

Developing a Convenient Balance Beam for Unknown Loads

Keon Young Yi* *Associate Professor*
Yong Jun Kim* *Graduate student*

Sam Yong Chung** *Team Leader*
Song Soo Han** *Senior Researcher/Ph.D*
Sang Heon Lee** *Senior Researcher/Ph.D*

*Dept. of Electrical Engineering
Kwangwoon University
Seoul 139-701, Korea

**Research Institute of Technology,
Samsung Corporation
270-1 Seohyun-dong, Bundang-gu,
Sungnam-si, Gyonggi-do, 463-824 Korea

Telephone : +822-940-5142
Fax : +822-942-0107
E-mail : keonyi@daisy.kw.ac.kr

Abstract: Balance beam, a controller that is built adopting the gyro effect, can freely control the attitude of an unstructured object by means of the position controlling of an inner gimbal. However in the former research, the weight (inertia) of a load should be known to issue a proper command for the gimbal, which makes it hard to operate the balance beam in field applications because the load can be changed frequently and, moreover, the inertia of the same load could be different according to how the load is held. Therefore an accident could be caused by the operation with an improper gimbal command.

One of the possible approaches to solve the problem is to give a balance beam controller an ability to detect the inertia of a load so that it can limit the velocity of the load ordered by a user. In this paper, we designed a controller that can estimate the inertia of the load based on the result we did before; the fact that when there is smaller inertia of load, the larger amount of the restoration displacement occurs. Thus, the load could be identified by issuing a predefined command to measure the amount of the restoration displacement, which makes us able to construct the controller that can limit the angular velocity of the load by planning the motion. Experimental results show the performance of the controller with some loads.

Keywords: gyro effect, balance beam controller, construction equipment, load estimation, gimbal

1. INTRODUCTION

In this paper, we designed the balance beam controller which can control unknown load using the CMG (control moment gyro) subsystem. Usually, gyro consists of a wheel spinning at high speed. It has a tendency to maintain its spin axis in a fixed direction in space. A torque exerted about any axis other than the spin axis produces a rotation about the axis that is orthogonal to the applied-torque axis[1][2]. We designed and implemented CGM subsystem for balance beam which has a rotating wheel at high speed and outer gimbal connected to the motor. As the attitude of the outer gimbal changes, rotation force occurs about the vertical axis if the balance beam is mounted on the object in air. We use the torque produced to control the attitude of the control object.

The CMG characteristics are addressed in a few researches such as the stabilizer for gondola and aircraft. Hiroshi KANKI and et al.[3] developed

CMG active vibration control device for gondola to reduce random wind force. And, Ahmed and et al.[4] studied on the gyro pendulum to eliminate the effects of mass imbalance in rotating bodies. Attitude control of spacecraft was addressed by Li and et al.[5]. Except for KANKI, all these studies have not addressed on an attitude control but on a stabilization of the spacecraft.

In our previous study, we expanded the application area of CMG subsystem from attitude control of the objects only to its stabilization in space. Furthermore, we designed an attitude controller of gimbal with gyro actuator that used wireless communication for actual application in field. However, in the unknown load inertia case, it is not easy even for skilled workers to operate a balance beam. That is caused by the difficulty in estimating the load inertia. If the excessive gimbal operation takes place with wrong estimations, accidents are likely to happen.

In this paper, we attached angular velocity sensor to gyro actuator to stabilize the attitude control of balance beam. Next, we estimated the inertia of load

using the output of angular velocity sensor and simple manipulation. Using the developed controller that can control the angular velocity of the balance beam, we make it easy to drive and strengthen the stabilization of the previous controller.

2. BALANCE BEAM

In this chapter, we will explain what the gyro effect is and how to build the balance beam. We will also briefly introduce the mathematical methods of the balance beam.

2.1 Gyro effect

In Figure 1, L_x represents angular momentum about x-axis, N_y and J_ω stand for torque about y-axis and the inertia of wheel, respectively.

