Toe Angle Measurement for z-Axis Calibrations of the Toe Sensor Based on MCU

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***Abstract*—This study aims at developing an alternative approach to the toe angle inspection system for the vehicle wheel alignments. It will apply the inertial sensor, including accelerometers and gyro, to implementing the MCU-based toe angle inspection system instead of the current commercial measures which adopt the computation vision-based techniques. The inspection system by the proposed approach is much cheaper and more convenient than those by the computer vision-based ones. The coordinate transformations from a vehicle to the inspection system are built in order to obtain the relation between the *x*-axis of the inspection system and that of the vehicle. The orientations of the wheel can be evaluated through the data including 3 axial accelerations and Euler angles acquired from the inertial sensor. Therefore, the toe angle can be calculated by the orientations of the wheels and the vehicle through some vector operations. This paper proposes an approach to calibrating the *z*-axis of the inspection system (sensor) from the misalignments to the based axes of the equipped gyro. The proposed approach is practical and feasible in application from the off-line authentication. The algorithm according to the proposed approach is also provided. This study will be expected to facilitate the toe angle inspection through the *z*-axis calibrations for the system. The integration of the toe angle and camber angle inspections form the proposed approach will achieve the goal to develop a wheel alignment inspection system that is affordable and more convenient to operate without downgrade of the precision. Besides, the evaluated results of camber angle inspections can be transmitted via the media such as RS232, Bluetooth, Wi-Fi, etc.**

***Index Terms*—coordinate transformation, inertial sensor, toe angle, wheel alignment**

I. Introduction

Vehicle wheel alignments include correct inspections and adjustments of wheel characteristic angles, which are camber angles and toe angles of wheels. The alignments become crucial inasmuch as the improper camber angle will induce the problems of steering controllability and stability, while the improper toe angle will reduce fuel efficiency, tire lifespan, and driving comfort [1]. In recent decades, the techniques developed for wheel characteristic angles evaluations have received lots of attention and have been a great improvement, i.e., the techniques moved from mechanical and electromechanical inspection devices to the so-called computer vision-based systems [2]-[4]. The precision of the evaluations by the former technique was gross, labor-intensive, and time-consuming. The later, by contrast, has improved the measurement precision a great deal. Nowadays, the precision for characteristic angle inspections is about $\pm 0.02^{o}$ in commercial applications generally. Fig. 1 shows a kind of computer vision-based inspection systems for wheel alignments in commercial applications. Computer vision-based inspection systems still have some shortcomings although the inspecting procedure and the precision have been meliorated [5].

Figure 1. A computer vision-based inspection system for wheel alignments [5].

This study proposes a feasible approach to the calibrating the *x*-axis of the by applying the inertial sensor including accelerometers and gyro. Furthermore, the proposed approach can implement the MCU-based toe angle inspection system instead of the current commercial measures which adopt the computation vision-based techniques. The calibrations of the inertial sensor for accelerometer and gyro are essential in this approach. The calibrations for the base axes of the accelerometer have been developed in [5], [6]. This paper considers the problems for misalignment calibrations for the *z*-axis of the sensor system to the base axes of the equipped gyro. This calibration is also crucial in developing the toe angle inspection systems. The procedure of the calibration between the toe inspection system and the gyro can follow the results of this paper and will pave the way for achieving the wheel characteristic angles inspections.

For the sake of convenience, this paper defines the 3-D components in a Cartesian Coordinate *A* as follows:

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$$\begin{pmatrix} x_A \\ y_A \\ z_A \end{pmatrix}_A \equiv \begin{bmatrix} \vec{i}_A & \vec{j}_A & \vec{k}_A \end{bmatrix} \begin{bmatrix} x_A \\ y_A \\ z_A \end{bmatrix}$$

where $\vec{i}_A$, $\vec{j}_A$, and $\vec{k}_A$ are the unit vectors of the *x*-, *y*-, and *z*-axes for Coordinate *A*, respectively. That is, $\begin{pmatrix} x_A & y_A & z_A \end{pmatrix}_A^T$ represents the vector in Coordinate *A* and $\begin{bmatrix} x_A & y_A & z_A \end{bmatrix}^T$ represents the 3x1 matrix according to the vector $\begin{pmatrix} x_A & y_A & z_A \end{pmatrix}_A^T$. *A* can be the gyro, or the camber inspection system (sensor) in this paper.

