# Control of a Balance-Beam with Unknown Loads Using the Restoration Angle of a Gimbal

**Keon Young Yi, Yong Jun Kim, Sam Yong Chung, Song Soo Han, and Sang Heon Lee**

**Abstract:** A controller built with the gyro effect for a balance-beam can freely control the attitude of an unstructured object by changing the position of an inner gimbal. In this paper, we propose a new balance-beam controller that can detect the inertia of the load to limit the velocity of the load commanded by a user. We found that when there was smaller load inertia, a larger restoration displacement occurred. Therefore, the load can be identified by issuing a predefined command to measure the restoration displacement, which enables us to construct a controller that can limit the angular velocity of the load by planning the motion. Experimental results show the performance of the controller with different loads.

**Keywords:** Balance-beam, construction equipment, gimbal, load estimation.

## 1. INTRODUCTION

In this paper, we describe the design of a balance-beam controller that can control an unknown load using the control moment gyro (CMG) subsystem. Usually, a gyro consists of a wheel rotating at high speed, which tends to maintain its spin axis 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 a CGM subsystem for a balance-beam that has a wheel rotating at high speed and an outer gimbal connected to the motor. As the attitude of the outer gimbal changes, a torque is generated about the vertical axis that turns the object attached under the beam. Therefore, we can use the torque produced to control the attitude of the controlled object.

The CMG characteristics are addressed in a few studies, such as a stabilizer for gondolas and aircraft. Kanki *et al*. [3] developed a CMG active vibration control device for a gondola to reduce random wind forces. Ahmed *et al*. [4] studied the gyro pendulum as a means of eliminating the effects of mass imbalance in rotating bodies. Attitude control of spacecraft was addressed by Li *et al*. [5]. All these studies, except [3], have not addressed attitude control but have concentrated on stabilization of the load.

In our previous papers [6] and [7], we extended the application of the CMG subsystem beyond stabilization to the attitude control of objects. Furthermore, we designed a controller having a wireless communication function to simplify field applications [7]. However, in the case of unknown load inertia, even skilled workers have difficulty operating a balance-beam. If excessive gimbal operation takes place with incorrect load estimation, accidents are likely to occur.

## 2. BALANCE-BEAM

The mathematical attributes of the balance-beam are briefly described. The laboratory-scale CMG subsystem is shown in Fig. 1, and the CMG portion is shown in greater detail in Fig. 2.

As shown in Figs. 1 and 2, the control system consists of a wheel spun by a motor, an inner gimbal supporting the wheel and the wheel motor fixed to the inner gimbal, and an outer gimbal supporting the inner gimbal and a gimbal motor fixed to the outer gimbal. The attitude, or position angle, of the inner gimbal can be controlled by the gimbal motor. As shown in Fig. 1, the CMG subsystem, or balance-beam, is suspended from a structure through a swivel hook that has a little friction.

The structure (B) is used to hold the load (D). The piezoelectric vibrating gyroscope sensor (E) is mounted on the top of the balance-beam, which

---

Manuscript received December 8, 2004; revised September 5, 2005 and March 3, 2006; accepted March 27, 2006. Recommended by Editorial Board member Won-jong Kim under the direction of Editor Keum-Shik Hong. This work was supported by the Research Grant of Kwangwoon University in 2003.

Keon Young Yi and Youn Jun Kim are with the Department of Electrical Engineering, Kwangwoon University, 447-1 Wolgye-dong, Nowon-gu, Seoul 139-701, Korea (e-mails: {keonyi, yjkim}@earth.kw.ac.kr).

Sam Yong Chung, Song Soo Han, and Sang Heon Lee are with the Research Institute of Technology, Samsung Corporation, 270-1 Seohyun-dong, Bundang-gu, Sungnam-si, Gyonggi-do 463-824, Korea (e-mails: {yongsam, songhan, shlee31}@samsung.com).