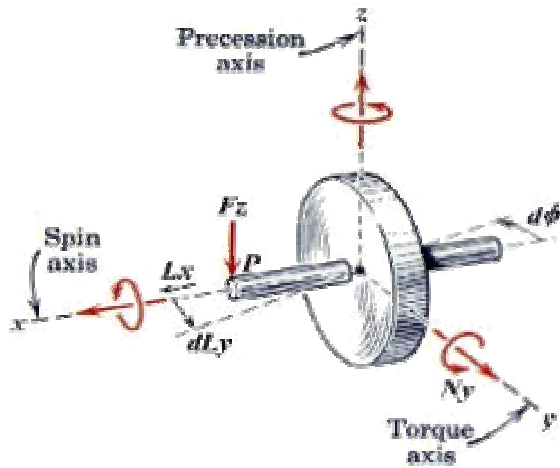


Figure 1. Gyro dynamics

Exerting force at arbitrary point P, we get a torque about y-axis, N_y , as bellow,

$$\frac{dL_y}{dt} = N_y \quad (1)$$

and we get a changed angular momentum

$$L = L_x + dL_y \quad (2)$$

Since a change of angular momentum, dL_y , is smaller than L_x

$$d\phi = \frac{dL_y}{L_x} \quad (3)$$

Substituting (1) into (3), we get

$$\frac{d\phi}{dt} = \frac{N_y}{L_x} \quad (4)$$

From this equation, one can see that rotational motion about the vertical axis, z, could be obtained by applying torque about y-axis.[1][2]

The other, rotational motion torque about horizontal axis, y, is obtained by gimbal motor. At the same time, ϕ , the rotation of load obtained by vertical axis, z.

2.2. CMG subsystem

In this section, the structure of the CMG subsystem, modeling of the system, the controller for the gimbal motor and the wheel motor are explained.

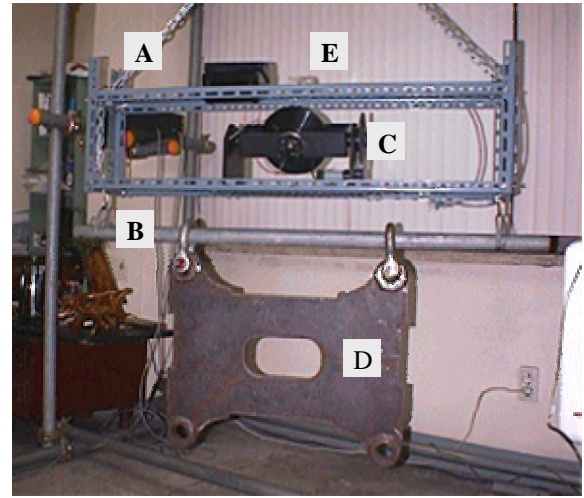


Figure 2. A balance beam system and load

The fabricated CMG subsystem in laboratory scale is shown in Figure 2, and enlarged gyro actuator is shown in Figure 3.

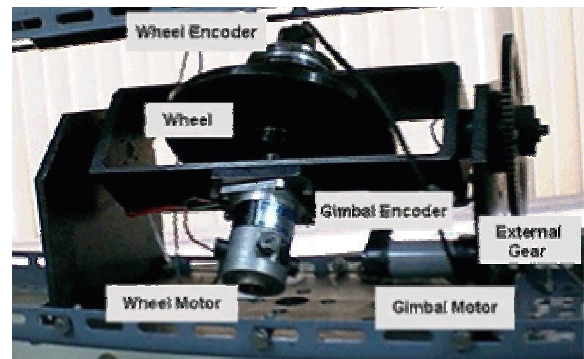


Figure 3. The structure of CMG subsystem

As shown in Figure 2 and 3, the control system consists of a wheel spinning by a motor, inner gimbal supporting the wheel and the wheel motor that is fixed to inner gimbal, and outer gimbal supporting the inner gimbal and gimbal motor that is fixed to outer gimbal. Inner gimbal position can be controlled by the gimbal motor. As shown in Figure 2, CMG subsystem is suspended from a structure through a swivel hook that has little friction.