II. Helpful Hints

Fig. 2 shows the toe angles of a vehicle. From the top view of a vehicle, the angle between the orientations of two wheels is called the toe angle. The toe angle can be toe-in and toe-out defined as that the forward angle shrinks and expands, respectively. Misalignments of wheel toe angles will cause the problems of fuel efficiency, tire lifespan, and driving comfort, etc.

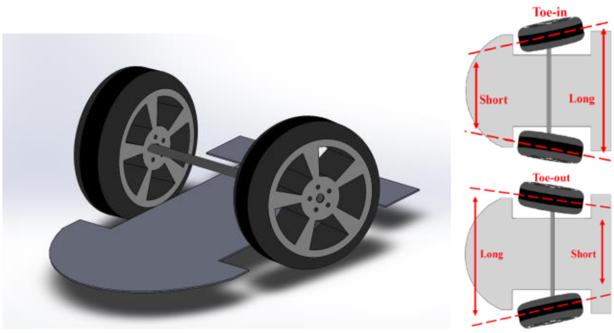

Figure 2. The toe angles of a vehicle.

A vector, $\begin{pmatrix} x_G & y_G & z_G \end{pmatrix}_G^T$, fixed on the gyro moves an orientation with an Euler angle set of this gyro including the yaw (ψ), pitch (θ), and roll (ϕ), becomes $\begin{pmatrix} x_{G_0} & y_{G_0} & z_{G_0} \end{pmatrix}_{G_0}^T$, i.e.,

$$\begin{pmatrix} x_{G_0} \\ y_{G_0} \\ z_{G_0} \end{pmatrix}_{G_0} = \begin{pmatrix} x_G \\ y_G \\ z_G \end{pmatrix}_G$$

From definition,

$$\begin{bmatrix} x_{G_0} \\ y_{G_0} \\ z_{G_0} \end{bmatrix} = T_\psi T_\theta T_\phi \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} \quad (1)$$

where G and G_0 are the gyro and original gyro coordinates,

$$T_\psi = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$T_\theta = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

and

$$T_\phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

The coordinate of the gyro initialized as power-on is so-called the original coordinate (Coordinate G_0), or the Euler angles of the gyro are all equal to 0, i.e., $\psi=0$, $\theta=0$, and $\phi=0$. For instance, the frame of an airplane equipped a gyro is in Coordinate G_0 as the gyro is initialized as shown in Fig. 3. The orientation of this frame varies as it moves with an Euler angle set of the gyro although it is fixed relative to the gyro coordinate (Coordinate *G*) as shown in Fig. 4. The gyro and the frame move with the same Euler angle set of the gyro simultaneously if their base axes are aligned exactly. The Euler angles of the gyro can be acquired from the gyro when moving the object which the gyro is mounted on as shown in Fig. 4. Accordingly, (1) is the coordinate transformation equation from the Coordinate *G* with an Euler angle set of the gyro to Coordinate G_0. That is, when a vector is fixed on the Coordinate *G* can be transformed to that in Coordinate G_0 with the Euler angle set of the gyro.

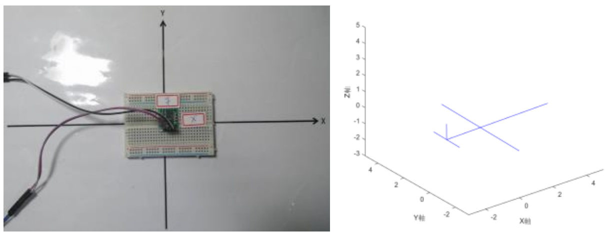

Figure 3. The original gyro coordinate (coordinate G0).