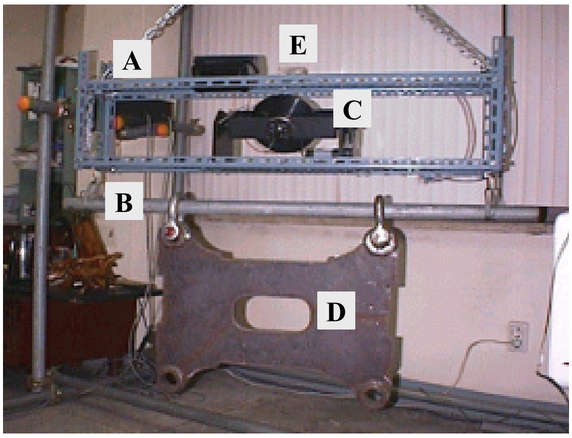


Fig. 1. A balance-beam system and load.

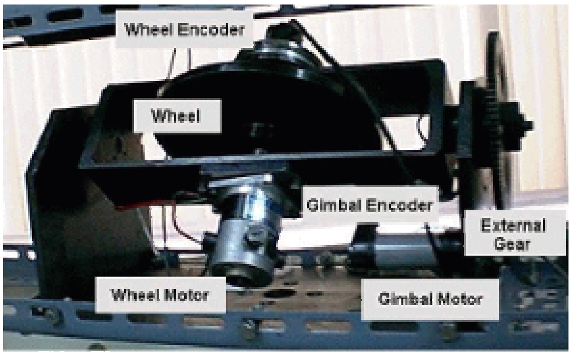


Fig. 2. The structure of CMG subsystem.

Table 1. The parameters of the system.

| Device | Specification |
|---|---|
| Wheel Motor | Tamagawa TRE PMDC 60W, 1000p/r Encoder |
| Gimbal Motor | Maxon Amax110857 DC 15W, 500p/r Encoder, 72:1 Reduction |
| Wheel mass /diameter | 2.69kg, 199.9mm diameter |
| CMG subsystem mass | 24.55kg |
| Frame mass and dimension | 9.3kg, 789 x 200 x 200mm |
| Balance beam inertia | 1.86kgm$^2$ |
| Sub board | 87c196CA Control Board with LMD18200 |

measures the velocity of the load to monitor the behavior of the controller. It is not part of the controller. Encoders attached to both axes of the wheel and the gimbal are used as sensors for the controller. The specifications of the major parts of the system are listed in Table 1.

The inertia of the balance-beam shown in Table 1 is obtained using the assumption that the frame and CMG are regarded as a rectangular parallelepiped over which its mass has been evenly distributed.

## 3. BALANCE-BEAM CONTROLLER

In this section, we describe the restoration of a gimbal and how it is used to determine the inertia of an unknown load. Furthermore, we present a controller incorporating the restoration that can control the angular velocity of an unknown load by adjusting the gimbal command.

### 3.1. Restoration angle of gimbal

When we issue a gimbal motion command, the load rotates in proportion to the command. However, if we reduce the power to the gimbal, which initiates the stabilizing mode of the balance-beam, it retreats from the reference position until the load stops. We define the restoration angle as the difference between the specified gimbal angle and the angle when the load stops.

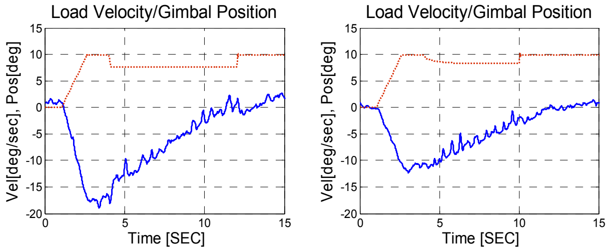
Here we investigate the relationship between the restoration angle and the load. The loads (the iron plates shown in Fig. 1) are summarized in Table 2, where the inertia values in parentheses are the values including the inertia of the balance-beam itself.

Loads 1 and 2 are the 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 shown in Fig. 3.

Note that the line marked with ‘load’ represents the

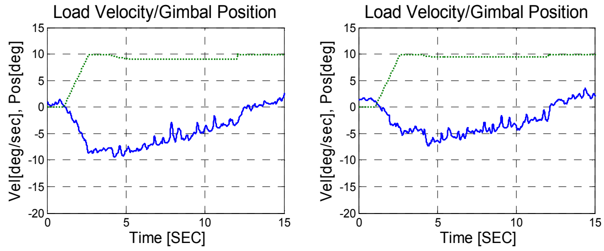
Table 2. Weight and inertia of load.

| Load | Weight [kg] | Inertia [kgm$^2$] |
|---|---|---|
| No load | 0 | 0.00 (1.86) |
| Load 1 | 55 | 0.74 (2.60) |
| Load 2 | 55 | 2.12 (3.98) |
| Load 3 | 120 | 5.06(6.92) |



(a) No load.

