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Map matching with kalman filter and location estimation

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Abstract

Known as Global Navigation Satellite Systems, GNSS is a geolocation service. GNSS systems used in the world are known as GPS in America, GLONASS in Russia, GALILEO in Europe, BEIDOU in China and IRNSS in India. However, GPS is the only one that works decisively today. GNSS systems are used effectively in the navigation of all types of land, sea and air vehicles such as search and rescue, target finding, and landing and take-off of airplanes with or without limited visibility. However, when environmental and weather conditions are unfavorable, the accuracy of the GPS systems in the GNSS may vary. This study is presented as a solution to the map matching problem by minimizing the error deviation rates of GPS data from NOVATEL and UBLOX based vehicle tracking devices with the help of Kalman Filter Algorithm. In addition, the deviation rate between the GPS data from the vehicle tracking system and the estimated point coordinates is provided in meters.

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1. Introduction

Global Positioning System (GPS) is a satellite-based navigation system which is used for the navigation of warships, positioning towards the targets of the soldiers, directing the landing of aircraft, as well as the development of many complex positioning systems used in the civil sector [1].

GPS data can show different points other than the actual location. The positioning accuracy of the GPS represents the complex and multidisciplinary process that requires different information, processing data and converting it into basic traffic parameters. For example, traffic engineering, mathematics, computer science and so on [2].

Reflecting the location information from GPS receivers to the street network and reconstructing routes between points is known as map matching. Map matching procedures are based on geometric strategy (such as point-to-point, point-to-curve and curve to curve), topological strategy (such as contiguity, linkage, and limitation between elements in the road network) and probability strategy (Kalman Filter, Fuzzy Logic Model, Bayesian Inference and derivatives) [3].

Position accuracy and estimation vary depending on the measurement noise of the system and the type of algorithm used. Although many positioning algorithms have emerged, Kalman Filter is often used in geolocation applications due to its outstanding performance in a wide variety of real-time applications [4].
In this study, Kalman Filter was applied to calculate the accuracy of GPS points received from vehicle tracking devices and to match the route.

2. Literature Review

Kalman filter optimizes the system according to the mathematical prediction of the future situation by filtering the errors by means of least squares method by working recursively over the noisy data obtained by the sensor [5].

This filtering technique achieves an optimal solution by reducing the estimated error covariance value. When some predicted conditions are met, it stops the recursive process and gives the optimal output value or the actual state of the measurement [6].
Kalman Filter is used for sensor fusion and data fusion. Typically, real-time systems produce a plurality of consecutive measurements instead of performing a single measurement to obtain the status of a system. At each time step, the Kalman Filter generates estimates of true unknown values along with their uncertainty. When the result of the next measurement is observed, these estimates are updated with the weighted average, giving more weight to uncertain uncertainties [7].

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Dai and Li (2016) proposed a Kalman filter based approach to improve location accuracy on the android-based Baidu Map. As a result of the study, it was observed that the GPS data on the map was positioned more accurately and always appeared within the road line. [8].

Another study focuses on the correct selection of satellites to improve location accuracy. By analyzing altitude angles and position information from multiple satellites with the help of Kalman filter, it makes the most accurate satellite selection [9].

Li, Quddus and Zhao (2013) have developed a model with the help of kalman filter in order to complete the information that cannot be obtained correctly, in case GPS coordinates are frequently interrupted in map matching methods. [10].

Map matching algorithms are divided into three groups according to geometric, topological and advanced level. The geometric map matching algorithm uses only geometric information (such as the shapes of road networks). Different approaches have emerged for geometric map matching algorithms. These are point-to-point, point-to-curve, and curve-to-curve matching. The accuracy of the geometric map matching algorithms varies between 80% and 85% when the correct connections are given [11].

The topological map matching algorithm uses topological information such as road connections and characteristics of roads (width, roundabouts, etc.). In order to correct the GPS values, a weighted topological map matching algorithm which is based on topological analysis of road networks and coordinate information has been developed [12]. The performance of the topological map matching algorithms is much better than the geometric algorithms. Accuracy ranges from 80% to 96% [13].

Advanced map matching algorithms use advanced statistical, mathematical and artificial intelligence techniques. Examples include Kalman Filter and fuzzy logic [14].

In this study, Kalman Filter was used to calculate the locations of GPS data and to draw a correct route on the map. A new approach was introduced to the literature by calculating the deviation rates of the corrected GPS points in meters.

3. Methods

In this study, Kalman Filter Algorithm was used as a method to correct the GPS points. In addition, after estimating the position, the deviation ratios of the coordinates are given in meters by Haversine Method.

