be estimated. The heading angle of the vehicle is estimated using the east and north GPS velocity measurement as shown in equation (1).

$$\psi_{GPS} = \tan^{-1}\left(\frac{V_{Y,GPS}}{V_{X,GPS}}\right) \tag{1}$$

The V describes the velocity, and X, Y, Z represent the east, north, and height in global coordinates, respectively. The slope angle of the road can be estimated based on the arctangent of the climb rate over the horizontal velocity measurement as shown in equation (2).

$$\theta_{GPS} = \tan^{-1}\left(\frac{V_{Z,GPS}}{\sqrt{V_{X,GPS}^{2} + V_{Y,GPS}^{2}}}\right) \tag{2}$$

The inertial measurement unit (IMU) provides three-axis turn rate and acceleration information; in addition, the four wheel speed sensors offer the rotational speed of each wheel. The road slope can also be estimated with an accelerometer and wheel speed sensors. Figure 3 shows that the gravitational acceleration originates from the road slope; therefore, the relationship between an accelerometer and wheel speed sensors can be expressed as shown in equation (3).

$$a_{accel} = \frac{d}{dt} V_{whl} + g \sin \theta_{accel} \qquad (3)$$

From this relationship, the road slope is calculated as shown in equation (4).

$$\theta_{accel} = \sin^{-1} \left(\frac{a_{acc} - \frac{d}{dt} V_{whl}}{g} \right) \qquad (4)$$

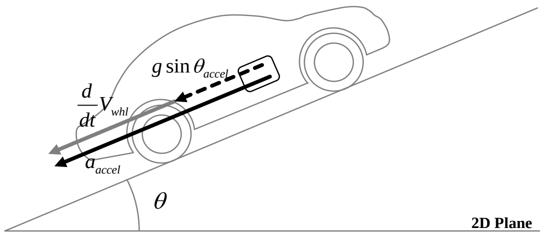


Figure 2. Longitudinal acceleration-based road slope estimation.

4 Optimal Smoothing of the Acquisition Data

The accurate, continuous, and reliable 3D position of the road profile is necessary to generate a 3D map for the energy management system of electric vehicles. The 3D position data of road geometry can be directly obtained from the GPS; however, it is not accurate and adequate for 3D map generation. Therefore, and information fusion algorithm improves the accuracy, continuity, and integrity of 3D position data from the GPS by combining other measurements such as GPS velocity, IMU, and wheel speed sensors.

In this paper, the Rauch-Tung-Striebel (RTS) optimal smoother is used for an information fusion algorithm. The process of an RTS smoother is divided into four steps: construction of system model, initialization, forward filter and backward filter.

4.1 Construction of process and measurement model

To apply the RTS smoother, a system model (which consists of a process and measurement model) should be prepared. The state of the system process model is composed of eight states $a_{XY}, V_{XY}, q, \theta, \psi, X, Y, Z$ that represent horizontal acceleration, horizontal velocity, pitch rate, road slope, heading angle, east position, north position, and height, respectively. The measurement vector of the system model consists of eight measurements $V_{XY\_GPS}, \psi_{GPS}, \theta_{GPS}, X_{GPS}, Y_{GPS}, Z_{GPS}, V_{XYZ\_Whl}, a_{x\_Accel}$ that describe horizontal velocity, heading, road slope, east, north, height from GPS, velocity from wheel speed sensor, and longitudinal acceleration from accelerometer, respectively. Equations (5) and (6) describe the system model for the RTS smoother.

Process model:

$$x_k = f_{k-1}\left(x_{k-1},\ u_{k-1},\ w_{k-1}\right)$$

$$= \begin{bmatrix} a_{XY_k} = a_{XY_{k-1}} \\ V_{XY_k} = V_{XY_{k-1}} + T \cdot a_{XY_{k-1}} \\ q_k = q_{k-1} \\ \theta_k = \theta_{k-1} + T \cdot q_{k-1} \\ \psi_k = \psi_{k-1} + T \cdot r_{gyro} \\ X_k = X_{k-1} + T \cdot V_{XY_{k-1}} \cos\left(\psi_{k-1}\right) \\ Y_k = Y_{k-1} + T \cdot V_{XY_{k-1}} \sin\left(\psi_{k-1}\right) \\ Z_k = Z_{k-1} + T \cdot V_{XY_{k-1}} \tan\left(\theta_{k-1}\right) \end{bmatrix} \qquad (5)$$

$$w_k \sim \left(0,\ Q_k\right)$$

Measurement model:

$$y_k = h_k\left(x_k,\ v_k\right)$$

$$\begin{bmatrix} \sqrt{V_{X,GPS_k}{}^2 + V_{Y,GPS_k}{}^2} \\ \psi_{GPS_k} = \tan^{-1}\left(\frac{V_{Y,GPS_k}}{V_{X,GPS_k}}\right) \\ \theta_{GPS_k} = \tan^{-1}\left(\frac{V_{Z,GPS_k}}{\sqrt{V_{X,GPS_k}{}^2 + V_{Y,GPS_k}{}^2}}\right) \\ X_{GPS_k} \\ Y_{GPS_k} \\ Z_{GPS_k} \\ V_{XYZ_k} = \frac{V_{FL,wheel_k} + V_{FR,wheel_k}}{2} \\ a_{x,acc_k} \end{bmatrix} = \begin{bmatrix} \hat{V}_{XY_k} \\ \hat{\psi}_k \\ \hat{\theta}_{k-1} \\ \hat{X}_k \\ \hat{Y}_k \\ \hat{Z}_k \\ \frac{\hat{V}_{XY_k}}{\cos\left(\hat{\theta}_{k-1}\right)} \\ g \cdot \sin\left(\hat{\theta}_{k-1}\right) + \frac{\hat{a}_{XY_k}}{\cos\left(\hat{\theta}_{k-1}\right)} \end{bmatrix}$$

$$v_k \sim \left(0,\ R_k\right)$$

(6)

4.2 Initialization

The RTS smoother should be initialized with a predefined state vector and covariance matrix as shown in equation (7).

$$\begin{aligned} \hat{x}_{f0}^{+} &= E\left(x_0\right) \\ P_{f0}^{+} &= E\left[\left(x_0-\hat{x}_{f0}^{+}\right)\left(x_0-\hat{x}_{f0}^{+}\right)^T\right] \end{aligned} \qquad (7)$$

4.3 Forward filtering

An extended Kalman filter is used for the forward filtering algorithm since the system model is nonlinear. The forwarded filter estimates the posterior state $\hat{x}_{f,k}^{+}$ and covariance $P_{f,k}^{+}$; subsequently, these estimates are saved for use in the backward filtering as shown in equation (8).

$$\begin{aligned} \hat{x}_{f,k}^{-} &= f_{k-1}\left(\hat{x}_{f,k-1}^{+},\, u_{k-1},\, 0\right) \\ P_{f,k}^{-} &= F_{k-1}P_{f,k-1}^{+}F_{k-1}^{T} + L_{k-1}Q_{k-1}L_{k-1}^{T} \\ K_{f,k} &= P_{f,k}^{-}H_k^T\left(H_kP_{f,k}^{-}H_k^T + M_kR_kM_k^T\right)^{-1} \qquad (8), \\ \hat{x}_{f,k}^{+} &= \hat{x}_{f,k}^{-} + K_{f,k}\left[y_k - h_k\left(\hat{x}_{f,k}^{-},\, 0\right)\right] \\ P_{f,k}^{+} &= \left(I - K_{f,k}H_k\right)P_{f,k}^{-} \end{aligned}$$

where $$F_{k-1} = \left.\frac{\partial f_{k-1}}{\partial x}\right|_{\hat{x}_{f,k-1}^{+}} \quad H_{k-1} = \left.\frac{\partial h_{k-1}}{\partial x}\right|_{\hat{x}_{f,k-1}^{-}}, \quad L_{k-1} = \left.\frac{\partial f_{k-1}}{\partial w}\right|_{\hat{x}_{f,k-1}^{+}} \quad M_{k-1} = \left.\frac{\partial h_{k-1}}{\partial v}\right|_{\hat{x}_{f,k-1}^{-}}.$$

4.4 Backward filtering

In the backward filtering algorithm, the smoothed state $\hat{x}_{b,k}$ and covariance $P_{b,k}$ are estimated as shown in equation (9).

