CONTROL FOR OTM(ON-THE-MOVE) ANTENNA DRIVEN BY INDIRECT SERVO MECHANISM WITH FLEXIBILITY

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Abstract: In this study, an OTM(On-The-Move) antenna which is mounted on ground vehicles and used for communication between vehicle and satellite was addressed. Since vehicles move during communication, active antenna LOS(line-of-sight) stabilization is a core technology to guarantee satellite communication quality. Stabilization control of the LOS of antenna which is driven by a motor coupled with gear and flexible driving shaft has been addressed. In the consideration of finite stiffness of the shaft, disturbance torque due to vehicle motion coupled with gear ratio, and kinematic coupling of the outer gimbal dynamics, a stabilization control has been proposed. The feasibility of the proposed control design was verified along with simulation results.

1 INTRODUCTION

Inertially stabilized platforms are used to stabilize and point sensors, image acquisition devices, telescopes, weapon systems, etc. These platforms are usually equipped on various moving vehicles such as ground vehicles, aircrafts, ships, satellites, submarines, and are even used on handheld devices(Hilkert, 2008; Debruin, 2008). This paper considers an OTM(on-the-move) satellite communication antenna mounted on a ground moving vehicle in the control aspects. In this application, LOS(line of sight) of antenna must be pointed to a fixed-satellite accurately while the vehicle on which the antenna is mounted is moving over a rough terrain to ensure good communication quality as shown in Fig. 1. To establish these requirements, a gimbaled platform, suitable sensors and active control are needed to stabilize the LOS(line-of-sight) in an inertial frame.

In the aspect of control, direct driven gimbal servo-mechanism is advisable (Kennedy et al., 2003), but a motor drive system equipped with gear train and flexible driving shaft is addressed in this paper. Certainly this indirect driving mechanism is cost effective then direct one. On the other hand, vibration suppression and disturbance rejection is an important problem in motion control. To overcome the problems, various control methods were suggested such as PI, PID, Optimal, Variable Structural Control, etc. (Nam et al., 2008; Zhang et al., 2000; Szabat et al., 2007; Hace et al., 2005). However, though the research of the flexible transmission control is widely present, the methods often do not address the load position control problem, which is a key issue in the LOS stabilization.

In this paper, we propose a control design technique which addresses the flexibility of torque transmission, the disturbance torque coupled with gear ratio and vehicle motion, and kinematic coupling that is inherent problem of all two-axis gimbals. The effectiveness of the proposed control is established along with some simulation examples.

2 DYNAMIC MODEL OF GIMBAL SYSTEM

A commonly used configuration for OTM antenna

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suspended by a two-axis gimbal (elevation over azimuth) system is illustrated in Fig. 1. The gimbal axes are orthogonal each other. An antenna comprised of an aperture and a supporting device is used to collect and direct RF energy from and to the satellite. A dish type aperture is used in a traditional antenna.

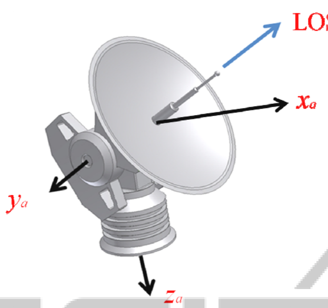

Figure 1: Structure of OTM Antenna.

To drive the antenna in Fig.1, two motors are used: one for the inner gimbal and the other for outer gimbal. A driving mechanism consists of a motor, a gear of gear ration N, a flexible shaft and load is shown in Fig. 2. Throughout this paper the subscripts m and L denote the motor and load, respectively. J is the moment of inertia, and ω is the angle velocity measured in inertial space. ω_h is the vehicle rotation. k_1 and k_2 are stiffness of the motor axis and the gear train output axis, respectively.

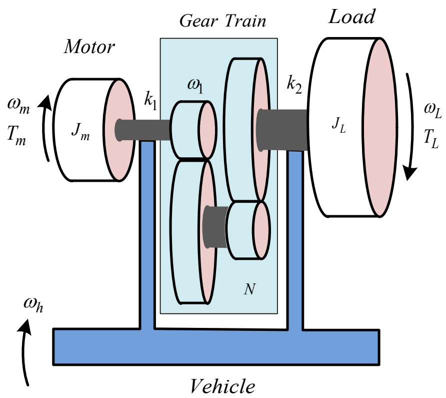

Figure 2: Schematic of gimbal driving mechanism.

To measure the pitch rate and yaw rate of the LOS, a set of orthogonal two-axis rate gyro is mounted on the antenna.