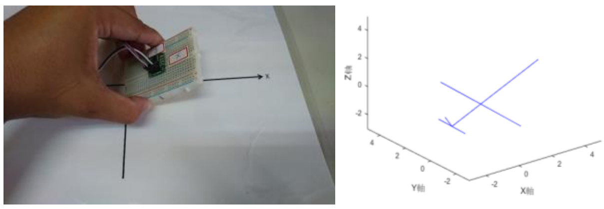

Figure 4. The orientation of the gyro from Euler angles.

In practice, the base axes of Coordinate *G* in a senor can not be exactly aligned to those of the sensor coordinate (Coordinate *S*) during fabrications. A feasible calibrations of the base axes between Coordinate *S* and Coordinate *G* become crucial for the MCU-based toe angle inspection system with inertial sensors since the inspection precision should be within $\pm 0.02^{\circ}$ according to the commercial applications requirements. For instance, the orientation of a vector fixed in Coordinate *G* can be evaluated in Coordinate G_0 form the Euler angles acquired from the equipped due to the definition of Euler angles. However, the orientation of a vector fixed in Coordinate *S* cannot be evaluated in Coordinate G_0 for the misalignments of base axes between Coordinate G and Coordinate S. Fig. 5 sketches the relations of Coordinates G_0, G, S_0 (0 Euler angles), and S with an Euler angle set of the gyro. The vector is fixed in Coordinate G, or simultaneously fixed in Coordinate S, with an Euler angle set of the gyro. In case the coordinate transformation is known between Coordinates G and S, a vector fixed in Coordinate S can be transformed to the vector in Coordinate G_0 through the coordinate transformation and the acquired Euler angle set from the equipped gyro. The problem of this study is how to evaluate the upward normal direction of the wheel inspection platform which is the same orientation as the z-axis of Coordinate S as the inspection system lies on the platform, or in short, the problem is to synthesize a feasible approach to the calibrations for the z-axis of the toe sensor from the acquired Euler angle set for the equipped gyro.

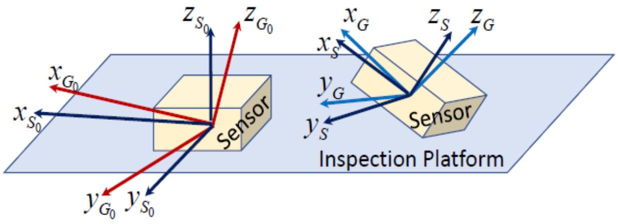

Figure 5. The sketch for coordinates G0, G, S0 (0 Euler angles), and S with an Euler angle set.

III. Calibrations for z-Axis of Sensor

Assume the sensor equipped with a gyro lies on the wheel inspection platform which is in horizon as shown in Fig. 5 (Coordinate S0 with zero Euler angles). The x- and y-axes of Coordinate S are on the platform while the z-axis is upward normal to the platform. Furthermore, the base axes of Coordinate G0 are the base axes of the gyro as the system is initialized, i.e., the system is power-on after the sensor lies on the platform steadily. Intuitively, the orientation of x-axis of Coordinate S is the vector that the x-axis of Coordinate G0 maps on the platform. However, the x-axis of Coordinate S cannot be calculated thus far since the z-axis of Coordinate S is still unsolved, or the normal direction in terms of the base axes in Coordinate G0 to the platform is unclear. That is, the z-axis of Coordinate S in Coordinate G0 is the kernel to calibrate the base axes between Coordinate G and Coordinate S.

The x-axis of the gyro is equal to $(1 \quad 0 \quad 0)^T_{G_0}$, or $\vec{V}_0$, as the sensor system is power-on. In case the sensor horizontally moves with any 2 different angles, or ψ_1 and ψ_2, sequentially in steady states on the platform as shown in Fig. 6, the orientations of the x-axis in the gyro, $\vec{V}_1$ and $\vec{V}_2$, can be evaluated through 2 different Euler angle sets respectively acquired from the gyro from (1).