(b) Load 1.



(c) Load 2.

(d) Load 3.

Fig. 3. The load angular velocity and gimbal trajectory.

Table 3. Gimbal restoration angle for loads.

| Load | Gimbal command | Restoration angle |
|---|---|---|
| No load | 10° | 2.25° |
| Load 1 | | 1.50° |
| Load 2 | | 0.89° |
| Load 3 | | 0.48° |

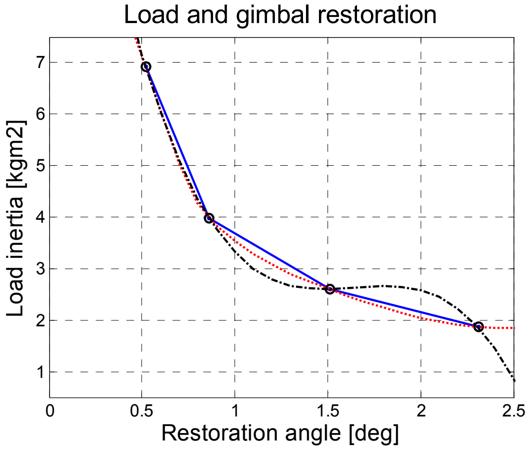


Fig. 4. Load inertia and gimbal restoration angle.

angular velocity of the load measured using the rate gyro sensor built in our lab [7]. The signal is noisy because the balance-beam was chattering due to the wheel noise. However, this is not important because the sensor information is only used to monitor the signal, as described above.

In Fig. 3, it can be seen that the restoration angles (A, B, C, and D) for the different loads decrease as the load increases. The results are summarized in Table 3.

The results for some other gimbal commands are not listed because too small angles that cannot give a distinct restoration angle, whereas too large a command made the load turn too much.

Now, we can obtain the relation between the load and the restoration angle. More experiments with various loads would be needed to obtain a more precise characteristics line, but we show four points (small dots are connected by solid lines in Fig. 4) in this paper.

It is possible to calculate the load if we measure the restoration angle by issuing a test command before the actual command. To do this, we have to find the relationship function between the load and the restoration angle by using a fitted third-order equation (dashed line), as follows.

$$\begin{aligned} &y = ax^3 + bx^2 + cx + d, \\ &a = -3.2199,\ \ b = 15.8953, \\ &c = -25.8905,\ \ d = 16.5378. \end{aligned} \tag{1}$$

This can be obtained using the Matlab function ‘fit’ with the fitting option ‘pchipinterp’ as shown in Fig. 4 (dotted line).

### 3.2. Load motion to gimbal command

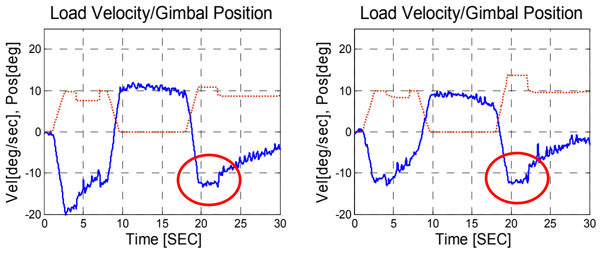
In the previous section, we derived an estimate of the inertia of the unknown load. It is necessary to decide the proper gimbal command angle for the load. To do this, it is necessary to derive the relationship between the load and the gimbal command angle, which requires extensive experimentation for many known loads at specific angular velocities.

The results for a target velocity of 12.5°/s are illustrated in Fig. 5 and summarized in Table 4.

