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A Study on Stabilization Errors of Vehicle-mounted System Using 2-axes Gyro Sensor

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Abstract: In stabilization systems disturbed by base motion, attitude estimation process is very important, because stabilization performance depends on disturbance rejection capability based on attitude estimation. For the accurate stabilization, at least 3 states representing system's rotational motion are required to be measured or estimated, and transforming these states to global coordinates should be accompanied in general. However in most practical cases of stabilization system mounted on a mobile vehicle, only 2-axes gyro sensor is used to sense the pitch and yaw angular rates of the system excited by vehicle motion. In this study, we analytically derived stabilization errors to be generated in system with 2-axes gyro sensor based on some reasonable assumptions, and verified them through simulation with various vehicle motions in typical traveling conditions. Simulation results and analytic error formulas show that stabilization performances are almost same regardless of coordinates-transformation process, and biased roll angle is the major source of the accumulation of errors when 2-axes gyro sensor is used for stabilization system.

Keywords: Attitude estimation, Coordinates-transformation, Gyro sensor, Stabilization

1. INTRODUCTION

Stabilization control techniques have been developed in many research areas. Their main objective is to make system aiming the desirable direction in a stable attitude with rejecting disturbances from base motion. Stabilization performance depends on disturbance rejection capability of controller, and accurate attitude estimation of the system must be guaranteed for the efficient disturbance rejection. There are a lot of sensors used to measure or estimate system's attitude in practical applications. For example, in case of shipboard stabilization system, two inclinometers or gyro sensors sense the roll and pitch motion, and gyrocompass measures the yaw angle of the system [1, 2]. In aircraft and satellite attitude control, a strap-down algorithm that 3-axes gyro sensor and accelerometers are fused to measure the three drift-free rotational motions of the system is used for attitude estimation [3-5]. Like these cases, for the accurate stabilization, at least three states representing system's motion are required to be measured or estimated, and transforming these states to global coordinates should be accompanied in general. However in most practical cases of stabilization system mounted on a mobile vehicle, only 2-axes gyro sensor is used to sense the pitch and yaw angular rates of the system excited by vehicle motion, and these two rate information is used to stabilize the pitch and yaw direction without additional signal processing [6-9].

In this study, we analytically derived stabilization errors to be generated in vehicle-mounted system with 2-axes gyro sensor with some reasonable assumptions, and verified them through simulation studies with various vehicle motions in typical traveling conditions. The validity of the conventional attitude estimation method for vehicle-mounted system is also discussed.

2. SYSTEM STRUCTURE AND MODELING

2.1 System structure

In vehicle-mounted stabilization system, 2-axes gimbal platform is widely used to compensate vehicle-induced pitch and yaw disturbances by actuating elevation and azimuth part. Our target system is also considered as 2-axes actuating system with several sensors as described in Fig. 1.

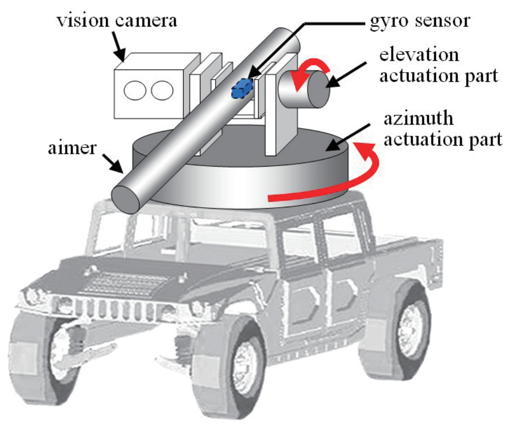


Fig. 1 System structure

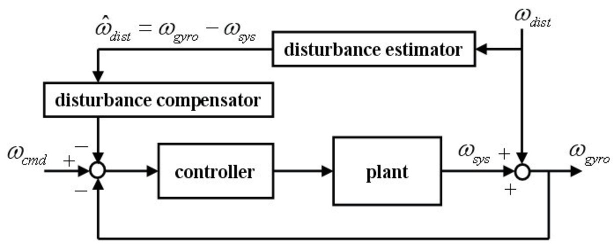
The aimer and vision camera are constrained to elevation part so that they are looking toward same direction all the time. Gyro sensor is located in the center of elevation axis line and measures inertial angular rates of the aimer. We assumed that the angular velocities of azimuth and elevation part are determined by user's joystick manipulation, and each actuation part has an encoder to sense the relative angular velocity with respect to the vehicle's longitudinal direction.

