

# A Ball-on-Beam System with an Embedded Controller

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**Abstract** --This paper describes the design and construction of a ball-on-beam balance system driven by an embedded controller. This embedded control system is intended for linear controls education. The advantages of this system are as follows: first, it can be used for demonstrating proportional, PI, PD, PID, and velocity feedback controllers in action. Among these controllers, the velocity feedback was implemented into the embedded controller for controlling the position of the ball on the beam. The velocity feedback controller was implemented as a C program executed by a Freescale MC9S12C microcontroller. Second, it is a complete embedded control system that includes all the typical components such as sensors, actuators, signal conditioning circuits, and control methods. The sensors used in this system were infrared distance sensors. The actuator was a servomotor controlled by a pulse-width modulated signal. The signal conditioning circuits were implemented with op amps for interfacing the sensor signals into the microcontroller. The control method used was velocity feedback. Third, this embedded system is inexpensive and mechanically simple for construction. This system has been used for demonstrating the applications of feedback control techniques.

## 1. Introduction

The ball-on-beam balance system is a classic example of feedback control systems. The problem is to maintain the position of a ball at the center of a beam on which the ball rolls along freely. The ball will return to the center position after it has been displaced from this location. This system is an effective educational tool for teaching feedback control principles. Some of these systems are commercially available<sup>[1,2,3]</sup>.

The set-up of our ball-on-beam system is shown in Fig. 1. The beam is a 55" long, grooved aluminum beam that a regular rubber ball can roll along freely. The beam is mounted at the center to a servo motor, which can tilt the beam in clockwise and counter-clockwise directions. The servo motor is secured on a vertical shaft. Mounted at both ends of the beam are infrared distance sensors for determining the position of the ball on the beam. When the position of the ball is disturbed off the center position, the sensors will register that. The embedded controller will rotate the beam to a direction so as to move the ball toward the center. This action continues until the ball becomes stationary at the center. A velocity feedback controller is used to reduce excessive oscillations.

The unique features of our ball-on-beam system are as follows: first, it is inexpensive compared to those commercially available. It consists of a servo motor, infrared distance sensors, simple amplifier circuits, a microcontroller module, an aluminum beam, and other small mechanical parts. All these components are low-priced and can be found easily. Second, the sensing of the ball position is by using two infrared distance sensors. There is no tear and wear by the motion of the ball. Some of the commercial ball-on-beam systems use conductive strips that suffer from tear and wear by the ball. Third, it uses a microcontroller for the implementation of the control algorithm. It enjoys all the convenience that comes with a microcontroller. For example, changing the control method from velocity feedback to PID is simply done by flashing the codes for the PID method into the microcontroller. It can be done on the fly with no change in the hardware. Fourth, the students can build this system from scratch in one semester and learn much about controls from it.

The rest of this paper is organized as follows: Section II covers the design of the embedded controller in the following order: the sensors, the signal conditioning circuits, the servomotor, the control method and the microcontroller. Section III describes the experimental results and findings. The last section provides concluding remarks.