If the moment of inertia of the gear train is small enough compared with those of motor and load, then the dynamic model can be represented by a two-inertia system as follows:

$$\begin{cases} J_m\dot{\omega}_m + K_{eq}\omega_m - NK_{eq}\omega_L = -K_{eq}(N-1)\omega_h + \dfrac{d}{dt}T_m \\ J_L\dot{\omega}_L + N^2K_{eq}\omega_L - NK_{eq}\omega_m = K_{eq}N(N-1)\omega_h + \dfrac{d}{dt}T_d \end{cases} \quad (1)$$

where $K_{eq} = k_1k_2/\left(N^2k_1 + k_2\right)$ is the equivalent stiffness represented in the motor side.

As can be seen in (1), vehicle motion coupled with gear ratio and equivalent stiffness affects as a torque disturbance on both the motor and load dynamics.

3 STABILIZATION CONTROL

3.1 Elevation Axis

The objective of stabilization control for antenna pitch-direction is absolutely nullifying the inertial angular rate of the load, i.e. $\omega_L = \omega_{y_a} = 0$. Thus the inner gimbal remains mass stabilized and does not need to move in inertial space to stabilize the LOS, and merely needs to drive to nullify the pitch rate gyro output.

To stabilize the model in (1) which has two vibration modes of no damping, we introduce a conventional IPD-control(T_{IPD}) + damping-control(T_{damp}) + vehicle motion feedforward compensation control (T_{vffc}) of the form

$$\begin{aligned} T_m &= T_{IPD} + T_{damp} + T_{vffc} \\ T_{IPD} &= \frac{K_i}{s}(\omega_r - \omega_L) - \left(K_d s + K_p^*\right)\omega_L \\ T_{damp} &= -K_m\left\{\omega_m + (N-1)\omega_h - N\omega_L\right\} \\ T_{vffc} &= -(N-1)J_m\dot{\hat{\omega}}_h \end{aligned} \quad (2)$$

where ω_r is the reference rate input and $\dot{\hat{\omega}}_h$ denotes the measured or estimated vehicle angular acceleration. The term in the parenthesis of the damping control implies relative twisting rate of the shaft between the motor and the load.

Applying the control (2) to the system (1) gives the closed-loop model as

$$\begin{aligned} \omega_L = {} & \frac{NK_{eq}K_i}{p(s)}\omega_r + \frac{N(N-1)K_{eq}}{p(s)}J_m\left\{\dot{\omega}_h - \dot{\hat{\omega}}_h\right\} \\ & + \frac{s\left\{J_m s^2 + K_m s + K_{eq}\right\}}{p(s)}T_d \end{aligned} \quad (3)$$

$$\begin{aligned} p(s) = & J_m J_L s^4 + J_L K_m s^3 + (J_L + N^2 J_m + NK_d) K_{eq} s^2 \\ & + (N^2 K_m + NK_p) K_{eq} s + NK_{eq} K_i \end{aligned} \tag{4}$$

From (3), we can see that the stabilization error due to vehicle motion can be reduced by the vehicle motion compensation. Certainly, from the closed-loop characteristic equation $p(s)$, the damping control gain K_m is necessary to stabilize the system. To design control gains, we employ a simple pole-assignment technique as follows:

$$p(s) = J_m J_o \left(s^2 + 2\varsigma\omega_n + \omega_n^2 \right)^2 \tag{5}$$

where ς and ω_n are the desired damping ratio and natural frequency, respectively.
The control gains can be easily determined from (4) and (5).

3.2 Azimuth Axis

Apart from the inner gimbal, the outer gimbal axis does not coincide with the antenna yaw axis. Thus the outer gimbal must be rotated to stabilize the LOS because of the kinematic coupling that is inherent problem of all two-axis gimbals.

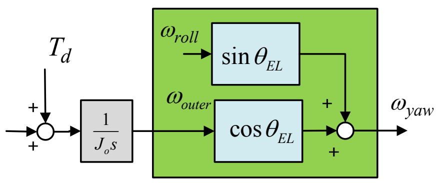

Figure 3: Yaw rate of LOS.

More precisely, as shown in Fig. 3, to stabilize the LOS, the outer gimbal must rotate to nullify yaw rate of the LOS. From the kinematic coupling, the yaw rate is given by

$$\omega_{yaw} = \cos\theta_{EL}\omega_{outer} + \sin\theta_{EL}\omega_{roll} \tag{6}$$

where ω_{yaw} is the yaw rate of the LOS, ω_{roll} is the roll rate of the outer gimbal, and θ_{EL} the inner gimbal angle.
Consequently, from (6), the outer gimbal rate should satisfy the following to stabilize the LOS.

$$\omega_{outer} = -\tan\theta_{EL}\omega_{roll} \tag{7}$$

In other words, the kinematic coupling has the same effect on the apparent motion of LOS as a torque disturbance acting in the opposite direction.