2.2 System modeling

Simulation model was designed by SimMechanics Toolbox, the commercial dynamic simulation program based on MATLAB SIMULINK. The model consists of 3 rigid bodies of azimuth part, elevation part(aimer) and vehicle(hull), and has actuating joints, joint sensors and a gyro sensor. Once we input the actuating forces or motion to the respective bodies through the actuating joints, each joint sensor outputs angle or angular rate. Linear viscous damping forces were considered between respective actuators and bodies. Especially, the gyro sensor was modeled to well reflect the physical characteristics of output signals. In this study, the measurement noise and nonlinear friction effect among system elements were not considered.

2.3 Control structure

We employed stabilization control algorithm with efficient disturbance rejection function which is widely used in vehicle-mounted system [10]. The basic concept is velocity control. Namely, the control objective is to make the gyro sensor output velocity (i.e. aimer's angular rate : ω_{gyro}) follow the user's velocity command (ω_{cmd}) with rejecting disturbances. Fig. 3 shows block diagram of the algorithm.



ω_{cmd} : user's velocity command

ω_{gyro} : gyro sensor output angular rate

ω_{sys} : relative angular velocity of each part

ω_{dist} : vehicle-induced disturbance

$\hat{\omega}_{dist}$: estimated disturbance

Fig. 2 Block diagram of stabilization control algorithm

The vehicle-induced disturbance is pre-compensated by feedforwarding the estimated disturbance through disturbance compensator block.

3. GYRO SENSOR SIGNAL PROCESSING

Gyro sensor has a characteristic that it outputs angular rates in reference to its body-fixed coordinates. Thus, for the accurate attitude estimation of an object, 3-axes gyro sensor is required to be equipped with the object, and three angular rates from the sensor should be transformed to global coordinates and integrated in general. However in most practical cases of stabilization system mounted on a mobile vehicle, only 2-axes gyro sensor is used to sense the pitch and yaw angular rates of the system, and these untransformed two rates are regarded as attitude information of the system without additional signal processing. Thus, this paper discusses stabilization errors between in the ideal case using 3-axes gyro sensor and in the conventional case using 2-axes gyro sensor. Considered gyro sensor signal processing methods are presented below.

(i) 3-axes gyro sensor output rates
→ transformation to global coordinates system
(ii) 2-axes gyro sensor output rates
→ transformation to global coordinates system
(iii) 2-axes gyro sensor output rates
→ no coordinates-transformation

As a coordinates-transformation method, we adopted Euler angle method described by Eq. (1).

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{1}$$

where ϕ, θ, ψ are roll, pitch and yaw Euler angle in global coordinates respectively, and ω_x, ω_y, ω_z are angular rates about respective axes in gyro sensor's body-fixed coordinates.

4. ANALYTIC DERIVATION OF STABILIZATION ERRORS

4.1 Basic assumptions

Let us consider that vehicle's roll angle, ϕ is induced within ±10° during travel, thus

$$\sin\phi \simeq \phi\ , \quad \cos\phi \simeq 1\,. \tag{*}$$

It is also assumed that pitch and yaw angular rates from gyro sensor are same in all methods, and their integrated values become approximately zero by stabilization of elevation and azimuth direction.

$$\begin{aligned} \omega_y &= \hat{\omega}_y = \tilde{\omega}_y \\ \omega_z &= \hat{\omega}_z = \tilde{\omega}_z \end{aligned} \tag{**}$$

$$\begin{aligned} \int \omega_y dt &= \int \hat{\omega}_y dt = \int \tilde{\omega}_y dt \simeq 0 \\ \int \omega_z dt &= \int \hat{\omega}_z dt = \int \tilde{\omega}_z dt \simeq 0 \end{aligned} \tag{***}$$