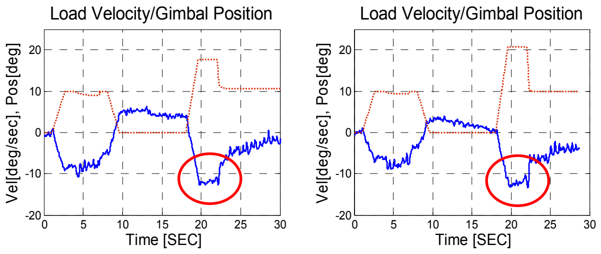
The circled sections in the figure are the angular velocities of the loads that we require, whereas the earlier sections are the initial operations to obtain the restoration angles (dotted line stands for the gimbal angle).

The relationship between load and gimbal command angle is shown in Fig. 6. From this figure, we derive the relationship function between load and gimbal command angle by fitting an equation to the result. This is obtained using the same method as used for Fig. 4.

$$\begin{aligned} &y = ax^3 + bx^2 + cx + d, \\ &a = -0.0286,\ \ b = -0.1327, \\ &c = 5.0765,\ \ d = 2.2008. \end{aligned} \tag{2}$$



(a) No load. (b) Load 1.



(c) Load 2. (d) Load 3.

Fig. 5. The load angular velocity and gimbal trajectory.

Table 4. Gimbal restoration angle vs. loads.

| Load | Inertia | Restoration angle | Gimbal command |
|---|---|---|---|
| No load | 1.86 | 2.31 | 11 |
| Load 1 | 2.60 | 1.51 | 14 |
| Load 2 | 3.98 | 0.86 | 18.5 |
| Load 3 | 6.92 | 0.52 | 21.5 |

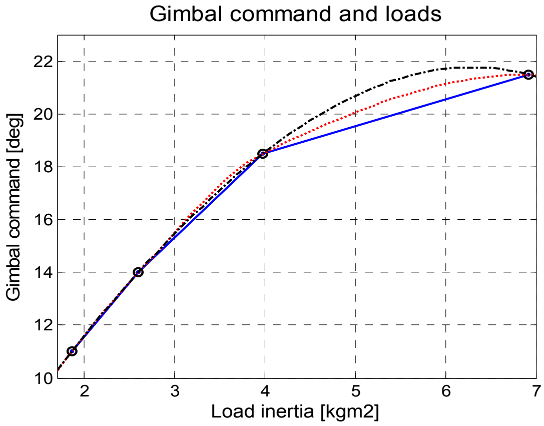


Fig. 6. Gimbal command and loads.

3.3. Load control

Using the procedures described above, we have velocity control of an unknown load using the balance-beam. We made an unknown load by putting an additional load on the frame carrying Load 1 shown in Table 2. Therefore, the unknown load had an inertia intermediate between the inertias of test Loads 1 and 2. However, it is not necessary to measure the load inertia, because the aim is to deal with an unknown load. The target velocity was 12.5°/s.

We estimated that the load was 4.62kgm$^2$ with a restoration angle of 0.77° (A in Fig. 7), which is the result from (1). The gimbal command angle of 19.5° was obtained from (2) by substituting the value of the estimated load.

The load estimated is larger than expected; however, it seems reasonable because the gimbal command angle for this load, 19.5°, is larger than the angle of test Load 2, 18.5°.

In Fig. 7, Load V is the angular velocity of the unknown load monitored by the gyro sensor, and Gimbal P is the angle of the gimbal. Note that the velocity of the unknown load is approximately 12.5°/s as desired (B in Fig. 7).

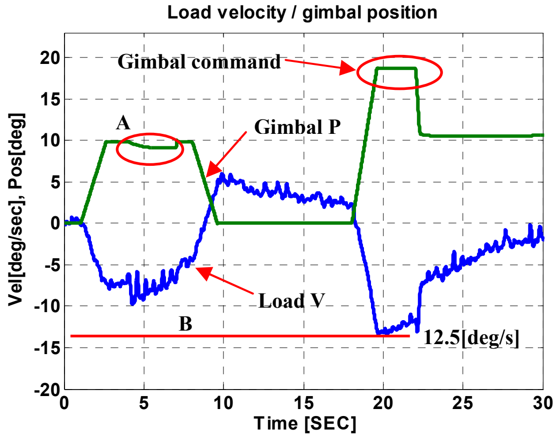


Fig. 7. Angular velocity of unknown load and gimbal trajectory.

