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Kinematic modeling of a track geometry using an Unscented Kalman Filter

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ABSTRACT

New data filtering methods based on the Kalman filter concept are investigated for application to track geometry, where a track trolley is normally used to measure the track coordinates, cant and gauge, among others. Continuous as well as discrete measurements of the trolley are conceptually modeled, and the accuracy of the sampling scheme is also investigated. For this, a modified kinematic model of the track geometry involving transition and circular curves is proposed based on the tangential as well as normal acceleration, and both a nonlinear Extended Kalman Filter (EKF) and an augmented Unscented Kalman Filter (UKF) are applied to optimize the measured data. The efficiency and accuracy of the proposed models of EKF and UKF having a new kinematic equation is verified with ideal track geometry and with statistical methods including Root Mean Square (RMS). In addition, field measurement data are also considered to check the applicability of the models. Finally, future work on track geometry modeling based on a high-speed measurement vehicle is briefly outlined.

1. Introduction

Track trolleys have been widely used in the maintenance as well as construction of railroad tracks and, although the basic concepts are the same, quite a number of different models have been released in the railroad market in these days. Recently, measurement technology has rapidly improved with the development of IT and GPS technology, and not only the track trolleys with GPS systems but also a Track Measurement Vehicle (TMV) with an Inertial Navigation System (INS) have been employed in the track field. In the case of the track trolley, a Total Station (TS) is widely used to locate the track, and sometimes GPS is employed to upgrade the efficiency of the measurement speed. Apart from the precise location of the track, various inclinometers are also utilized to capture the cant and/or the gradient angle. In addition, the tachometer and LVDT are employed to measure the driving distance and the track gauge, respectively. Measurement is usually done by a discrete stop-and-go scheme, but continuous measurement without stop is also possible although the measurement error is inevitably larger than that of the discrete method. Fig. 1 shows a typical track trolley which is being developed and, for simplicity, TS without GPS is solely used to measure the location of the track.

In accordance with hardware development, software technology has also advanced in recent years, and numerous accomplishments have been achieved in terms of data filtering. After the invention of Kalman filter in the 1960s, various nonlinear filtering schemes have been proposed and verified with field data. For example, an Extended Kalman Filter is linearizing about the current mean and variance using a Taylor series expansion of the nonlinear trajectory, while a linearized Kalman filter can be used if the nominal values are known beforehand. Another nonlinear filtering model, called an Unscented Kalman Filter, is to use the unscented transformation of the variables and variances without using a linearized Jacobian transformation shown above [15].

In terms of the track geometry, the track coordinates and distance from the origin, among others, are nonlinear in nature due to the transition and circular curves of the track. In this regards, a few attempts have been made to realize a nonlinear track model, e.g., Glaus [5] proposed an Extended Kalman Filter (EKF) to optimize measurement data having nonlinear geometric information. The model was implemented into the Swiss trolley [4] and its efficiency was verified with field data. Meanwhile, Akpinar and Gulal [1] modified Glaus' model and included a tangential acceleration into their EKF model. They also developed their own trolley with GPS as well as TS and demonstrated its accuracy with field data. A Kalman Filter (KF) has also been applied to TMV and, in this regard, Tsunashima et al. [13] used the car body accelerations and KF to obtain track geometry data. Recently, Georgy et al. [3]

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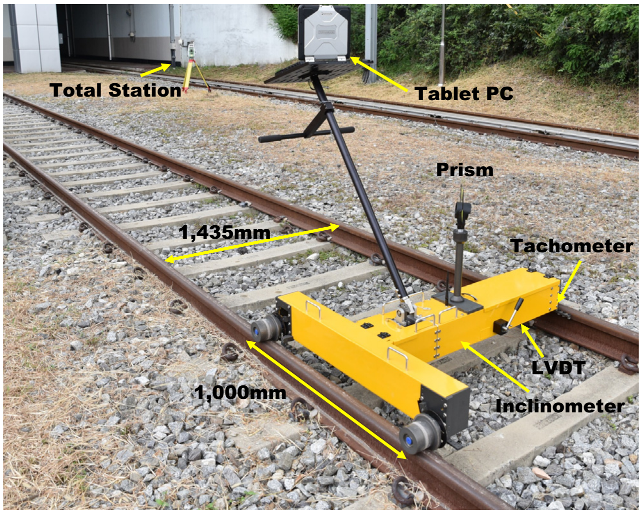

Fig. 1. A typical track trolley.

introduced a Particle Filter (PF) concept to the Inertial Measurement Unit (IMU) together with GPS data to obtain the accurate position of the vehicle. Further application of KF can be found in Kim et al. [8] where the location of high-speed train was estimated using various sensors such as IMU and GPS, and using a Federated Kalman Filter (FKF).

In this paper, a new kinematic model that will be used in the measurement of the track geometry is proposed by improving Glaus [5] and Akpinar and Gulal [1]. Furthermore, an Unscented Kalman Filter (UKF), a well-known tool for the nonlinear modeling of kinematic motion, together with EKF will be considered to investigate the advantages/disadvantages of the models during the modeling of the track geometry. For this, numerical examples with ideal track geometry will be introduced and various parametric studies will be conducted. Field measurement data will also be considered to find the applicability of the proposed model. Finally, future work on the modeling of track geometry based on TMV will be outlined.