4.2 Stabilized angular rates in the method that 3-axes gyro sensor is used.

By applying the assumption (*) to Eq. (1), stabilized angular rates in the ideal case using 3-axes gyro sensor can be arranged by Eq. (2).

$$\dot{\phi} = \omega_x + \phi\omega_y \tan\theta + \omega_z \tan\theta$$
$$\dot{\theta} = \omega_y - \phi\omega_z \tag{2}$$
$$\dot{\psi} = \frac{\phi}{\cos\theta}\omega_y + \frac{1}{\cos\theta}\omega_z$$

4.3 Stabilization errors in the method using 2-axes gyro sensor with coordinates-transformation

In this method, roll motion of the system cannot be measured, i.e. $\hat{\omega}_x = 0$. Thus, stabilized angular rates can be derived as follow.

$$\dot{\hat{\phi}} = \hat{\phi}\hat{\omega}_y \tan\hat{\theta} + \hat{\omega}_z \tan\hat{\theta}$$
$$\dot{\hat{\theta}} = \hat{\omega}_y - \hat{\phi}\hat{\omega}_z \tag{3}$$
$$\dot{\hat{\psi}} = \frac{\hat{\phi}}{\cos\hat{\theta}}\hat{\omega}_y + \frac{1}{\cos\hat{\theta}}\hat{\omega}_z$$

If stabilization errors are defined as yaw and pitch angle differences between in this method and in former ideal method,

$$\psi_{err} = \hat{\psi} - \psi = \int(\dot{\hat{\psi}} - \dot{\psi})dt \tag{4}$$
$$\theta_{err} = \hat{\theta} - \theta = \int(\dot{\hat{\theta}} - \dot{\theta})dt$$

the errors are derived as Eq. (5).

$$\int(\dot{\hat{\psi}} - \dot{\psi})dt = \int(\frac{\hat{\phi}}{\cos\hat{\theta}}\hat{\omega}_y + \frac{1}{\cos\hat{\theta}}\hat{\omega}_z - \frac{\phi}{\cos\theta}\omega_y - \frac{1}{\cos\theta}\omega_z)dt \tag{5}$$
$$\int(\dot{\hat{\theta}} - \dot{\theta})dt = \int(\hat{\omega}_y - \hat{\phi}\hat{\omega}_z - \omega_y + \phi\omega_z)dt$$

If stabilized pitch angles in the ideal method and this method are almost same,

$$\theta \simeq \hat{\theta} \tag{****}$$

and with assumption (**), the errors are arranged by

$$\int(\dot{\hat{\psi}} - \dot{\psi})dt = \int\frac{(\hat{\phi} - \phi)}{\cos\theta}\omega_y dt \tag{6}$$
$$\int(\dot{\hat{\theta}} - \dot{\theta})dt = -\int(\hat{\phi} - \phi)\omega_z dt$$

The estimated roll angle in this method is presented as

$$\hat{\phi} = \int\dot{\hat{\phi}}dt = \int(\hat{\phi}\hat{\omega}_y \tan\hat{\theta} + \hat{\omega}_z \tan\hat{\theta})dt$$
$$= \hat{\phi}\tan\hat{\theta}\int\hat{\omega}_y dt - \int\frac{d}{dt}(\hat{\phi}\tan\hat{\theta})(\int\hat{\omega}_y dt)dt \tag{7}$$
$$+ \tan\hat{\theta}\int\hat{\omega}_z dt - \int\frac{d}{dt}(\tan\hat{\theta})(\int\hat{\omega}_z dt)dt$$

From the assumption (***), this can be approximated by

$$\hat{\phi} \simeq 0.$$

Thus, the stabilization errors are finally presented as

$$\psi_{err} = -\int\frac{\phi}{\cos\theta}\omega_y dt \tag{8}$$
$$\theta_{err} = \int\phi\omega_z dt$$