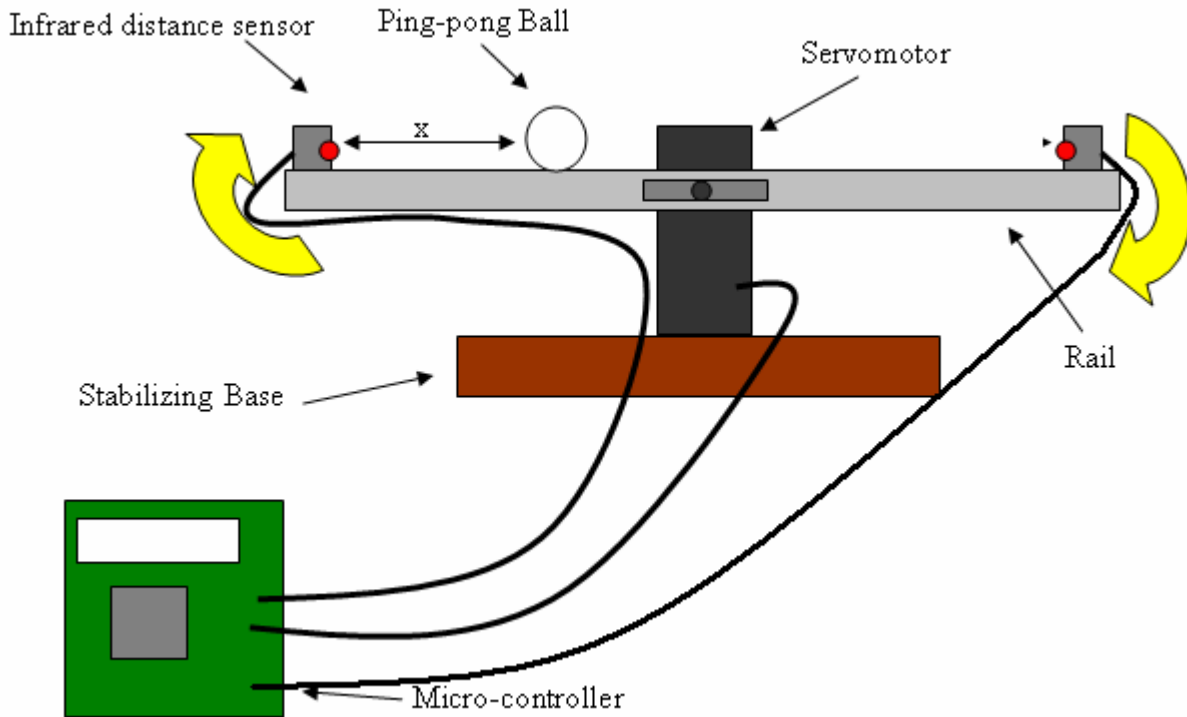


Figure 1: The set-up of the ball-on-beam system

## 2. Components of the ball-on-beam system

The ball-on-beam system contains typical components of an embedded control system. The components include sensors and their signal conditioning circuits, actuator, control methods and a microcontroller. Details of these components are provided below.

### 2.1. Sensors

The Sharp GP2D12 infrared distance sensors<sup>[4]</sup> were chosen for the project because they were inexpensive and sensitive enough for registering the location of the ball on the beam. Also the infrared beam is narrowly confined that adjacent objects does not easily interfere with the detection of the ball position.

The output of the GP2D12 distance sensor is a voltage that is exponentially related to the distance. The range of the distance measured by the sensor is from 10cm to 80 cm. For the range over 40cm, the sensitivity decreases rapidly (see Fig. 2). To increase the sensitivity over the entire length of the beam, two sensors are used instead of just one. The two sensors are mounted on opposite ends of the beam. The difference of the two voltages is used as the position signal. The voltages of the two sensors were experimentally measured against distance and are shown in Fig. 3. The difference of these two signals (the position signal) is also shown in the same figure. When the ball is on the left half of the beam, the

position signal is negative. When the ball is on the right half of the beam, the position signal is positive. When the ball is at the center of the beam, the position signal is zero. The position signal is approximately linear in the range of operation. The two sensor approach for registering the position is more accurate than the one sensor approach.

