Computers and Electronics in Agriculture 153 (2018) 196–201

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Steering angle adaptive estimation system based on GNSS and MEMS gyro

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ARTICLE INFO

Keywords:
Double GNSS antennas
MEMS gyroscope
Steering angle
Adaptive Kalman filter
Lever-arm

ABSTRACT

In automatic driving system research of precision agriculture, the wheel steering angle was usually measured by the non-contact absolute angle sensor such as Hall-effect sensor and angle encoder sensor. The problem of those angle sensors was the complex mechanical structure which result in the difficulty of installation and maintenance. However, the gyroscope had the advantages of simple installation and long working life. But the gyroscope bias causes the error accumulates over time in automatic driving system. To solve this problem, a wheel steering angle measurement system based on double Global Navigation Satellite System (GNSS) antennas and two Micro-Electro-Mechanical System (MEMS) gyroscopes was proposed. The double GNSS antennas system provided the speed, attitude angle, latitude and longitude of the vehicle. In addition, one MEMS gyroscope was mounted on the wheel and measured the steering rate and another MEMS gyroscope was mounted on the vehicle to measure the heading angular rate. Meanwhile, an adaptive Kalman filter using the above data was designed to correct the errors of integration of the gyroscope data. The adaptive filter could adjust the noise matrix according to the changes of system noise caused by road conditions and different tools. At the same time, the lever-arm compensation algorithm was used to solve the speed error caused by lever-arm. Experiment was carried out to verify the effectiveness of the system. The average error of the straight line experiment was 0.06 and the error variance was 0.215 and the curve line experiment's mean error was 0.746 and the error variance was 0.908. The result of the experiments showed that this system could meet the request of automatic driving system.

1. Introduction

During the past decades, the precision agriculture has a rapid development. The extensive research of the precision agriculture not only benefits productivity and environmental conditions, but also improves the working conditions of farm managers, laborers, and operators (Kenji Imou et al., 2009). As a result, the autopilot system which is the key technology of the precision agriculture has received an increasing awareness from the research community. The autopilot system can replace operator to do the monotony work and never has the mental fatigue (Wang He and Jingtao, 2014; Mousazadeh, 2013). Higher accuracy is the direction of the autopilot system's development to steering accurately within tight rows and lanes without causing any damage to the vegetation while maintaining a suitable working space (Roviramás, 2010). For the autopilot system, the accuracy of steering angle's measurement directly affects the accuracy of the autopilot (Dickson et al., 2002).

Currently, there are two main kinds' sensors to measure the steering angle: one is the absolute angular displacement sensor (Han et al., 2015). Nagasaka et al. (2004) and his team proposed an autonomous guidance system for rice transplanting. This system used an absolute rotary encoder to sense the steering angle. Xiao (2016) devised a giant magnetoresistance sensor which is precision and low-cost non-contact steering angle sensor. The absolute angular sensor has more connections and complex mechanical structure (Bayar et al., 2015; Yang et al., 2010), so it is to have malfunction and difficult to check and replacement which can result in a waste of manpower and reducing the productivity (Groves, 2015). Another kind sensor is relative angle sensor such as MEMS gyroscope which get the angle by integral the sensor's output (Jun and Changying, 2002). Gyroscope as the inertial device has the advantage of small volume and easy to install and replace. But the output of gyroscope contains the zero bias and random drift. All this measurement error course the steering angle's error accumulate over time (Zhang, 1999). To solve this problem, some researchers build the Auto-Regressive and Moving Average Model (ARMA) time-series model of MEMS gyroscope drift signal and use the Kalman filter to filter the drift signal (Santana-Fernndez et al., 2010). Although this method can reduce the effect of gyroscope random drift, the error caused by zero

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https://doi.org/10.1016/j.compag.2018.08.019
Received 4 August 2017; Received in revised form 30 July 2018; Accepted 9 August 2018

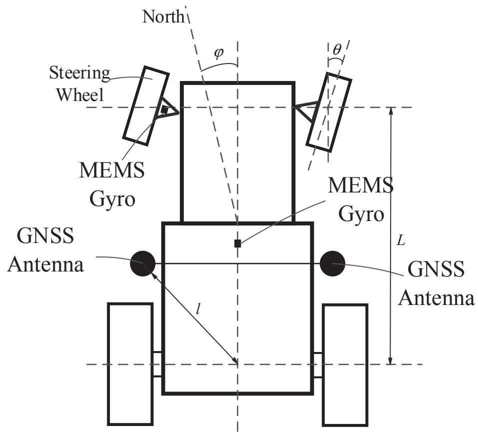

Fig. 1. Diagram of system installation.

bias still accumulate over time.

