Experiment

Objective: The objective of this experiment is to model the magnetic levitation (MAGLEV) plant and to design a controller that levitates the ball from post and ball position tracks a desired trajectory.

Apparatus/software required: MATLAB, Magnetic levitation kit, Q8-USB, UPM-2405 amplifier.

Theory:

1. **Description:** The "MAGLEV" experiment consists of an electromagnet encased in a rectangular enclosure. One electromagnet pole faces a black post upon which a 2.54 cm diameter steel ball rests. The ball elevation from the post is measured using a sensor embedded in the post. The post is designed such that with the ball at rest on its surface, it is 14 mm from the face of the electromagnet.

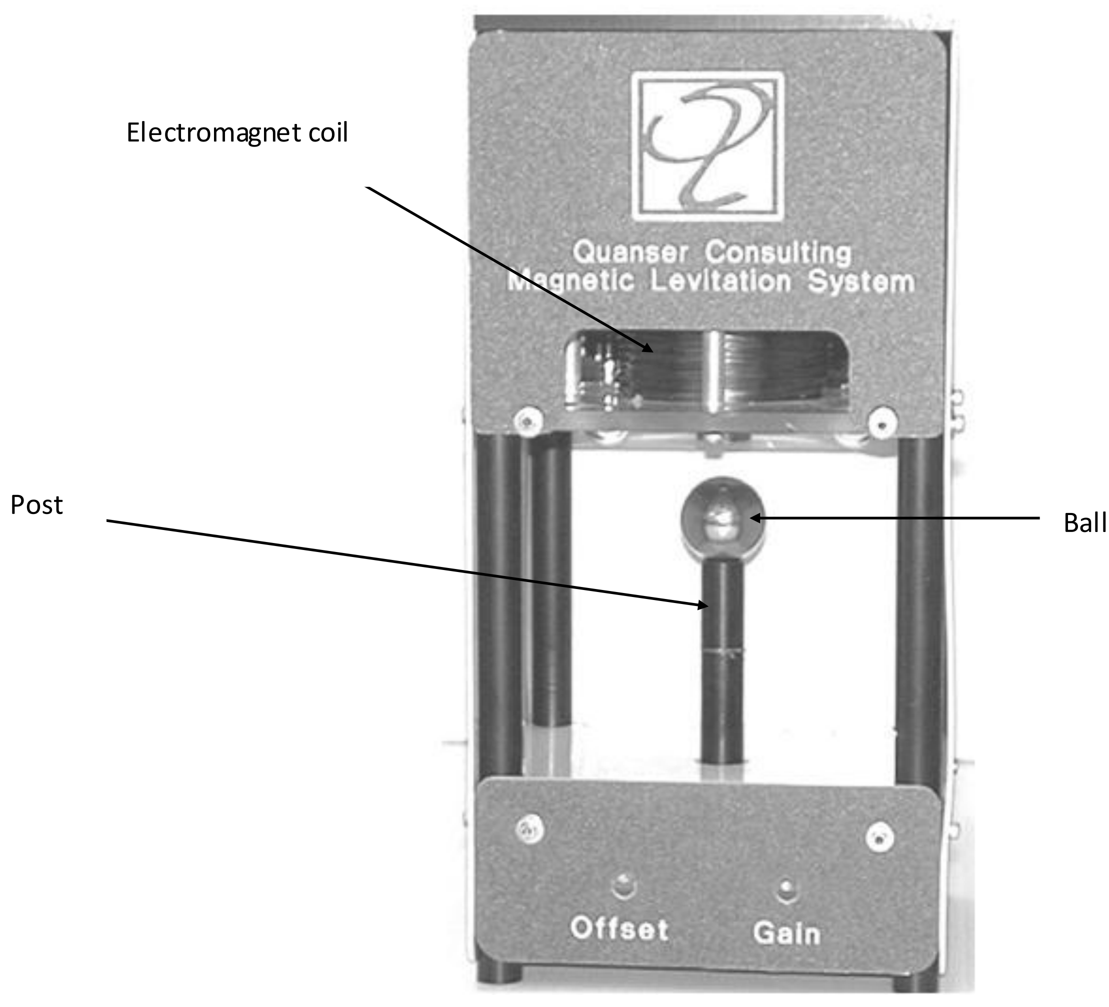

Figure 1: The magnetic levitation experiment

2. Mathematical Model:

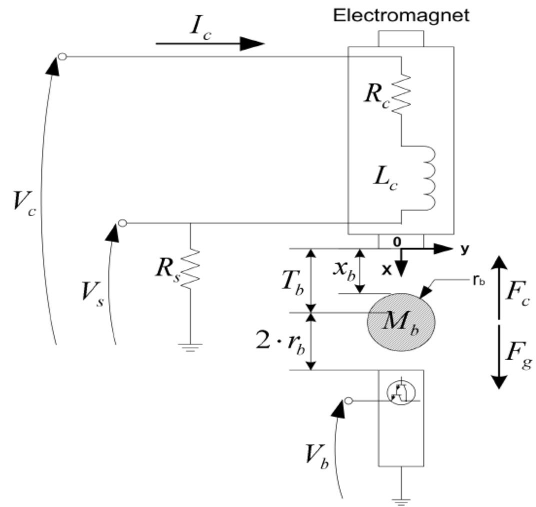

Figure 2: schematic of MAGLEV plant

2.1 Electrical systems The coil used in the electromagnet has an inductor and a resistance. The voltage applied to the coil results in a current governed by the differential equation.

$$V(t) = i(t)R_c + L\frac{di(t)}{dt} \tag{1}$$

The ***actual system*** is equipped with resistor Rs in series with the coil whose voltage V can be measured using the A/D. The measured voltage can be used to compute the current in the coil. The sense resistor in the circuit results in the equation:

$$V(t) = i(t)(R_c + R_s) + L\frac{di(t)}{dt} \tag{2}$$

Applying the Laplace transform to Equation [2] and rearranging yields the desired open loop transfer function is in the MAGLEV electrical system:

$$G_c(s) = \frac{I(s)}{V(s)} = \frac{K_{c_{dc}}}{\tau_c s + 1} \tag{3}$$

Here, $Kc_{dc} = \frac{1}{R_c + R_s}$ and $\tau = \frac{L_c}{R_c + R_s}$

Such a system is stable since its unique pole (system of order one) is located on the left-hand-side of the s-plane. Nor pole at the origin of the s-plane, so *Gc(s)* is of type zero.