The structure (B) to be hung the load (D) is shown

in Figure 2, and the details of CMG subsystem (C) is shown in Figure 3. The CMG subsystem consists of a high speed wheel and a gimbal that can control the attitude of the balance beam by means of adjusting the wheel rotation axis.

The piezoelectric vibrating gyroscope sensor is shown in Figure 2 (E). It can measure the load inertia using measurements of rotation velocities of the load. Also, a motor and an encoder are attached to both the axis of the wheel and the axis of gimbal.

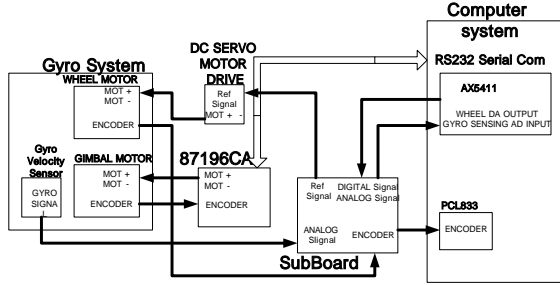


Figure 4. System block diagram

Subsystem block diagram in Figure 2 is shown in Figure 4. The control system consists of a 32-bit computer, Pentium-133MHz, an AX5411 A/D-D/A converter by Axiom Co., PLC833 3-axis quadrature encoder by Adventech, and an amplifier working in torque mode which has been built with power driver module, 12A8E, 5A5 by Advanced Motion Control. One encoder is used to measure the angular velocity of wheel, and the other encoder is used to measure inner gimbal position and velocity (500pulse through 18:1 gear reduction, and 4:1 external gear). Because the encoder body which measures angular velocity of the wheel can not be fixed firmly to wheel shaft, some noise is made. We solved this problem using second order butterworth filter in CMG control program. The wheel motor is 60[W] DC motor by Tamagawa seiki and gimbal motor is 15[W] DC motor by Maxon.

Also, we attached piezoelectric vibrating gyroscope sensor for sensing the angular velocity of load. 12-bits digital value that is changed by AX5411 A/D-D/A converter installed in computer could be measured by that sensor. The attitude of gimbal motor is controlled by means of the LMD18200. Control Board, 87C196 that is developed in our laboratory can control the attitude of load.

The specifications of the major parts organization of the system are listed in Table 1. The inertia of the balance beam is obtained by assumption that the frame and CMG are regarded as a rectangular parallelepiped of which mass has been distributed evenly.

2.3 CMG subsystem modeling

We derive the modeling of CMG subsystem from assumptions that gimbal is lighter than wheel (weight of the gimbal can be regarded as load), a viscous-

friction of swivel hook and bearing is very small, and motor inductance is negligible.

Table 1. The parameters of the system

Device	Specification
Wheel Motor	Tamagawa TRE PMDC 60[W], 1000p/r Encoder
Gimbal Motor	Maxon Amax110857 DC 15[W], 500p/r Encoder, 72:1 Reduction
Wheel mass /diameter	2.69[kg], 199.9[mm] diameter
CMG subsystem mass	24.55[kg]
Frame mass and dimension	9.3[kg], 789x200x200[mm]
Balance beam inertia	1.86[kgm ²]
Main Controller	87c196CA Control Board

The transfer function from the voltage applied to the angle of the gimbal motor is

$$G_1(s) = \frac{\theta_{gc}(s)}{v_a(s)} = \frac{k_m}{s(\tau_m s + 1)}$$

$$k_m = \frac{k_1}{(k_k k_b + f_m R_a)}$$

$$\tau_m = \frac{(J_{gr} + J_c) R_a}{(k_k k_b + f_m R_a)}$$
(5)

Where, k_b , k_t , and τ_m are back-emf constant, torque constant, and time constant, respectively [8]. R_a stands for armature resistance, J_{gr} represents rotor inertia of gimbal motor, J_c for the wheel inertia of circular disk turning about its radial axis.