The purpose of this paper is to present a steering angle measurement system based on the double GNSS and two MEMS gyroscopes to replace the traditional angle sensor. This system uses the error equation of steering angle and the vehicle kinematics model to build an adaptive Kalman filter which can correct the angle error caused by gyroscope zero bias. At the same time, the lever-arm compensation is proposed to correct the speed error caused by the lever-arm.

2. Materials and methods

2.1. System, sensors and algorithm

As shown in the Fig. 1, the sensors of steering angle measurement system contain double GNSS antennas and two MEMS gyroscopes. The double GNSS antennas are mounted on the both sides of the main body of the vehicle. The line between the two GNSS antennas is perpendicular to the central axis of the vehicle. The GNSS antenna can provide the speed, latitude and longitude of the vehicle. The MEMS gyroscope which was mounted on the steering wheel measures the wheel steering rate with the sensitive axis perpendicular to the ground. The MEMS gyroscope mounted on the vehicle body measures the heading angular rate.

The wheel MEMS gyroscope's output contains the heading angle change rate of vehicle and the wheel steering rate, expressed as follows:

$$\omega_A = \dot{\varphi} + \dot{\theta} \tag{1}$$

where

ω_A – the ideal output of gyroscope
$\dot{\varphi}$ – the heading angle change rate of vehicle
$\dot{\theta}$ – the wheel steering rate

The heading angle change rate of vehicle $\dot{\varphi}$ was measured by the MEMS gyroscope mounted on the vehicle body. The wheel steering angle can be obtained by integral the wheel steering rate $\dot{\theta}$ which can be expressed as follow:

$$\theta = \int (\omega_A - \dot{\varphi})dt \tag{2}$$

where

θ – the wheel steering angle

Due to the characteristics of inertial devices, there are zero bias and random drift in the gyroscope's output, so the integral error of the wheel steering angle accumulates over time. It is necessary to design a Kalman filter to correct the angle output error.

The calculation of angle can be expressed as:

$$\hat{\theta} = \theta + \delta_\theta \tag{3}$$

where

$\hat{\theta}$ – the angle calculation
δ_θ – the error of angle calculation

Derive the Eq. (3):

$$\dot{\hat{\theta}} = \dot{\theta} + \dot{\delta}_\theta \tag{4}$$

In the Eq. (4), the calculation of angle rate can be expressed as:

$$\dot{\hat{\theta}} = \omega_A - \dot{\varphi} + \varepsilon \tag{5}$$

where

ε – the zero bias of gyroscope

The error differential equation can be obtained by Eqs. (5) and (2):

$$\dot{\delta}_\theta = \dot{\hat{\theta}} - \dot{\theta} = \varepsilon \tag{6}$$

The zero bias of MEMS gyroscope can be considered as the first order Markov process which can expressed as:

$$\dot{\varepsilon}_i = - \frac{1}{\tau}\varepsilon_i + \xi_\varepsilon \tag{7}$$

where

τ – time constant of the MEMS gyroscope
ξ_ε – drive noise

According to the vehicle kinematics model (Chi et al., 2012), the relationship between steering angle and the heading angle change rate of vehicle can be expressed as follow:

$$\dot{\varphi} = v\frac{\tan\widetilde{\theta}}{L} \tag{8}$$

where

L –vehicle wheelbase
v – the speed of vehicle
$\widetilde{\theta}$ – the expected steering angle

Thus, the expected steering angle can be calculated by the outputs of sensors:

$$\widetilde{\theta} = \arctan\frac{\dot{\varphi}L}{v} \tag{9}$$

With the known measurement accuracy of the wheel speed and yaw rate, the measurement accuracy of the ideal steering angle sensor can be estimated in term of the variance propagation theory by

$$\sigma^2_{\delta\theta'} = \left(\frac{\partial\widetilde{\theta}}{\partial v}\right)^2\sigma_v^2 + \left(\frac{\partial\widetilde{\theta}}{\partial\dot{\varphi}}\right)^2\sigma_{\dot{\varphi}}^2 = \left(\frac{\dot{\varphi}L}{v^2+(\dot{\varphi}L)^2}\right)^2\sigma_v^2 + \left(\frac{vL}{v^2+(\dot{\varphi}L)^2}\right)^2\sigma_{\dot{\varphi}}^2 \tag{10}$$

2.2. Lever-Arm definition

In Eq. (9), the speed v which use to calculate the ideal steering angle is the speed of the rear axis of the vehicle. But the GNSS antenna isn't mounted at the center of the rear axis in the practical application as shown in the Fig. 2. When the vehicle is on curve movement, there are error caused by the lever-arm effect (Jiancheng et al., 2013; Xianghong et al., 2013).

Defining $\boldsymbol{l}$ as the lever-arm vector from the vehicle reference point to the positioning antenna in body, expressed as follow