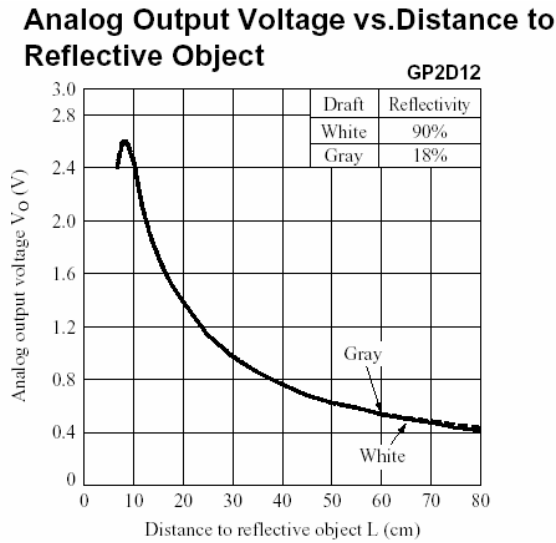


Figure 2: GP2D12 infrared distance sensor output voltage from the datasheet

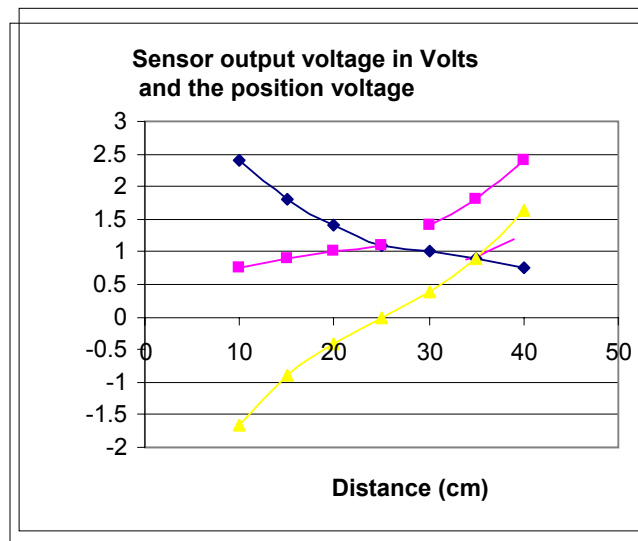


Figure 3: Measured output voltages of the two GP2D12 infrared distance sensors (the curves in black and pink on the upper half of the graph) and their difference (the curve in yellow)

## 2.2. Signal conditioning circuits

The signal conditioning circuits for the infrared sensors consist of five stages. The block diagram of the signal conditioning circuits is shown in Fig. 4. The schematic diagram is shown in Fig. 5. The voltages V5 and V6 in Fig. 5 are the signals of the infrared distance sensors #1 and #2 in Fig. 4, respectively.

The first stage of the conditioning circuit amplifies the two sensor voltages by a magnitude of two. The voltage range of the amplified sensor voltage is approximately from 1 V to 5 V. The second stage takes the difference of the two amplified voltages using a difference amplifier. The voltage range of the difference amplifier output is approximately from -4 V to 4 V. The third stage maps the voltage range of the second stage (-4 V to 4 V) to a range acceptable by the analog-to-digital converters of the microcontroller, which is from 0 V to 5 V. Such conditioning of the signal requires amplification and biasing with a positive voltage. The output voltage of the third stage is used as the position signal.

This position signal is also sent to the fourth stage of the signal conditioning circuits for generating the velocity signal, which is proportional to the derivative of the position signal. A differentiator is used to generate the derivative of the position signal. This velocity signal is used for reducing the oscillations of the ball about the center of the beam. The range of this derivative signal is from -4 V to 4 V. The fifth stage converts the derivative signal from the range of -4 V to 4 V to the range of 0 V to 5 V. This range is acceptable by the analog-to-digital converters of the microcontroller.