2.2 Mechanical System

. The force due to gravity applied to the ball is expressed by:

$$F_g = M_b g \tag{4}$$

$$F_c + F_g = -\frac{1}{2}(\frac{K_m I_c^2}{x_b^2}) + M_b g \tag{5}$$

Where 'I_c', is the current in Ampere,' x_b' is the distance from the electromagnet face in mm and 'g' is in mm/sec2, K_m is the magnetic force constant for the electromagnet/ball pair and M_b is the mass of the ball in Kgms. Applying Newton's second law of motion to the ball, the following non-linear Equation of motion (EOM) comes:

$$F_c + F_g = F = M_b \ddot{x}_b$$

$$\ddot{x}_b = g - \frac{1}{2}(\frac{K_m I_c^2}{x_b^2 M_b}) \tag{6}$$

In order to design and implement a linear position controller for our system, the Laplace open-loop transfer function can be derived. However, by definition, such a transfer function can only represent the system's dynamics from a linear differential equation. Therefore, the EOM should be linearized around a quiescent point of operation. In the case of the levitated ball, the operating range corresponds to small departure positions, xb1, small departure currents, Ic1, from the desired equilibrium point (xb0, Ic0). Therefore, xb and Ic can be expressed as the sum of two quantities, as shown below:

$x_b = x_{b0} + x_{b1}$ And $I_c = I_{c0} + I_{c1}$, also $\frac{d}{dt}x_b = \frac{d}{dt}x_{b1}$, $\frac{d}{dt}I_c = \frac{d}{dt}I_{c1}$

At equilibrium, all time derivative terms equate to zero and Equation [6] becomes:

$$M_b g - \frac{1}{2}(\frac{K_m I_c^2}{x_b^2}) = 0$$

Because, $F_c = -F_g$ The coil current at equilibrium,

$$I_{c0} = \sqrt{(\frac{2M_b g}{K_m})} * x_{b0} \quad (7)$$

The first specification is to design the ball position controller for the following operating position (a.k.a. Equilibrium position), xb0: 6mm. This gives value of I_{c0} using (7).