## 4. CONCLUSIONS

We designed a balance-beam controller that can estimate the inertia of an unknown load and control its angular velocity. The controller for an unknown load can be derived by investigating the characteristics of the restoration angle of the balance-beam. We defined the equation of best fit for the balance-beam to estimate the load using the measured restoration angle. We also defined another equation of best fit that can estimate the gimbal command angle from the estimated load. Finally, we were able to implement a balance-beam that could control the velocity of unknown loads without an angular velocity sensor. Experimentally we demonstrated that the controller we developed was a very convenient new tool for construction.

## REFERENCES

[1] V. D. Barger and M. G. Olsson, *Classical Mechanics*, McGraw-Hill, pp. 193-195, 1995.

[2] S. T. Stefani, C. J. Savant, B. Shahian, and G. H. Hostetter, *Design of Feedback Control System*, Oxford University Press, pp. 44-45, 2002

[3] H. Kanki, Y. Nekomoto, H. Monobe, H. Ogura, and K. Kobayashi, "Development of CMG active vibration control device for gondola," *JSME Int. J. Series C*, vol. 37, no. 3, pp. 468-470, 1994.

[4] J. Ahmed, R. H. Miller, E. H. Hoopman, V. T. Coppola, D. S. Bernstein, T. Andrusiak, and D. Acton, "An actively controlled control moment gyro/gyropendulum testbed," *Proc. of IEEE Int. Conf. on Control Applications*, Hartford, CT, pp. 250-252, October 1997.

[5] F. Li, P. M. Bainum, N. G. Creamer, and S. Fisher, "Rapid reorientation maneuvers of experimental spacecraft with a pendulum appendage," *J. of Guidance Control & Dynamics*, vol. 21 no. 1, pp. 164-171, 1998.

[6] K. Y. Yi and Y. G. Chung, "An implementation of a gyro actuator for the attitude control of an unstructured object," *Proc. of IEEE Int. Conf. Robotic and Automation*, Detroit, Michigan, vol. 2, pp. 1626-1631, May 1999.

[7] M. O. Kwon and K. Y. Yi, "An attitude control and stabilization of an unstructured object using CMG subsystem," *Proc. of ISIM*, Kyongnam, Korea, pp. 311-316, October 2000.

**Keon Young Yi** received the B.S., M.S., and Ph.D. degree in Electrical Engineering from Hanyang University in 1982, 1984, and 1993, respectively. He is a Professor in the Dept. of Electrical Engineering, Kwangwoon University, Korea. His research interests include adaptive control, robotics, real-time system, and microprocessor applications.

**Yong Jun Kim** was born in Korea 1978. He received the B.Sc. degree in Electrical Engineering from the Kwangwoon University of Korea in 2003, and the M.Sc degree in 2005. He has employed as InterFace FirmWare Engineer in Solution Group of TSST (Toshiba Samsung Storage Technology) Korea Corporation since he graduated a graduated school.

**Sam Yong Chung** graduated with the B.S. degree in Architectural Engineering from Sungkyunkwan University, Korea, in 1984. He has been with Samsung Corporation, Korea, since 1983 and is currently a Leader of Construction Equipment Research Part. His area of interest includes analysis and optimiza-tion of high-rise lifting plan and automation of construction equipment based on his field experience such as in Petronas Twin Tower Project in Malaysia, Tower Palace Project in Korea, and Burj Dubai Project in UAE.

**Song Soo Han** graduated from Seoul National University, Korea, in 1985 with the B.S. degree in Mechanical Design & Production Engineering. He received both the M.S. degree in 1987 and Ph.D. degree in 1995 in Mining Engineering, Colorado School of Mines, Colorado, USA. Currently, he is a Senior Researcher in Samsung Corporation, Korea. His research interests include the high-pressure water jet cutting, and development of construction equipment.

**Sang Heon Lee** graduated with the B.S. degree in Precision Mechanical Engineering from Hanyang University, Seoul, Korea in 1992. He received the M.S. degree in Precision Engineering from KAIST, Taejon, Korea in 1994 and the Ph.D. degree in Mechanical Engineering from KAIST in 2001. Currently, he is a Senior Researcher in Samsung Corporation, Korea. His research interests include the kinematic/dynamic analysis on multi-body system, application of field robots, and automation in construction.