2. Kinematic model of track geometry with Kalman filters

The optimization or filtering of the measurement data from the track trolley is the first step to estimate the track geometry accurately and efficiently. Compared with the design geometry, the cross level, longitudinal level, alignment and gauge difference of the track can then be identified. The optimization is mostly performed by KF with the proper dynamic equation of the track and the measurement data from the trolley. In the following sections, a new dynamic equation, or a kinematic equation in our case, having nonlinear characteristics in nature, is proposed and UKF as well as EKF are introduced to establish the update scheme of the track geometry based on the measurement data.

2.1. Kinematic model of track geometry

To define the track geometry and to establish the dynamic equation of the track trolley, various variables such as spatial coordinates, cant, gradient and gauges, among others, need to be introduced based on the differential geometry. Fig. 2 illustrates a track curve $\vec{R}(t)$ including transition and circular arc. Any point along the track curve at time $t + \Delta t$ w.r.t. time t can be represented by the following Taylor series:

$$\vec{R}(t+\Delta t) = \vec{R}(t) + \frac{\partial \vec{R}}{\partial t}\Delta t + \frac{1}{2}\frac{\partial^2 \vec{R}}{\partial t^2}\Delta t^2 + \frac{1}{6}\frac{\partial^3 \vec{R}}{\partial t^3}\Delta t^3 + H.O.T. \tag{1}$$

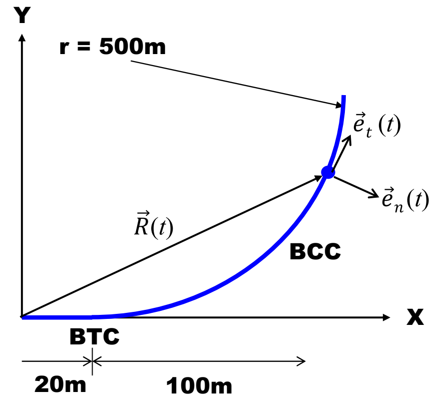

Fig. 2. Track with transition and circular curve.

where, H.O.T. represents the higher-order terms and can be neglected if the time interval Δt is small. Alternatively, if the normal acceleration is not zero and if the Frenet equation [9] with negligible torsion is introduced, Eq. (1) can be rewritten as [5]

$$\vec{R}(t+\Delta t) = \vec{R}(t) + v\vec{e}_t\Delta t + \frac{1}{2}(a_t\vec{e}_t + a_n\vec{e}_n)\Delta t^2 + \frac{1}{6}(j_t\vec{e}_t + j_n\vec{e}_n)\Delta t^3 \tag{2}$$

where, v is the velocity along the arc length l between time t and $t + \Delta t$ and

$$\begin{aligned} &a_t = a: \quad \text{tangential acceleration} \\ &a_n = v^2\kappa: \quad \text{normal acceleration} \\ &j_t = -v^3\kappa^2 + j: \quad \text{tangential jerk} \\ &j_n = 3\kappa v a + v^3 c: \quad \text{normal jerk} \\ &c = \tfrac{\partial \kappa}{\partial l}: \quad \text{curvature rate} \end{aligned} \tag{3}$$

In Eq. (3), j and κ represent the algebraic jerk and curvature, respectively [5], and the following definitions are used in the derivation:

$$\begin{aligned} v(t) &= \dot{l}(t) \\ a(t) &= \ddot{l}(t) \\ j(t) &= \dddot{l}(t) \end{aligned} \tag{4}$$

If the trolley motion is assumed to be uniform and if the time interval is small as in Glaus [5], the tangential acceleration and algebraic jerk will be zero. Meanwhile, Akpinar and Gulal [1] assumed that the normal acceleration due to a centripetal force be neglected and the errors were compensated by considering noises due to the neglected terms. In this study, the tangential and the normal acceleration are not neglected within the framework of kinematic motion of the track trolley and, therefore, Eq. (2) without higher order terms can be directly used in the dynamic equation where the coordinate system of the track geometry is shown in Fig. 2 with the height of track being H.

$$\begin{aligned} X_k &= X_{k-1} + v_{k-1}\sin\phi_{k-1}\Delta t + \frac{1}{2}(a_{t,k-1}\sin\phi_{k-1} + v_{k-1}^2\kappa_{k-1}\cos\phi_{k-1})\Delta t^2 \\ Y_k &= Y_{k-1} + v_{k-1}\cos\phi_{k-1}\Delta t + \frac{1}{2}(a_{t,k-1}\cos\phi_{k-1} - v_{k-1}^2\kappa_{k-1}\sin\phi_{k-1})\Delta t^2 \\ H_k &= H_{k-1} + v_{k-1}\sin\alpha_{k-1}\Delta t + \frac{1}{2}a_{t,k-1}\sin\alpha_{k-1}\Delta t^2 \end{aligned} \tag{5}$$

where, ϕ and α are the azimuth and gradient of the track center line, respectively. Likewise, the other variables of the track geometry can be similarly defined. It is noted that the higher-order terms in Eq.