Then, we assume that the gimbal is lighter than wheel. We considered the case which the load is attached to the gyro actuator.

The relationship between the attitude of the inner gimbal, θ_{gc} , and rotation about vertical axis, ϕ , is

$$(J_{gr} + J_c) \frac{d^2 \theta_{gc}}{dt^2} + f_m \frac{d \theta_{gc}}{dt} = J_w \omega_w \frac{d \phi}{dt} - J_l \frac{d^2 \phi}{dt^2}$$

$$J_w = M_w \frac{r^2}{2}$$

$$J_l = M_l \frac{(a^2 + b^2)}{12}$$

$$J_c = M_w \frac{r^2}{4} + M_w \frac{h^2}{12}$$
(6)

Where, M_w and M_l are mass of wheel and mass of load, respectively. r , h , a and b represent radius of wheel, thickness of wheel, length of load, and width of load, respectively. J_w means wheel inertia about spin axis. Then, transfer function $G_2(s)$ is

$$G_2(s) = \frac{\phi(s)}{\theta_{gc}(s)} = -\frac{(J_{gr} + J_c)s + f_m}{J_l s - J_w \omega_w} \quad (7)$$

Transfer function of the overall system $G(s)$ is obtained from (5) and (7) as following:

$$\begin{aligned} G(s) &= -G_1(s)G_2(s) \\ &= \frac{1}{s} \frac{(J_{gr} + J_c)k_m s + k_m f_m}{J_l \tau_m s^2 + (J_l s - J_w \omega_w \tau_m)s - J_w \omega_w} \\ &= \frac{1}{s} \frac{b_1 s + b_0}{s^2 + a_1 s - a_0} \end{aligned} \quad (8)$$

Where, a_0 , a_1 , b_0 , b_1 are determined by the motor parameters and the shape and angular velocity of the wheel. Notice that a_1 depends on the load inertia, and transfer function has an unstable pole.

3. BALANCE BEAM CONTROLLER

In this chapter, we will explain what the restoration of a gimbal is and how to use it to figure out the inertia of an unknown load. Furthermore, we will present a controller incorporating the restoration that can control the angular velocity of an unknown load by adjusting the proper gimbal command.

3.1 Restoration angle of gimbal

When we issue the gimbal motion command, the load rotates according to the amount of the command. However, if we cut the power of the balance beam, which initiates the stabilizing mode of the balance beam, it goes backward to stop the load. At this time we define the restoration angle as the difference between the issued gimbal angle and the angle when the load stops.

Here we investigate the relationship between the restoration angle and the load.

The loads, iron plate shown in Figure 2, considered here are summarized in Table 2, where the inertia values in the parentheses are the values including the inertia of the balance beam.

Table 2. Weight and inertia of load

Load	Weight [kg]	Inertia [kgm ²]
No load	0	0.00 (1.86)
Load 1	55	0.74 (2.70)
Load 2	55	2.12 (4.12)

Actually, loads are same, but the hanging direction is different; one is crosswise and the other is lengthwise. The motions of different loads to the gimbal command, 10 degrees, are depicted in Figure 5.

Note that the line marked as load represents the angular velocity of the load measured using the rate gyro sensor built in our lab [6]. The signal seems too noisy since the balance beam was chattering caused by the wheel noise. Actually, the sensor information is not involved in the controller, but it is just a monitoring signal to check the load angular velocity in this study.

In Figure 5, we can see the restoration angles (A, B, C) for different loads, which are getting smaller as the load increasing. Note that the figure (c) is enlarged for the purpose of the comparison. The detailed results are summarized in Table 3.