The Haversine Theorem is used to calculate the distance of two points on the earth's surface. Latitude, longitude and the world's radius (6,367.45 km) are used in the calculation [15].

$$a = \sin^2(\Delta\varphi/2) + \cos\varphi 1 \cdot \cos\varphi 2 \cdot \sin^2(\Delta\lambda/2)$$
$$c = 2 \cdot \operatorname{atan2}(\sqrt{a}, \sqrt{(1-a)}) \quad (1)$$
$$d = R \cdot c$$

Equation – 1 Haversine formula

In above formula – 1 [16], φ latitude, λ longitude, R represents the radius of the earth.
The Kalman filter operates in five steps as shown below;
Apply the Kalman filter to a problem, we must follow some equations. First, the value of each signal must be calculated.

$$x_t = Fx_{t-1} + Bu_t + W_{t-1} \quad (2)$$

Each signal (x_t) is calculated using formula-2. When calculating x_t value; above the previous value (x_{t-1}), the control signal u_t and the previous process noise W_{t-1}. The control signal (u_t) is not always used. After these procedures, formula - 3 should be applied as follows to calculate the measured value.

$$Z_t = Hx_t + v_t \quad (3)$$

If the measurement value (Z_t), which we are not sure for certain, is; signal value (x_t) and measurement noise (v_t). Process noise (W_{t-1}) and measurement noise (v_t) are statistically independent of each other [17]. The F, B and H values shown in these equations are given only as a numerical value for signal problems. Often these values are assumed to be constant at each stage.

<u>Time Update (prediction)</u>

$$\hat{x}_t^- = F_t\hat{x}_{t-1} + W_t \quad [18]$$
$$\hat{P}_t^- = F_tP_{t-1}F_t^T + Q_t \quad [19]$$

<u>Update measurement (accurate data)</u>

$$K_t = P_t^-H_t^T(H_tP_t^-H_t^T + R)^{-1} \quad [20]$$
$$\hat{x}_t = \hat{x}_t^- + K_t(\hat{z}_t - H_t\hat{x}_t^-) \quad [21]$$
$$P_t = (I - K_tH_t)P_t^- \quad [22]$$

$\hat{x}_{t-1}$, Predictable State Vector
F_t, Transition Matrix Transferring State Vector to Another

W, System Noise Ratio
P, State Covariance Matrix
Q, Noise Covariance Process
K, Kalman Gain
H_t, Measuring Matrix
R, Measuring Noise Covariance
$\hat{z}$, Vector of Observed Values

F_t is the transition matrix that transfers the previous state ($\hat{x}_{t-1}$) to the next time period t. W_t, R covariant measuring noise in detail. R is the amount of noise measured in the environment. P_t is the error covariance. That is, the amount of common change of error. K_t, Kalman detailed income. Among all the variables found in the Kalman gain equation. In the Kalman gain calculations for the situation in time t. If the Kalman gain is taken as 0.5, the equation will be transformed into a average finding function.

4. Experimental Studies

In this study, Python software language is used to construct the proposed algorithm and to analyze the data set.

4.1. Dataset

As the data set, the road routes of the Beşiktaş, Ortaköy, Palanga, Büyükdere and Eski Büyükdere locations in Istanbul were taken as vehicle location (latitude and longitude) information. The latitude and longitude information was obtained by using GNSS based NOVATEL and UBLOX devices which can make GPS measurements. The difference between Novatel and Ublox devices is that Ublox can measure more accurately than Novatel [23]. Therefore, the data obtained from Ublox constitutes our ground truth.

The coordinates from Ublox and Novatel consist of raw data. The format of this raw data comes from the protocol of the National Marine Electronics Association (NMEA). NMEA is a protocol produced by the US National Maritime Electronics Association. Python programming language was used to analyze the NMEA format and get latitude and longitude information. 1407 latitude and longitude points were extracted for the data set. The obtained data set was processed with the help of Kalman Filter and the position estimation was made.

4.2 Analysis of algorithm

The latitude and longitude data obtained from the less accurate Novatel meter was calculated with the Kalman filter and compared with the actual path information obtained from the Ublox meter on the Open Street Map. Correlation coefficient and error rates (MAE, RMSE, MSE) were calculated between the estimated location data and the actual road information data by Kalman filter.

Mean Absolute Error (MAE); averages the absolute values of the differences between the test and forecast values [24].

$$\text{MAE} = \frac{\left|\sum_{i=1}^{N}(p_{u,i} - r_{u,i})\right|}{N} \qquad (4)$$

In above formula – 4, where N represents the number of observations, $pu,\ i\ ve\ ru$, are represents test and prediction data respectively.

$$\text{MSE} = \frac{\sum_{i=1}^{N}(p_{u,i} - r_{u,i})^2}{N} \qquad (5)$$

In above formula – 5, mean square error (MSE); shows the average of the actual path information and the square of the differences of the predicted data [25].

Root squares mean error (RMSE); it is used to measure the difference between the predicted and predicted values.

Formula 8 is shown below [26].

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(p_{u,i} - r_{u,i})^2}{N}} \qquad (8)$$

Correlation is a statistical measure that indicates the extent to which two or more variables fluctuate together. The correlation value is between "-1" and "+1. The magnitude of the correlation coefficient indicates the strength of the relationship. The closer the value is to +1, the stronger the relationship in the same direction, and the closer the value to -1, the stronger the opposite [27].

$$r(x,y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2 . \sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (9)$$

In above formula – 9, x presents the values calculated by the kalman filter, and y presents the ground truth values.