2.3 Electromechanical System Modeling: EOM Linearization and Transfer Function:

Linearization about (xb0, Ic0) using Taylor series:

$$\frac{\partial^2}{\partial t^2} x_{b1} = -\frac{1}{2}\frac{K_m I_{c0}^2}{M_b x_{b0}^2} + g + \frac{K_m I_{c0}^2 x_{b1}}{M_b x_{b0}^3} - \frac{K_m I_{c0} I_{c1}}{M_b x_{b0}^2} \quad (8)$$

Now put the value of Km in (8), we get the linearized equation as,

$$\frac{\partial^2}{\partial t^2} x_{b1} = \frac{2 g x_{b1}}{x_{b0}} - \frac{2 g I_{c1}}{I_{c0}} \quad (9)$$

Now apply Laplace transform to eq (9)

$$\frac{x_{b1}(s)}{I_{c1}(s)} = G_{b1}(s) = -\frac{Kb_{dc}\omega_b^2}{s^2 - \omega_b^2} \quad (10)$$

Here, $Kb_{dc} = \frac{x_{b0}}{I_{c0}}$ and $\omega_b = \sqrt{(\frac{2g}{x_{b0}})}$

Equation [10] shows a second-order system of type zero. The two open-loop poles are located on the real axis at the s = ± ω. Having one pole in the Right-Half Plane (RHP), the open-loop system is unstable and feedback control is required.

3. **Controller design:**

   3.1 Coil current controller design: pole placement: Prior to control the steel ball position, the current flowing through the electromagnet needs to be controlled. The electromagnet current control loop consists of a Proportional-plus-Integral (PI) closed-loop scheme.

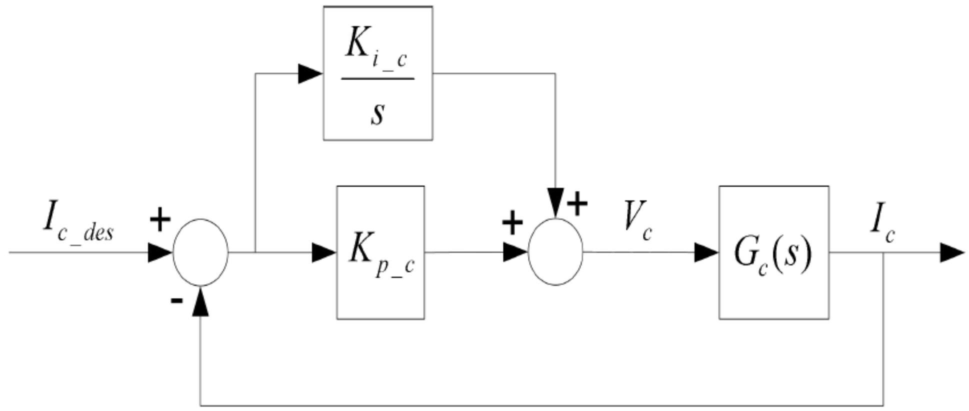

Figure 3: Block diagram of coil current controller

Find the transfer function for above block diagram: $T_c(s) = \dfrac{I_c(s)}{I_{des}(s)}$ and then get the normalized characteristic polynomial of this electrical system ?

Now let desired poles be *pc1* and *pc2 (*-235-/+70i rad/s)*,* and then the normalized equation can be written as follows:

$$s^2 + (-p_{c1} - p_{c2})s + p_{c1}p_{c2} = 0 \tag{11}$$

$$s^2 + 2 * \zeta\omega_n s + \omega_n^2 = 0 \tag{12}$$

Compare calculated normalized equation with this equation and find out values of Kp_c and Ki_c?

3.2 Ball Position Controller Design: Pole Placement: The steel ball position is controlled by means of a Proportional-plus-Integral-plus-Velocity (PIV or PID) closed-loop scheme with the addition of a feed-forward action.