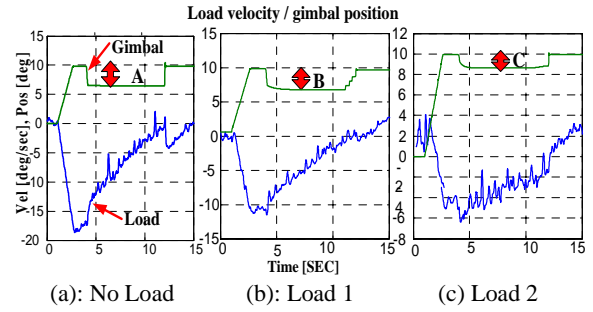


Fig. 5 The load angular velocity and gimbal trajectory

Table 3. Gimbal restoration angle for loads

Load	Gimbal command	Restoration angle
No Load	10°	3.27
Load 1		2.10
Load 2		1.58

The results for the different gimbal commands are not listed here since angles which are too small cannot give distinct restoration angle, whereas a too large one would make the load turn too much; exceeding testing angles. More experiments with various kinds of loads are needed to obtain the more precise characteristics line, but we present 3 points (small circles in the Figure 6) in this experiment.

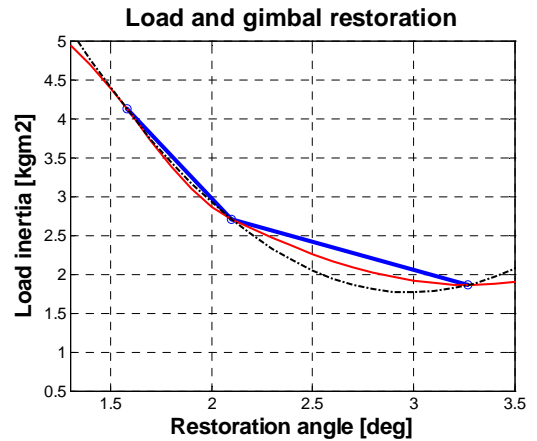


Figure 6. Load inertia and gimbal restoration angle

It is possible to figure out the load if we measure the restoration angle by issuing test command before the actual command. To do this, we have to find the relationship function between load and restoration angle by the second order fitting equation to the results in Figure 6 (dashed line), as follows. This can be obtained using the Matlab function 'fit' with the fitting option 'pchipinterp' as shown in the figure (light solid line).

$$y = ax^2 + bx + c \quad (9)$$

$$a = 1.1910, b = -7.1137, c = 12.3864$$

The algorithm to implement this procedure, unknown load estimation, is as follows.

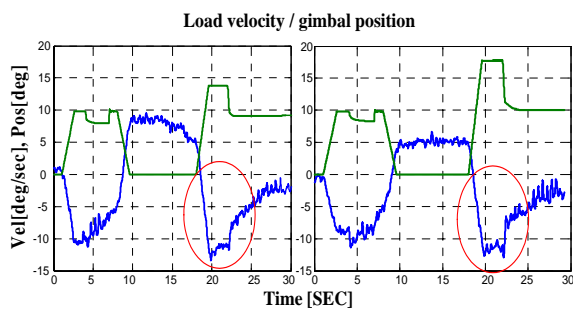
- STEP 1 :** Detect peak value of the gimbal with given gimbal command.
- STEP 2 :** Enter stabilizing mode by turning off the power of gimbal.
- STEP 3 :** Detect level value of the gimbal when load stops.
- STEP 4 :** Calculate restoration angle by subtracting the peak value with the level value.
- STEP 5 :** Find the inertia of the unknown load from the fitting equation.

3.2 Load motion to gimbal command

In the previous section, we could estimate the inertia of the unknown load. Now it is necessary to decide proper gimbal command angle for the load. To do this, figuring out the relationship between load and gimbal command angle is needed, which requires extensive experiment for many known loads at specific angular velocity of the loads, 12.5 [deg/sec]. The results are shown in Table 4 and some are illustrated in Figure 7.