Theorem 1. The orientation for the unit vector which is normal to the platform is $\vec{k}_{S_0}$ and

$$\vec{k}_{S_0} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}_{S_0} = \frac{\Delta\vec{V}_1 \times \Delta\vec{V}_2}{\left\|\Delta\vec{V}_1 \times \Delta\vec{V}_2\right\|} \tag{2}$$

where

$$\Delta\vec{V}_1 \equiv \vec{V}_1 - \vec{V}_x$$

and

$$\Delta\vec{V}_2 \equiv \vec{V}_2 - \vec{V}_x$$

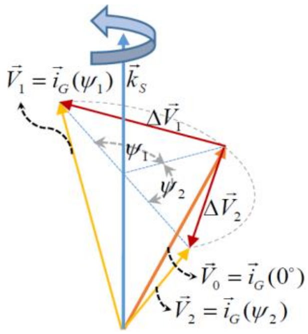

Figure 6. Calibrations for the z-axis of sensor S.

It is clear that both vectors $\Delta\vec{V}_1$ and $\Delta\vec{V}_2$ are on the platform, or the x-y plane of the sensor. If the vectors, $\vec{V}_x$, $\vec{V}_1$, $\vec{V}_2$, $\Delta\vec{V}_1$, and $\Delta\vec{V}_2$, are all in terms of Coordinate G_0, $\vec{k}_{S_0}$ can be in terms of Coordinate G_0, i.e.,

$$\vec{k}_{S_0} = \begin{pmatrix} x^k_{G_0} \\ y^k_{G_0} \\ z^k_{G_0} \end{pmatrix}_{G_0}$$

Theorem 1 provides a practical and feasible algorithm to calibrate the z-axis of Coordinate S. The algorithm is listed as follows.

Algorithm to calibrate the z-axis of Coordinate S:

Step 1: Set the toe angle inspection system (sensor system) lying on the wheel inspection platform where the orientation of x-axis is in forward direction.

Step 2: Turn on the inspection system and initialize the sensor system, or the Coordinate S. The angles of the Euler angle set are all zero, i.e. $\vec{V}_0 = (1 \quad 0 \quad 0)^T_{G_0}$.

Step 3: Rotate the sensor system in a counterclockwise angle, ψ_1, and save the Euler angle set. Calculate $\vec{V}_1$, the x-axis of the gyro, through this Euler angle set.

Step 4: Rotate the sensor system in a clockwise angle, ψ_2, from initial position and save the Euler angle set. Calculate $\vec{V}_2$, the x-axis of the gyro, through the Euler angle set.

Step 5: The vector operations in (2) can be applied directly since the vectors, $\vec{V}_x$, $\vec{V}_1$, $\vec{V}_2$, $\Delta\vec{V}_1$, and $\Delta\vec{V}_2$, are all in terms of the same coordinate, or Coordinate G_0. The z-axis of Coordinate S, $\vec{k}_{S_0}$, can be obtained from Theorem 1.

The calibration for *z*-axis of Coordinate *S*, the toe angle inspection system, is the kernel to calibrate the other axes of Coordinate *S* by some vector operations, i.e., the *x*-axis and *y*-axis of Coordinate *S* in terms of Coordinate *G*. It can make the toe angle evaluation feasible by this system if all the base axes of Coordinate *S* are calibrated.

IV. Conclusions

This paper proposes an approach to calibrating the *z*-axis of the toe sensor systems. The result shows that the proposed approach is practical and feasible in applications. An algorithm of the calibration procedure for the *z*-axis is also provided. It is also crucial to achieve the toe angle inspection. However, the measurement noises induced from the inertial sensors are troublesome in calibrations and inspections, indeed. To realize the toe angle inspection systems will confront the problems for the measurement noises which will dilute the inspection precision. To attenuate the measurement noises will be one of the significant issues in the future study.

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