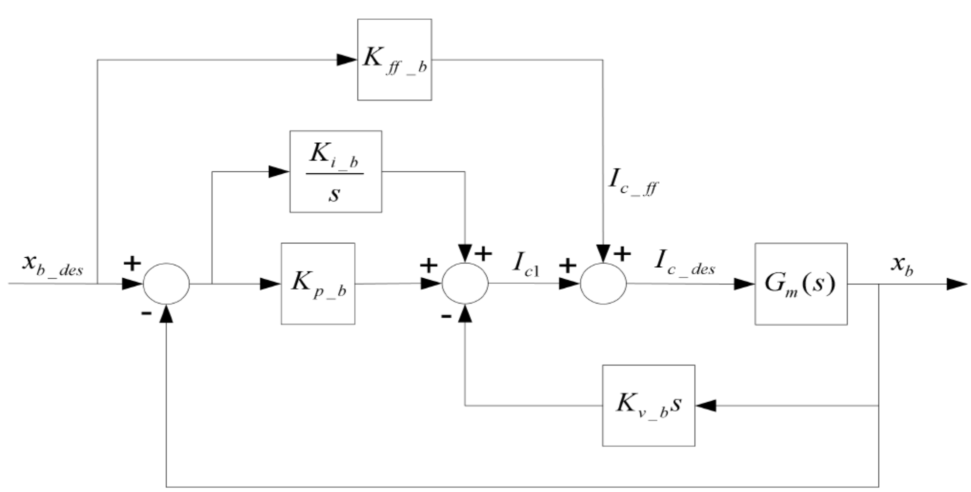

Figure 4: Block diagram of Ball Position Controller

Find the transfer function, $T_b(s) = \frac{x_b(s)}{x_{bdes}(s)}$ and let desired poles are -pb1,-pb2 &-pb3 (-2.5,-44,-51.6 rad/s) so desired characteristic equation with these poles is given for the third order system by:

$$s^3 + (-p_{b1} - p_{b2} - p_{b3})s^2 + (p_{b1}p_{b3} + p_{b1}p_{b2} + p_{b2}p_{pb3})s - p_{b1}p_{b2}p_{b3} = 0 \quad (13)$$

$$(s+p)(s^2 + 2*\zeta\omega_n s + \omega_n^2) = 0$$

Characteristic equation calculated by student for Tb(s) in figure 4. should be same as:

$$s^3 - \frac{2\,g\,K_{v\_b}\,s^2}{I_{co}} + \left(-\frac{2\,g}{x_{bo}} - \frac{2\,g\,K_{p\_b}}{I_{co}}\right)s - \frac{2\,g\,K_{i\_b}}{I_{co}} = 0 \quad (14)$$

4.ASSIGNMENT:

(1) Find out the desired pole's location (pc1,pc2) for overdamped system ($\zeta > 1$ say,1.8) and settling time Tr<= 0.35 seconds and have no steady state error for coil current controller and then find the values of Ki_c and Kp_c for PI design by calculating the transfer function $T_c(s) = \frac{I_c(s)}{I_{des}(s)}$ of the block diagram shorn in fig.3 and compare its characteristic equation with the desired characteristic equation.

(2) Find out the desired pole's location for a ball position controller with percent overshoot, PO <=15% and settling time, Ts<=1 second. Find out the value of Ki_b, Kp_b and Kv_b for PIV design and feed forward gain $K_{ff} = \frac{I_{c0}}{x_{b0}}$ by calculating transfer function Tb(s) of block diagram shown in fig 4. And compare its characteristic equation (which is product of first and second order system) with a desired characteristic equation with poles at pb1, pb2 and pb3?

Hint: some important formulae,

$$PO = exp(-\frac{\zeta}{\sqrt{(1-\zeta^2)}} * \pi) * 100,\qquad settling\ time, T_s = \frac{4}{\zeta\omega_n},\quad \text{(for the 2\% criteria)},$$

$$damped frequency, \omega_d = \omega_n * \sqrt{(1-\zeta^2)},\quad rise\ time, T_r = \frac{\pi - \beta}{\omega_d},\quad \beta = tan^{-1}\frac{\sqrt{(1-\zeta^2)}}{\zeta}$$

Second order system poles can be given as,

$$pc1 = -\zeta\omega_n - \omega_n\sqrt{(\zeta^2-1)};\qquad pc1 = -\zeta\omega_n + \omega_n\sqrt{(\zeta^2-1)} \tag{15}$$

5. In-Lab Procedure

5.1. Experimental Setup and Wiring: Even if you do not configure the experimental setup entirely yourself, you should be at least completely familiar with it and understand it. Please get your circuit checked by the Teaching Assistant assigned to the lab. When you are confident with your connections, you can power up the UPM. The MAGLEV inside the chamber should light up. You are now ready to begin the lab.