4.4 Stabilization errors in the method using 2-axes gyro sensor without coordinates-transformation

In this method, pitch and yaw angular rates from gyro sensor are respectively regarded as elevation and azimuth angular rates in global coordinates.

$$\dot{\tilde{\theta}} = \tilde{\omega}_y \tag{9}$$
$$\dot{\tilde{\psi}} = \tilde{\omega}_z$$

Thus, the stabilization errors are arranged by

$$\psi_{err} = \int(\dot{\tilde{\psi}} - \dot{\psi})dt = \int(\tilde{\omega}_z - \frac{\phi}{\cos\theta}\omega_y - \frac{1}{\cos\theta}\omega_z)dt$$
$$\theta_{err} = \int(\dot{\tilde{\theta}} - \dot{\theta})dt = \int(\tilde{\omega}_y - \omega_y + \phi\omega_z)dt$$

From the assumption (**), these become

$$\psi_{err} = -\int(\frac{\phi}{\cos\theta}\omega_y + \frac{1-\cos\theta}{\cos\theta}\omega_z)dt \tag{10}$$
$$\theta_{err} = \int\phi\omega_z dt$$

4.5 Analysis of the error formulas

We can deduce in Eq. (8, 10) that unmeasured roll motion coupled with the other attitude information induces stabilization errors when 2-axes gyro sensor is used for the system. If the second term of yaw angle error in Eq. (10) is negligible,

$$\int(\frac{1-\cos\theta}{\cos\theta}\omega_z)dt \simeq 0 \tag{*****}$$

the stabilization errors in both methods become same. Thus, it can be concluded that stabilization errors are almost same regardless of coordinates-transformation process if 2-axes gyro sensor is used for the system. We can also consider the situation that vehicle's roll angle is non-zero mean valued, i.e. vehicle is running with inclining to the constant roll direction. In this situation, we predict that integrated roll bias will induce the linear accumulation of errors.

5. SIMULATION STUDY

For the verification of assumptions established in analytic derivation process and confirmation of the predicted phenomena, we conducted stabilization simulations with various vehicle traveling conditions.

5.1 Simulations for vehicle motion generation

We performed simulations for acquisition of vehicle motion disturbing stabilization of the system with CarSim, the vehicle dynamics simulation software. A straight, harmonic and circular path based on RRC-9 stabilization bump course [7, 8, 12] were modeled to induce various vehicle motion. We measured vehicle's roll, pitch and yaw angles in conditions that it runs on the respective paths at the constant speed of 16 km/h. The vehicle's running characteristics during 100 sec were presented in Table 1.

Table 1 Running characteristics during 100 sec

		path type		
		straight	harmonic	circular
maximum peak (degree)	roll	0.3	0.8	8.0
	pitch	9.5	9.5	9.3
	yaw	0.15	14.3	-
main freq. band (Hz)	roll	0~1	0~1.5	0~1.5
	pitch	1	1	1
mean value (degree)	roll	**0.026**	**0.022**	**0.905**
	pitch	0.51	0.50	0.37

5.2 Stabilization simulation

Simulation was conducted to compare the stabilization performances in former discussed three gyro sensor signal processing methods. The performances were evaluated by error angles to the reference in global coordinates.

First, we stabilized both azimuth and elevation angles to 0 rad in global coordinates. Simulation results show that both direction angles are steadily well stabilized to zero angle with little perturbation in all traveling conditions when 3-axes gyro sensor is used. However in the methods with 2-axes gyro sensor, it appears that the errors are accumulated with a regular trend and little perturbation regardless of coordinates-transformation process. For example, Fig. 3 presents the results on circular path. We can observe the linear accumulation of errors in both directions. For the convenience of comparison, we distinguished the errors into standard deviation and mean gradient, and arranged the overall simulation results in Fig. 4. The standard deviations of stabilization errors appeared almost same in all methods. The accumulated errors(i.e. mean gradients) were presented as same considerable values in the methods with 2-axes gyro sensor regardless of coordinates-transformation process while they were near zero in the method with 3-axes gyro sensor. In particular, the accumulated errors became larger as the vehicle traveling condition goes from the straight path to the circular path.