Table 1. Error Rates

Algorithm	R^2	RMSE	MAE	MSE
Kalman Filter	0.826	0.000194	0.000120	3.775

In Table 1, the error rates of latitude and longitude data that we apply the Kalman Filter are shown as R^2 0.8269

(83%) and RMSE value as 0.000194. According to this data, we can say that the algorithm that makes the position estimation gives approximately 83% accurate results.

The data to be corrected by the algorithm (with incorrect measurements), the estimated GPS latitude and longitude data as well as the actual route information are shown on the three-dimensional map as follows in comparison.

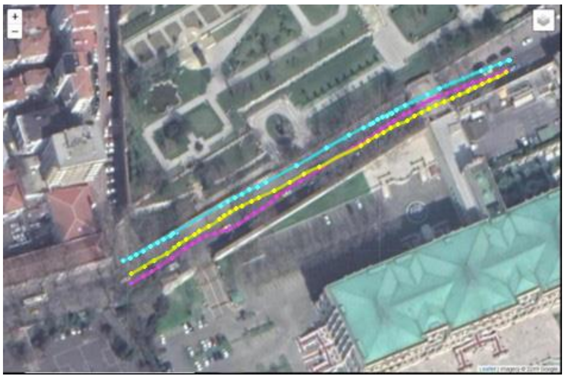

Figure 1. Location Data

Figure 2. Location Data Showing Actual Road Information

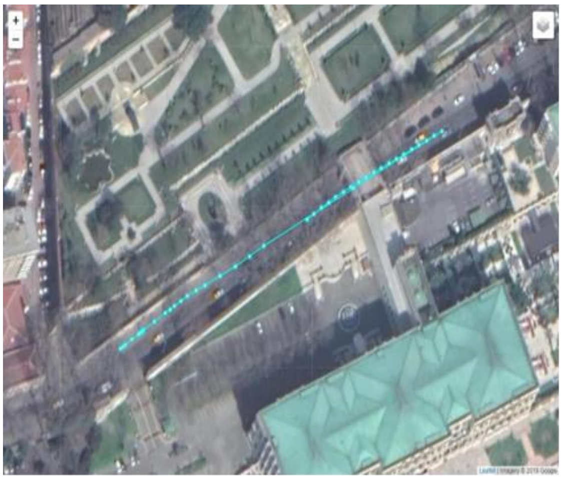

Figure 3. Estimated Location Data

In Fig. 1, the vehicle GPS information that is not processed by the algorithm is shown in three dimensions on the map. [28]. When you look carefully on the map, the measured position data seems to have deviated from the route.

In Fig. 2, the road information obtained by making more accurate measurements is shown on the map. This data is accepted as the ground truth value in the algorithm that we use Kalman Filter.

In Fig. 3, the estimation values calculated by our algorithm are shown on the map. Accordingly, it was observed that the incorrect coordinate values were corrected, and it made more accurate position estimation when compared to the actual path information.

Two-dimensional display of results on Open Street Map is as follows;

Figure 4. First GPS Location Data and Forecast Data

Figure 5. Forecast Data with Actual Road Information

Fig. 4 shows the first position information (blue) and forecast data (red) from the GPS in two dimensions on OSM (Open Street Map). It has been observed that the estimation data on OSM make accurate location estimation.

Fig. 5 shows the ground truth information (green) and estimation data (red) obtained by GNSS-based devices capable of accurate position measurements in two dimensions on OSM (Open Street Map). When we compare the predicted location data with the actual road information, it has been observed that it gives good results.

Table 2. Incorrect Deviation Rates (in Meters)

Kalman Filter			GPS		Distance (Deviation Ratio)
Latitude	Longitude	Latitude		Longitude	Meter
41.04410506	29.01486518	41.0441195		29.014753	9.54416252
41.04414236	29.01494283	41.04415167		29.014839	8.76895176
41.04417789	29.01502226	41.04418633		29.01492667	8.07159224
41.04421081	29.01510458	41.04421817		29.01502167	7.00114578
41.04424125	29.0151883	41.04425267		29.01511583	6.2082758
41.04427077	29.01527151	41.0442955		29.01520583	6.15650907
41.0443013	29.01535364	41.04432283		29.01529767	5.26959956
41.04373476	29.01394512	41.043646		29.01364167	27.2960566
41.04370114	29.01387296	41.0436755		29.01371467	13.57764187
41.04366641	29.01379503	41.04373617		29.0138635	9.65042764

The deviation rates between the prediction points calculated using the Kalman Filter and the position points from the GPS device according to the values shown in Table 2 were measured by Haversine Theorem. Accordingly, it was observed that the incorrect coordinate values give a deviation rate of up to 27 meters.

5. Conclusions

As a result of this study, it was observed that Kalman Filter gives a good result on location data which has a noisy data type. Corrected location data was used for map matching. In order to see the performance of the filter, the estimated location data are shown on the map in three dimensions and in two dimensions (on Open Street Map) in comparison with the first location and actual route information from the GPS. Then, the deviation rate between the location estimation data and GPS points is calculated and shown in meters.

It is thought that better results can be obtained by using advanced map matching algorithms such as machine learning algorithms for further studies.

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