5.2. Real-time Implementation: Tuning Of the Feed-forward-Plus-PIV Position Control Loop

5.2.1. Experimental Procedure:

Step 1:Run the MATLAB script called *setup_lab_maglev_piv.m*, to put all gain values manually in command window.

Step 2: Open the Simulink model file named *q_piv_maglev.mdl.* You should obtain a diagram similar to the one shown in Figure 5. The model implements a Feed forward-plus-Proportional-plus-Integral-plus-Velocity (PIV) closed-loop. You should also check that the signal generator block properties are properly set to output a square wave signal, of amplitude 1, and of frequency 0.25 Hz. It should be noted that a simple low-pass filter of cut-off frequency 80 Hz (set by *'tau_xb'*) is added to the ball position sensor output signal in order to attenuate its high-frequency noise content. Moreover, the ball vertical velocity is estimated by differentiating the ball position analog signal. Therefore, to get around potential noise problems, a second-order filter of cut-off frequency 100 Hz . (set by *'wcf'*) and damping ratio 0.9 (set by *'zetaf'*) is also introduced after the differentiated velocity signal.

Although introducing a short delay in the signals, low-pass filtering allows for higher controller gains in the closed-loop system, and therefore for higher performance.

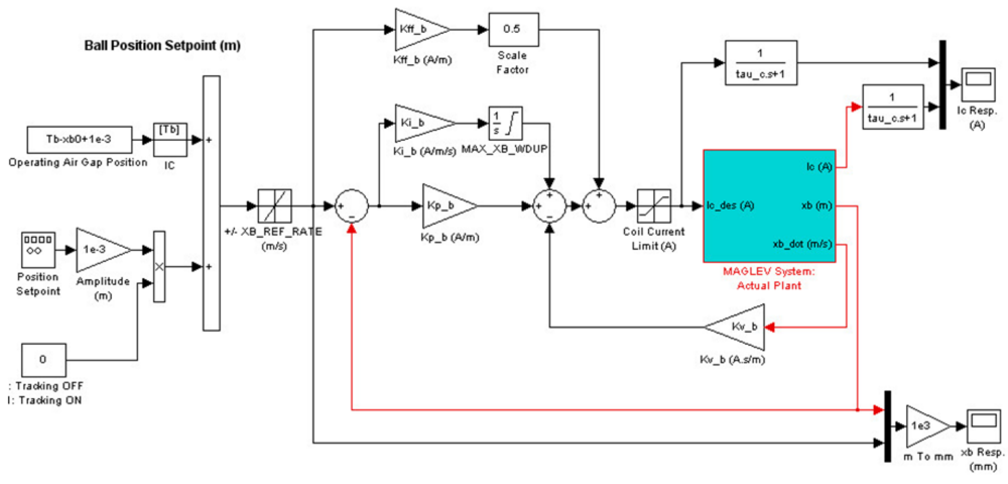

Figure 5: simulink diagram of Ball Position Controller (outer loop)

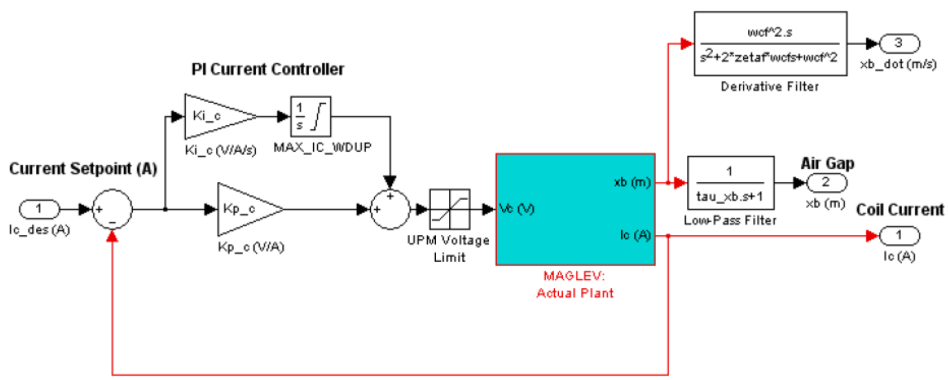

Figure 6: Simulink mordel of Coil current Controller (inner loop)

Step 3. Place the steel ball on the pedestal inside the MAGLEV chamber.