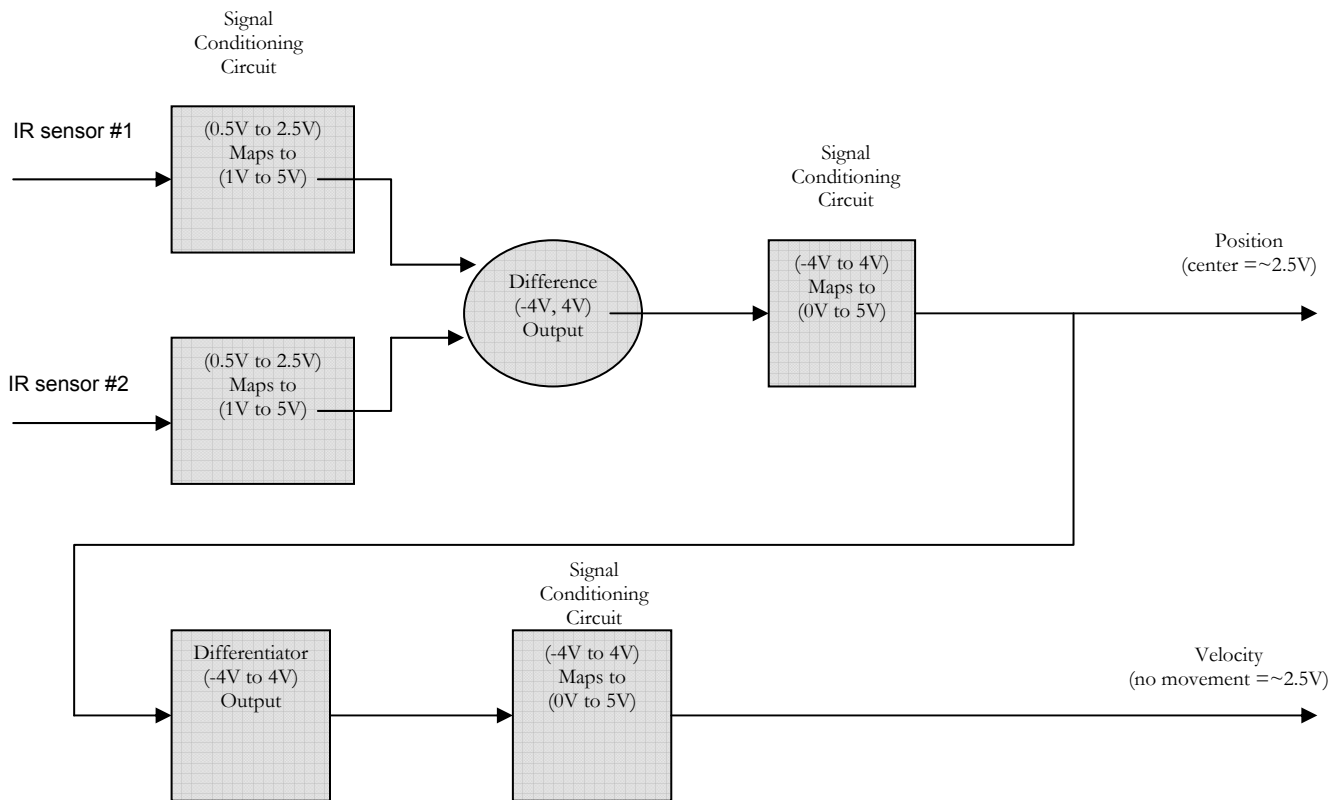


Figure 4: Block Diagram of the Signal Conditioning Circuits

### 2.3. The actuator

A Hitec HS-805BB servomotor<sup>[5]</sup> was chosen to drive the beam. The servomotor uses a heavy-duty nylon gear train and a heavy-duty 10 mm 15-tooth output shaft. The HS-805BB develops sufficient torque (300

ounce-in) to move the beam quickly enough to control it in real time. The servo is driven by a 50 Hz pulse width modulated signal, which pulse width is between 1 to 2 ms with 1.5 ms representing center position.