Table 4. Gimbal restoration angle for loads

Load	Inertia	Restoration angle	Gimbal command
Load 1	1.86	3.27	11
Load 2	2.70	2.10	14
Load 3	4.12	1.58	18



(a): Load 2 (b): Load 3
Figure 7. The load angular velocity and gimbal

trajectory

The circled parts, in the figure, stand for the angular velocity of the load that we have to notice whereas the beginning parts are for the operation to obtain the restoration angles. The details of the gimbal operation are as following:

- Operation 1: position command, 10 degree, at 1 second.
- Operation 2: motor power off at 4 second.
- Operation 3: motor power on at 7 second.
- Operation 4: position command, 0 degree, at 8 second.
- Operation 5: position command, desired degree, at 18 second.
- Operation 6: motor power off at 22 second.

The relationship between load and gimbal command angle is as in Figure 8. From this figure, we can find the relationship function between load and gimbal command angle by fitting an equation to the result. This can be obtained using the method used for the Figure 6.

$$y = ax^2 + bx + c \quad (10)$$

$$a = -0.3339, b = 5.0938, c = 2.6805$$

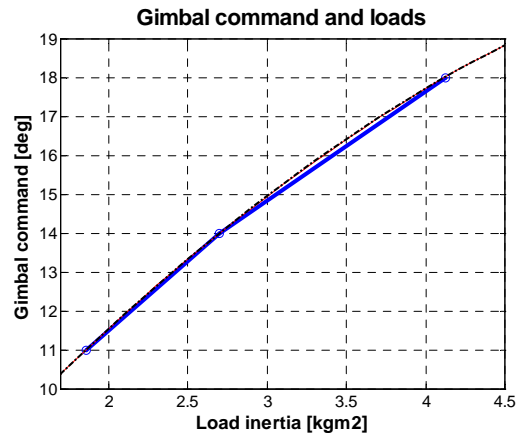


Figure 8. Gimbal command and loads

3.3 Load control

Following the procedures listed above, we demonstrate velocity control of an unknown load using the balance beam. We made unknown load by putting two stuffs on the frame hanging the load 1 shown in Table 2, which has inertia between load 1 and load 2 but it is not necessary to measure it because we have to deal with the unknown load. The target velocity is 12.5 [deg/sec].

We could have estimated the load to be 5.27 since we have the restoration angle 1.27 (A in the Figure 9), which came from the fitting equation (9) in Section 3.1 and is bigger than we expected. However, it seems reasonable because the gimbal command angle for this load, 20.25 in degree, is bigger than the angle of the load 3, 18.0 in degree.

The gimbal command angle was obtained from

the fitting equation (10) in Section 3.2, which had been modified by the controller based on load had estimated.

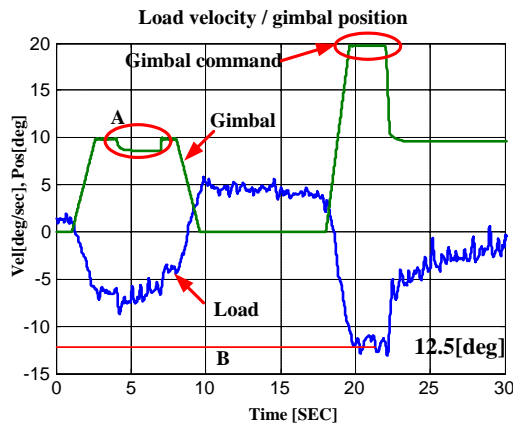


Figure 9. Angular velocity of unknown load and gimbal trajectory

In the figure, 'Load' stands for the angular velocity of the unknown load monitored by the gyro sensor, 'Gimbal' represents the angle of the gimbal. Note that the velocity of the unknown load is about 12.5 [deg/sec] as expected (B in the figure).

4. CONCLUSION

In this work, we designed a balance beam controller that can estimate the inertial of unknown load and control the angular velocity of it.

Unknown load could be estimated by investigating the characteristics of the restoration angle of the balance beam. We defined the fitting equation to estimate the load with the restoration angle measured. We also defined another fitting equation which can decide gimbal command angle by the estimated load. Finally, we could be able to implement the balance beam which can control the velocity of the unknown loads without an angular velocity sensor.

Thru an experiment we were able to show that the controller we developed is very convenient in handling construction work.

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