Step 4. Build the real-time code corresponding to your diagram, by using the *QuaRC / Build* option from the Simulink menu bar. Once the code is successfully built, select the *QuaRC / Start* option from the Simulink menu bar.

Step 5. This should levitate the ball halfway between the post and the electromagnet core face, with an air-gap of xb0. If the ball is swaying left and right, you can gently put your hand in and dampen the motion. Once the ball is stabilized at the operating point, change the value of the Simulink constant block named *0: Tracking OFF; 1: Tracking ON* from 0 to

1. The ball should start tracking the desired ±1-mm square wave setpoint around the operating position.

Step 6. In order to observe the system's real-time responses from the actual system, open the three following scopes: *xb Resp. (mm)*, *Ic Resp. (A)*, and *V Command (V)* scope located, for example, in the following subsystem path: *MAGLEV System: Actual Plant/MAGLEV: Actual Plant*. You should now be able to monitor on-line, as the ball moves, the actual ball position, coil current, and command voltage (proportional to the control effort) sent to the power amplifier, as the ball tracks the pre-defined reference input.

Step 7. Assess the actual performance of the ball position response and compare it to the design requirements. Measure the response actual settling time.

Note: Fluctuations in the position signal can be due to actual fluctuations of the ball vertical position but also to swaying (due to the hemispheric surface of the ball).

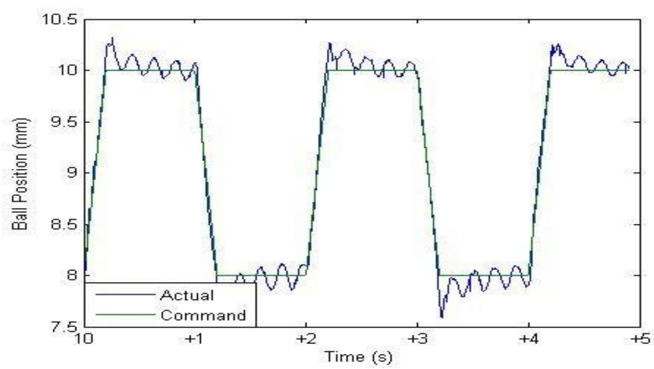

Figure 7 Actual Ball Position Tracking Response

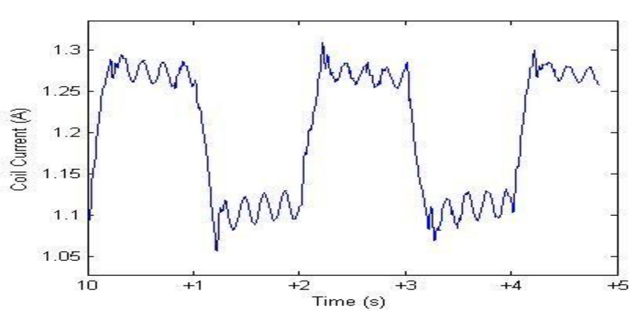

Figure 8.Actual Coil Current Response

Step 8. Include in your lab report your final values for Kff_b, Kp_b, Ki_b, and Kv_b, as well as the resulting response plot of xb versus xb_des, and the corresponding plots of Ic and Ic_ref.

Attach the table with your lab report and fill the calculated value and attach all results of ball position response and current response for the different values of given parameters.

Controller gains	Value
Kp_c	
Ki_c	
Kff_b	
Kp_b	
Ki_b	
Kvv_b	

Table of parameters

Symbol	*Description*	*Value*	*Unit*
I_{c_max}	Maximum Continuous Coil Current	3	A
L_c	Coil Inductance	412.5	mH
R_c	Coil Resistance	10	Ω
N_c	Number Of Turns in the Coil Wire	2450	
l_c	Coil Length	0.0825	m
r_c	Coil Steel Core Radius	0.008	m
K_m	Electromagnet Force Constant	6.5308E-005	$N.m^2/A^2$
R_s	Current Sense Resistance	1	Ω
r_b	Steel Ball Radius	1.27E-002	m
M_b	Steel Ball Mass	0.068	kg
T_b	Steel Ball Travel	0.014	m
g	Gravitational Constant on Earth	9.81	m/s^2
i_0	Magnetic Permeability Constant	4ð E-007	H/m
K_B	Ball Position Sensor Sensitivity (Assuming a User-Calibrated Sensor Measurement Range from 0 to 5 V)	2.83E-003	m/V