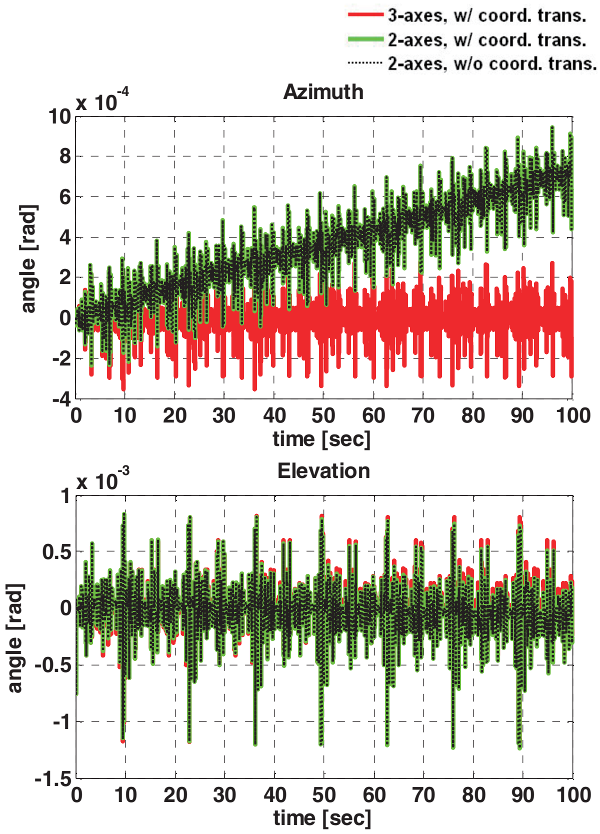
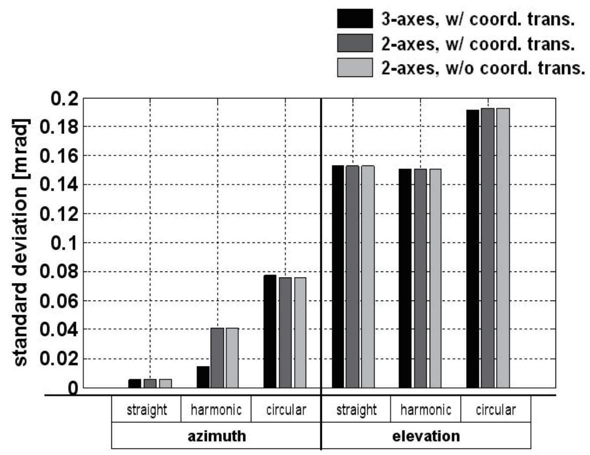
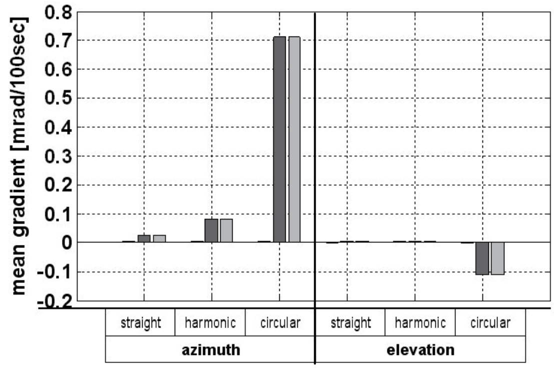


Fig. 3 Simulation results on circular path



(a) Standard deviation



(b) Mean gradient

Fig. 4 Simulation results arrangement

We also conducted simulations to investigate behavior of stabilization errors with respect to the change of elevation reference angles. The range of reference angles was limited within ±1.1 rad, because it was confirmed that if elevation angle gets out of the range and approaches the singular points, deterioration of control performance induces additional numerical errors in our model. Same as the former cases, this simulation result also shows that the angles are well stabilized to the reference when 3-axes gyro sensor is used. In the methods with 2-axes gyro sensor, it is observed that the errors are accumulated with a regular trend regardless of coordinates-transformation process. Especially, the overall shape of errors with respect to the change of elevation reference angles appeared similar to the inverse of $\cos\theta$. But the accumulated errors of azimuth direction were presented as an even function form, and those of elevation direction were presented as an odd function form. The overall accumulated errors in simulations with circular path were arranged in Fig. 5.