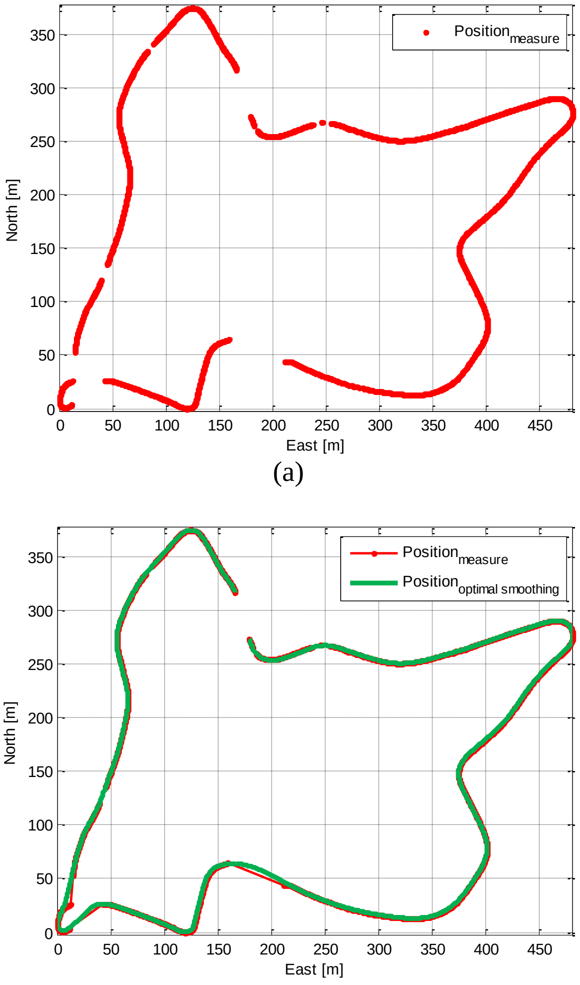
$$\begin{aligned} \hat{x}_{b,N} &= \hat{x}_{f,N}^{+} \\ P_{b,N} &= P_{f,N}^{+} \\ K_{b,k} &= P_{f,k}^{+}F_k^T\left(P_{f,k+1}^{-}\right)^{-1} \qquad (9) \\ P_{b,k} &= P_{f,k}^{+} - K_{b,k}\left(P_{f,k+1}^{-} - P_{b,k+1}\right)K_{b,k}^{\;T} \\ \hat{x}_{b,k} &= \hat{x}_{f,k}^{+} + K_{b,k}\left(\hat{x}_{b,k+1} - \hat{x}_{f,k+1}^{-}\right) \end{aligned}$$

5 Experimental Results

The experiments were performed at the Hanyang University Seoul campus. A GPS signal was not always available since the campus has many tall buildings and structures. Figure 3 (a) describes the results of the GPS position measurements at Hanyang University. It was not possible to use only the GPS for map generation due to the many discontinuous and unreliable measurements caused by GPS outage.

The information fusion of GPS with on-board vehicle sensors (based on a RTS smoother) was applied to the map generation to overcome the problem of unstable GPS position measurements. Figure 3 (b) represents the results of the map generation algorithm. The 3D map generation results show precise, continuous, and reliable road geometry information since the discontinuous and unreliable GPS position measurements were complemented by vehicle on-board sensors based on the RTS smoother.

Figure 4 shows the estimation results of road height; the most important information for an energy management system. The shaded area represents areas where the GPS signal was not available. GPS height measurements were unreliable in these regions. However, the integration of on-board sensor information to the GPS using RTS-smoother resulted in a more stable and continuous height estimate.



(a)

(b)

Figure 3: Experimental results of the information fusion algorithm.

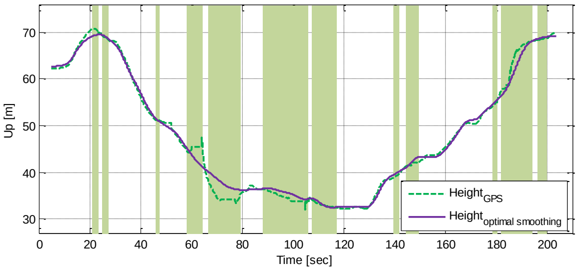


Figure 4: Estimation results of height; the most important factor for an energy management system

6 Conclusion

This paper presents an estimation algorithm of three-dimensional (3D) road geometry using GPS and several on-board vehicle sensors. 3D road geometry information is crucial for the energy management systems of electric vehicles (EV) or hybrid electric vehicles (HEV) to generate an optimal energy management strategy. A single GPS receiver can provide 3D position information for road geometry; however, it is not suitable to apply to an energy management system due to the lack of accuracy and reliability. A fixed-interval optimal smoother based information fusion algorithm that integrates the GPS and vehicle on-board sensors (including gyro, accelerometer, and wheel speed sensors) was proposed to improve the accuracy, continuity, and reliability of road geometry measurements. A Rauch-Tung-Striebel (RTS) smoother was used for the optimal smoother due to the computational efficiency.

The proposed algorithm was evaluated using measurements from a probe car equipped with GPS and on-board sensors. The experimental results show that the 3D road geometry estimation results were sufficiently accurate and reliable even under poor GPS conditions.

Acknowledgments

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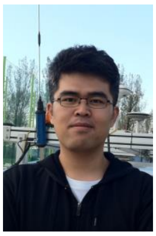

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