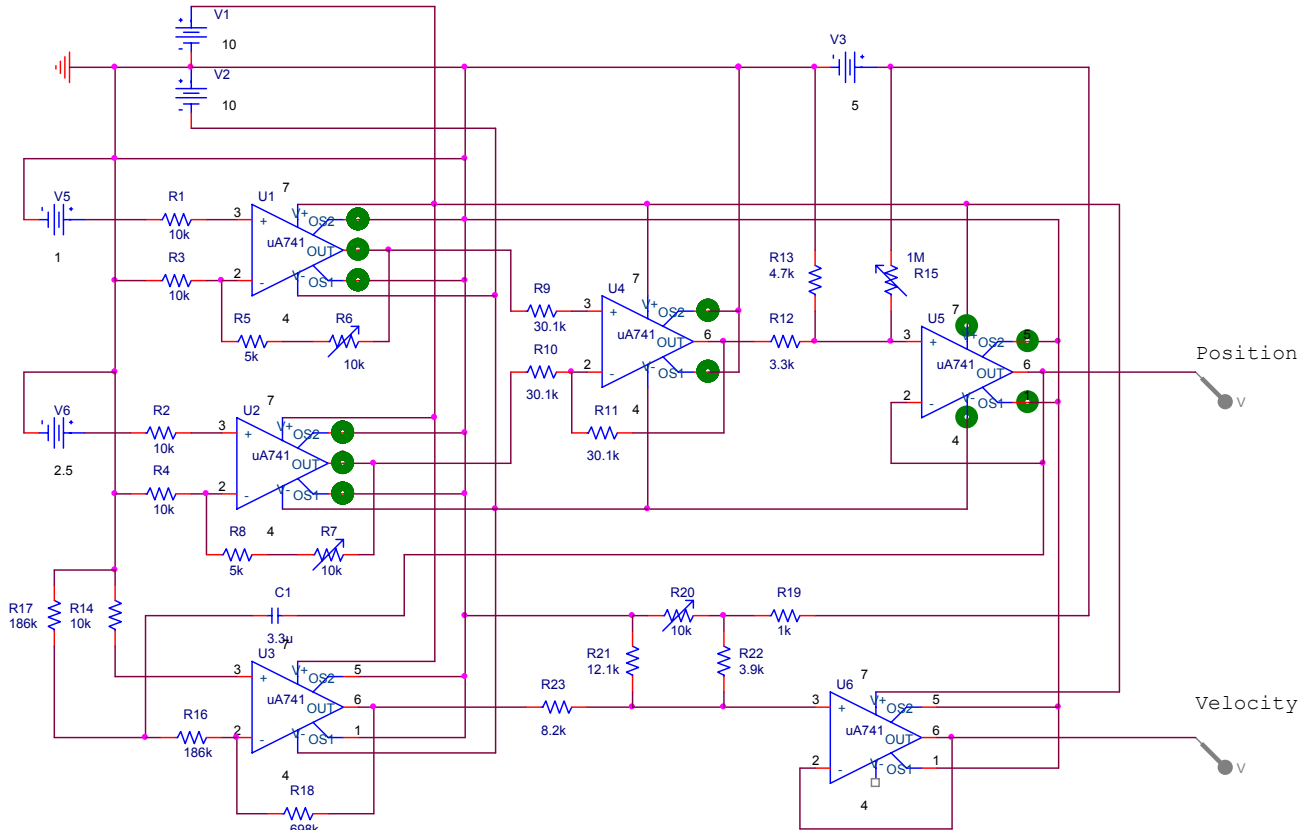


Figure 5: Schematics of the signal conditioning circuit

#### 2.4. The control method and the microcontroller

Fed into the analog-to-digital converters are the signal conditioned position voltage at the third stage and the velocity (derivative) voltage at the fifth stage of the signal conditioning circuits. The digitized position voltage is compared to the reference input. The reference input is the digitized position voltage when the ball is at the center of the beam. The error signal is computed by the microcontroller. The microcontroller controls the angle of the beam proportional to the error signal. This proportional control results in oscillations about the center of the beam. To reduce the oscillations, the velocity signal (multiplied by a gain factor) is subtracted from the error signal. The proportional and velocity gain factors were obtained experimentally in such a way that the ball would return to the center position in the shortest amount of time and least amount of oscillations. The error signal with the velocity correction is converted to a value<sup>[6]</sup> representing the duty cycle of a pulse width modulated signal for driving the servomotor, which controls the angle of the beam. The resolution of the pulse width modulated signal is 16 bit.