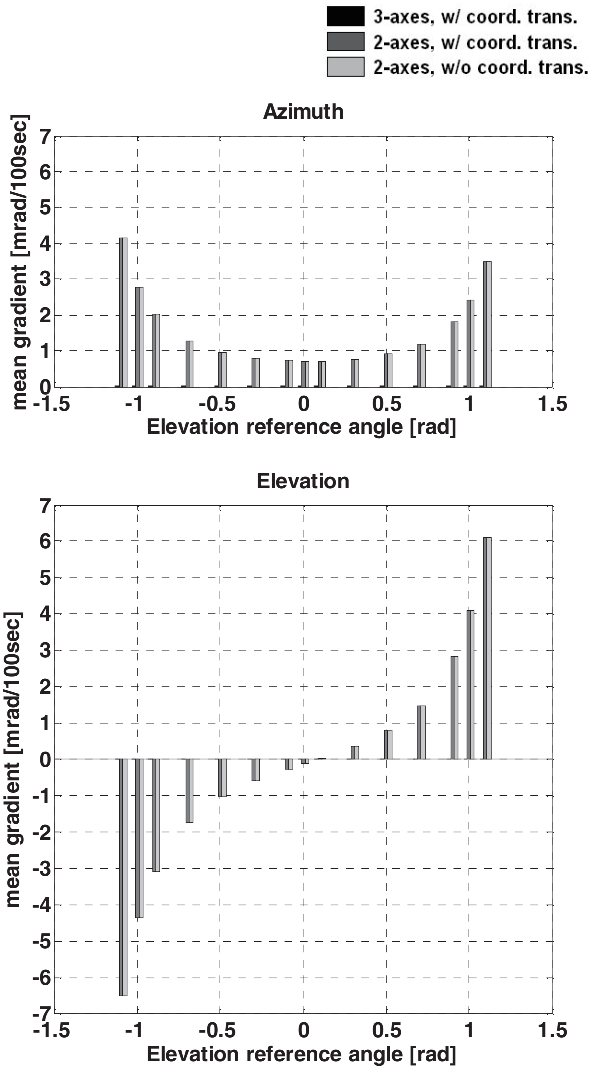


Fig. 5 Mean gradients with respect to the change of elevation reference angles on circular path

5.2 Analysis of simulation results

Through the various simulations, we confirmed that the standard deviations of stabilization errors are almost same in all methods, and the considerable accumulation of errors shows up in the methods with 2-axes gyro sensor. This accumulation of errors is regarded as the effect of roll motion that 2-axes gyro sensor didn't measure. The phenomenon that the accumulated errors are exponentially increased as the traveling condition goes from the straight to the circular path is considered due to the mean values of the vehicle's roll angle as we predicted in the analysis of the error formulas. The overall aspect of accumulated errors with respect to the change of elevation reference angles is also well reflecting the analytic error formulas with the shape similar to the inverse of $\cos\theta$.

6. CONCLUSION

In this paper, we analytically derived stabilization errors to be generated in vehicle-mounted system with 2-axes gyro sensor based on some reasonable assumptions, and verified them with various simulation studies.

Simulation results show that the analytic model well describes the behaviors of stabilization errors. Thus, we conclude that the assumptions established in the derivation process are reasonable, and this model can be applied to the characteristic analysis for stabilization errors in vehicle-mounted system using 2-axes gyro sensor.

Synthesizing the results and analysis, it is also concluded that 2-axes gyro sensor can be used in the condition that the vehicle's roll angle is within ±10° and zero-mean valued during travel such as on a straight flat road or on a straight gravel road. And coordinates-transformation process is unnecessary when 2-axes gyro sensor is used for the vehicle-mounted system. With avoiding this process, we could reduce the computational load to achieve same stabilization performances.

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