In the consideration of the kinematic coupling, the control in (2) is modified to include secant gain correction and roll motion compensation as follows:

$$\begin{aligned} T_m &= T_{IPD} + T_{damp} + T_{vffc} + T_{roll} \\ T_{IPD} &= \frac{1}{\cos\theta_{EL}}\left[\frac{K_i}{s}\left(\omega_r - \omega_{yaw}\right) - \left(K_d s + K_p^*\right)\omega_{yaw} \right] \\ T_{damp} &= -K_m\left\{\omega_m + (N-1)\omega_h - N\omega_{outer}\right\} \\ T_{vffc} &= -(N-1)J_m\dot{\hat{\omega}}_h \\ T_{roll} &= -\left\{ \frac{\tan\theta_{EL}}{N}(J_L + N^2 J_m)s \right\}\omega_{roll} \end{aligned} \tag{8}$$

Then the closed-loop yaw rate is given by

$$\begin{aligned} \omega_{yaw} = & \frac{NK_{eq,m}K_i}{p(s)}\omega_r + \frac{s^3\left\{J_m J_o s + J_o K_m\right\}}{p(s)}\sin\theta_{EL}\omega_{roll} \\ & + \frac{s\left\{J_m s^2 + K_m s + K_{eq,m}\right\}\cos\theta_{EL}}{p(s)}T_d \end{aligned} \tag{9}$$

Without the roll compensation in (8), the closed-loop yaw rate due to the coupling is given as

$$\omega_{yaw}\Big|_{roll} = \frac{s^2\left\{J_m J_L s^2 + J_o K_m s + (J_L + N^2 J_m)K_{eq}\right\}}{p(s)}\sin\theta_{EL}\omega_{roll} \tag{10}$$

Comparing (9) with (10), we can expect the roll compensation can attenuate stabilization error due to the kinematic coupling.

4 SIMULATION EXAMPLES

To evaluate the feasibility of the proposed control, some simulations were carried for the outer gimbal of the OTM antenna under consideration. A controller was designed according to the method in the previous section. Throughout the simulations, the sampling frequency was kept at 1 kHz.

Some simulation results conformed the damping control is necessary to stabilize the system. Also we found that the vehicle motion compensation can perfectly cancel the disturbance torque coupled with gear ratio and vehicle angular acceleration when the vehicle acceleration is measured accurately.

To establish the stabilization performance of the roll motion compensation, a response to a typical vehicle motion were simulated. For the simplicity, the angular acceleration of the vehicle roll motion was assumed to be a chirp signal of which frequency varies linearly from 0.1Hz to 5Hz within 5 s. The magnitude of the acceleration at each frequency was kept to be 10 rad/s^2. The elevation angle was assumed to be 45^o. Fig. 4 shows the stabilization error resulted from the controls with and without the roll compensation. As expected from (9) and (10), the responses exhibited the effectiveness of the roll compensation for attenuating stabilization error due to the gimbal kinematic coupling.

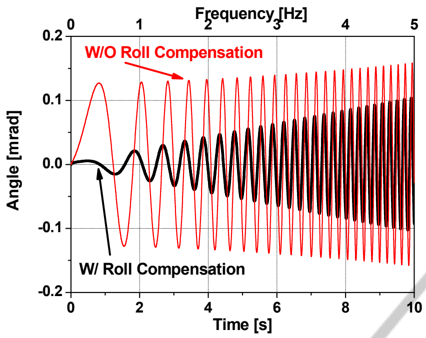

Figure 4: Stabilization error – azimuth direction.

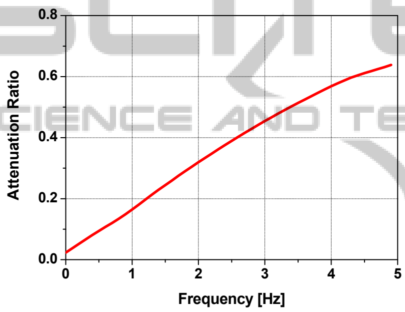

Figure 5: Stabilization error attenuation ratio.

The stabilization error ratio which calculated from the magnitude of error with compensation over the magnitude of error without compensation is shown in Fig. 5. Evidently, the error is largely attenuated in low frequency region, and the lesser as increasing frequency. This result is consistent with the analytical results in (9) and (10). From the simulation results, we can conclude the control proposed in this paper is effective to improve stabilization performance of OTM antenna.

5 CONCLUSIONS

In this work, an inertial stabilization control for the LOS of an OTM antenna driven by a motor coupled with gear and flexible driving shaft has been addressed. In the consideration of flexibility of the shaft, disturbance torque due to vehicle motion coupled with gear ratio, and kinematic coupling of the outer gimbal dynamics, a stabilization control has been proposed. The control consists of a conventional IPD-control, damping-control, vehicle motion feed-forward compensation-control, and roll motion feed-forward compensation control.

The simulation results demonstrated that the proposed control design guarantees system stability and effective to attenuate the stabilization error due to the disturbance torque related to vehicle motion and kinematic coupling.

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