The Freescale MC9S12C32 microcontroller<sup>[7]</sup> was used to perform all the operation described above. The microcontroller is a 16-bit device containing standard on-chip peripherals such as a 6-channel pulse width

modulator, an 8-channel 8/10-bit analog-to-digital converter, 32K bytes of Flash EEPROM, 2K bytes of RAM, and other resources.

### 3. Experimental Results and findings

A picture of the ball-on-beam system that we built is shown in Fig. 6. The system was working properly. When the ball was displaced from the center position, the servomotor drove it back to the center every time. Although the system worked well, there are some issues with noise. The noise from the sensors agitated the ball at the center position. To reduce the noise, a low pass filter was used. However, the filter created a significant delay. This delay caused extra oscillation. The system became unstable. Future effort will be directed toward overcoming this problem.

This system has been used for demonstration in the classroom to the students and in open houses. In the classroom demonstration, the students were impressed to see the applications of the microcontroller in controlling the ball at the center of the beam. In the open houses, this project is such a visual one that the audience can see easily the value of the controls education.

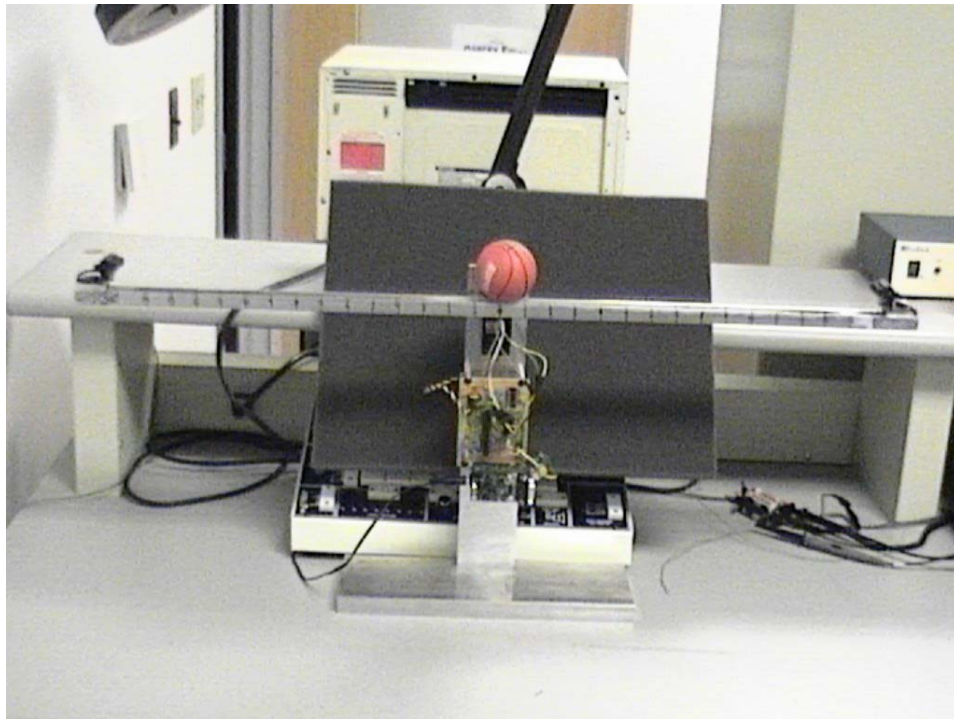


Figure 6: Ball-on-beam system

### 4. Concluding remarks

The ball-on-beam system is useful for demonstrating the benefits of basic control methods and for demonstrating the effect of delay in a feedback control system. The students can see control theory in action through this project. It is an inexpensive educational tool for teaching systems and controls and for showing the value of controls education. It is also a good project for embedded control because its design and implementation involve all the basic components of an embedded control system and is simple enough to be constructed in one semester.

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## Biographical information

David Evanko and Arend Dorsett were electrical engineering students of the University of North Florida.

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