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EKF-based State Estimation for Train Localization

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Abstract—Determination of longitudinal acceleration of a land-vehicle regardless its inclination is a common problem for systems of localization. This paper addresses a solution for railway applications by combining a low-cost MEMS IMU (Inertial Measurement Unit) equipped with a 3-axis accelerometer and a 3-axis gyrometer and an algorithm for data fusion. In particular, the impact of adding attitude and velocity observations into a Kalman filter is studied. Compared to conventional methods that use regular Kalman filter with external aiding sensors such as GPS or tachometers, the proposed approach uses an Extended Kalman Filter which exploits an augmented state vector. A velocity estimation obtained by a method observing the spectral analysis of the vertical accelerometer and the attitude estimation obtained by a complementary filter compose the observation vector with the accelerometer and the gyrometer data. At last, experimental results performed on an urban train are presented.

Keywords - Kalman filter; Compelmentary filter; MEMS; Spectral analysis; Data fusion; Train localization

I. INTRODUCTION

The European Train Control System (ETCS) aims to provide an accurate train localization [1]. This information is vital for the traffic and the safety. To achieve this localization, several onboard sensors and a clever fusion guarantees good performance and reliability of the velocity and position estimations. GPS reciever and tag reader - tags are positioned along the track - are usually used to detect the train position. During the time laps where no information are available, inertial sensors, tachometers and Doppler radar are used to estimate the position and velocity of the train. The goal of this plurality of sensors is to provide an accurate reliable data in any environmental conditions (weather, wheels/rails adhesion conditions, GPS signal, tunnels or buildings presence, ...). Our contribution is to enhance the current inertial system by providing the longitudinal acceleration (gravity compensation) and the velocity of the train based only on inertial sensors, 3-axis gyrometer and 3-axis accelerometer. The purpose of this paper is to enhance the method proposed in [2] thanks to the use of an Extended Kalman Filter (EKF) integrating, in its observation vector, velocity and attitude estimations obtained respectively from a spectral analysis and a complementary filter. Fig. 1 shows an overview of the proposed state estimator.

II. ESTIMATION METHOD

A. Velocity Observation

The accelerometer measures the specific force applied on its three axis. This specific force includes the gravity, the train accelerations (longitudinal and centripetal) and the Coriolis acceleration. The centrifugal force due to the earth rotations is neglected in this work. However, accelerometer measures the vibrations too. According to [3], vibrations are directly impacted by the sensors placement, the undercarriage, the motion and the velocity of the train. Thus, the analysis of vibratory phenomena wheels/rails has contributed of the estimation of the velocity [3], [4] and geometrical characteristic of railways [5]. Different sources of vibrations are shown in Fig. 2.

The method proposed in [2] allows an observation of the velocity \( v_{vel} \) by using over the time a linear fitting (1) of the spectral analysis of data from the vertical accelerometer.

\[
v_{vel} = \rho \sqrt{S} + \beta
\]

Where \( \rho \) is a scale factor which has been determined by means of experimental results. \( \beta \) is a bias which is calculated during the initialization phase of the inertial system. \( S \) is the sum of euclidean norms of the Fast Fourier Transformation (FFT) components of the vertical accelerometer output. \( S \) is defined by the equation (2).

\[
S = \sum_{k=0}^{N/2} \| H_k \|_2
\]
Where the measures of the accelerometer angles, $\phi$, filter, the gyrometer. As the ranges of the roll and pitch angles sensor. In the case of accelerometers and gyrometers, the sensors by choosing the best frequency response of each element and the observation vector of the EKF algorithm.

C. Extended Kalman Filter

The Extended Kalman Filter (EKF) is a common estimator for data fusion [7]. The main interest of this filter is its ability to deal with non linear equations. Fig. 3 shows an overview of the EKF algorithm.

![Extended Kalman Filter overview](image)

Where $\dot{\phi}, \dot{\theta}, \psi$ are the rates of the roll, pitch and yaw angles, $(\phi, \theta)$ are the roll and pitch angles, $(\dot{x}_n^b, \dot{y}_n^b, \dot{z}_n^b)$ are the linear accelerations of the train defined in the body frame, $\dot{x}_n^b$ is the velocity of the train defined in the body frame and $(b_{gx}, b_{gy})$ are the X-axis and Y-axis biases of the gyrometer. These vectors are integrated in the functions $f$ and $h$ of the Kalman algorithm. The prediction model, i.e. the function $f$, is defined by the system of equations (6):

$$
\begin{align*}
\phi_{k+1} &= \phi_k + w_{\phi_k} \\
\theta_{k+1} &= \theta_k + w_{\theta_k} \\
\psi_{k+1} &= \psi_k + w_{\psi_k} \\
\phi_{k+1} &= \Delta t * \phi_k + \phi_k + w_{\phi_k} \\
\theta_{k+1} &= \Delta t * \theta_k + \theta_k + w_{\theta_k} \\
\dot{x}_{n+k}^b &= \dot{x}_{n+k}^b + w_{x_k} \\
\dot{y}_{n+k}^b &= \dot{y}_{n+k}^b + w_{y_k} \\
\dot{z}_{n+k}^b &= \dot{z}_{n+k}^b + w_{z_k} \\
\dot{x}_{n+k}^b &= \Delta t * \dot{x}_{n+k}^b + \dot{x}_{n+k}^b + w_{x_k} \\
\dot{y}_{n+k}^b &= \dot{y}_{n+k}^b + w_{y_k} \\
\dot{z}_{n+k}^b &= \dot{z}_{n+k}^b + w_{z_k} \\
\end{align*}
$$

Where $\Delta t$ is the sampling period of the Kalman filter and $w_k$ represents the process noise defined by the covariance matrix $Q$. By the same way, the observation model, i.e. the function $h$, is defined by the system of equations (7):

$$
\begin{align*}
\omega_{x_k} &= \dot{\phi}_k - \sin\theta_k \dot{\psi}_k + b_{gx} + \nu_{\omega_{x_k}} \\
\omega_{y_k} &= \cos\phi_k \dot{\theta}_k + \sin\phi_k \cos\theta_k \dot{\psi}_k + b_{gy} + \nu_{\omega_{y_k}} \\
\omega_{z_k} &= -\sin\phi_k \dot{\theta}_k + \cos\phi_k \cos\theta_k \dot{\psi}_k + \nu_{\omega_{z_k}} \\
\dot{x}_{n+k}^b &= \dot{x}_{n+k}^b - g \sin\theta_k + \nu_{f_{x_k}} \\
\dot{y}_{n+k}^b &= \dot{y}_{n+k}^b + g \sin\phi_k \cos\theta_k + \nu_{f_{y_k}} \\
\dot{z}_{n+k}^b &= \dot{z}_{n+k}^b + g \cos\phi_k \cos\theta_k + \nu_{f_{z_k}} \\
\phi_{inc_k} &= \phi_k + \nu_{\phi_k} \\
\theta_{inc_k} &= \theta_k + \nu_{\theta_k} \\
\nu_{vel_k} &= \dot{v}_{n+k}^b + \nu_{\nu_{vel_k}} \\
\end{align*}
$$

Where $g_D$ is the gravity and $\nu_k$ represents the measurement noise defined by the covariance matrix $R$. In order to conserve the covariance matrix $P$ symmetric and positive definite, a factorized form of the algorithm is used [7].

III. EXPERIMENTAL RESULTS

A. Experimental Setup

These experiments have been carried out on an urban train from the company ZELC running on the metro network in Ankara (Turkish). The track route corresponds to the M1 line which is 14.7km long route and crosses 12 stations. All data have been recorded by the IMU SX43030 from MEGGITT Sensorex [8]. In the following figures, the results of our approach is compared to the data recorded by a high performance inertial navigation system, HPINS, (cost ≥ 100k$) and by the tachometers from the ETCS. Both systems can be considered as references. The presented results have been obtained after the train has run several times the line M1 for 1h30 corresponding to a covered distance of 36.768km.
B. Results

Fig. 4 presents the relative errors on the longitudinal and centripetal accelerations (HPINS as reference). The RMS error is equal to 4mg (Max error 25mg) for a ±140mg acceleration range. The acceleration errors depend directly of the accuracy of the attitude estimations. Fig. 5 presents the relative errors on the estimation of the roll and pitch angles (HPINS as reference). We observe along the experimentation a RMS error equals to 0.2° (Max error 1.0°) for a ±6° angle range.

Fig. 6: Train velocity error observed during the experimentation

Fig. 7: Train covered distance error observed during the experimentation

IV. Conclusion

In this paper, a state estimator method combining an Extended Kalman Filter with velocity observation based on a spectral analysis and attitude observations based on a complementary filter is presented in order to estimate the longitudinal acceleration of a train. The interest of this method is to propose a state estimation for train localisation without any external aiding source. The performances of the method have been tested on an urban train and results are compared to an estimation given by an high performances inertial navigation system (navigation grade) and the train tachometers. Finally, the performances during 1h30-experiment lead to a RMS error of 4mg on the longitudinal acceleration and an error of 6.4km on the covered distance.

REFERENCES