

# EE191 Balance Beam Project Presentation

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# Project Overview

- **PID Feedback Control:** PID controllers continuously adjust beam angle based on ball position, enabling dynamic stabilization through feedback.
- **System Components:** Ultrasonic sensors detect ball position; servo motors adjust beam angle correcting ball displacement effectively.
- **Real-World Relevance:** Balance beam control exemplifies robotics applications, highlighting control systems in automation and dynamic stabilization.



# Project Goals & Learning Objectives

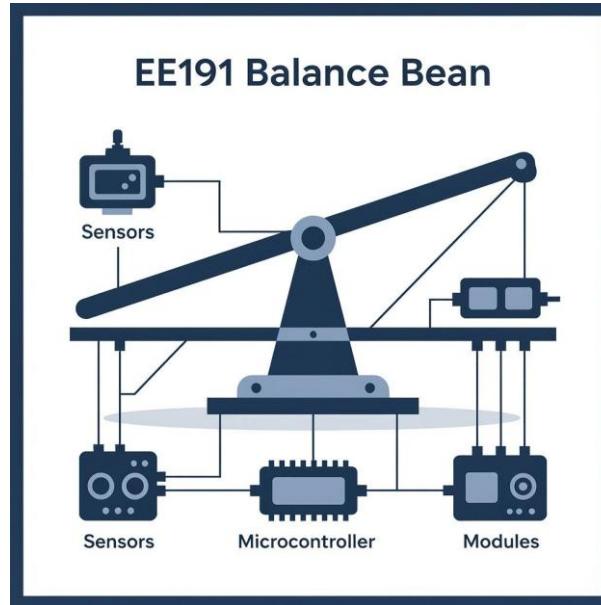
- **Ball Stabilization:** Achieve precise control to maintain the ball's position at center through dynamic beam adjustments.
- **Apply System Dynamics:** Integrate theoretical system dynamics principles into practical control algorithm development and implementation.
- **Team Collaboration:** Enhance cooperative skills by coordinating tasks, sharing knowledge and solving complex problems collectively.

# Hardware Components

- **Ultrasonic Sensor:** Measures ball distance by emitting sound waves and detecting echo time for precise position feedback.
- **Servo Motor:** Adjusts beam angle via controlled rotation, translating PID commands into precise dynamic positioning.
- **Aluminium Beam:** Rigid structural element providing stable platform and consistent response to motor-induced angular changes.

# System Architecture Diagram

- **Sensor Measurement Input:** Ultrasonic sensor continuously measures ball position, providing real-time feedback to the PID controller.
- **PID Controller Processing:** PID block analyzes error between desired and actual ball position, generating corrective motor commands.
- **Motor-Driven Beam Adjustment:** Servo motor actuates beam angle based on PID output, dynamically stabilizing ball position on beam.



# Ball Motion Theory

- **Rolling Ball Dynamics:** A ball rolling down an incline accelerates due to gravitational force component along the slope.
- **Key Equation:** Acceleration formula  $a = (3/5) g \sin(\theta)$  accounts for rotational inertia of a solid sphere rolling without slipping.
- **Force Components:** Forces include gravity, normal force, and friction, which enable rolling motion without slipping on inclined beam.

# Air Resistance

- **Terminal Velocity Measurement:** Release object at rest and measure steady velocity where drag equals gravitational force precisely.
- **Drag Coefficient Derivation:** Calculate drag coefficient from force balance equation using measured terminal velocity and object properties.
- **Graphical Illustration:** Diagram depicts velocity-time curve stabilizing at terminal velocity, with corresponding drag force opposed to gravity.

# Laplace & Transfer Function

- **Differential Equation Transformation:** Apply Laplace transform to  $\theta$  equation, converting time-domain dynamics into algebraic s-domain expressions.
- **Transfer Function Derivation:** Derive  $H(s) = \Theta(s)/\text{Torque}(s) = 3g / 5s^2$  by isolating output-over-input ratio in Laplace domain.
- **Transfer Function Block Diagram:** Block diagram shows input torque entering transfer function block with output beam angle  $\Theta(s)$  representing system.



# Servo Motor Theory

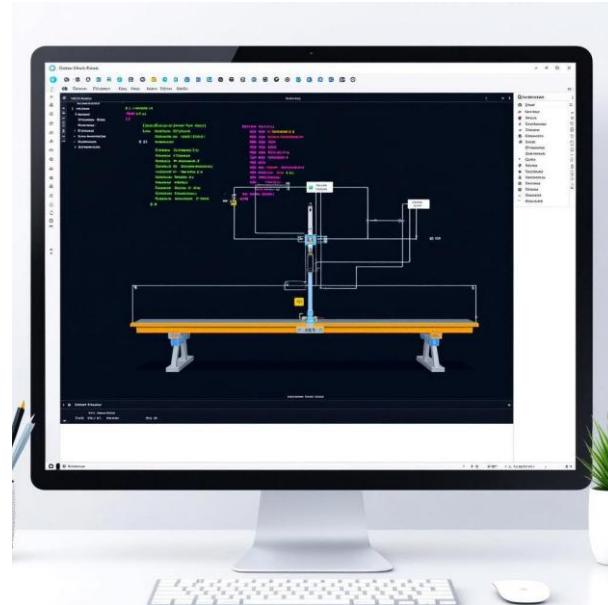
- **Back EMF Generation:** Back electromotive force emerges opposing input voltage, proportional to rotor angular velocity affecting control dynamics.
- **Torque Equation:** Motor torque  $\tau = K_t \times I$  relates torque to current via motor constant for precise torque control implementation.
- **Control Mechanism:** Pulse-width modulation adjusts input voltage, regulating current and torque to achieve desired servo motor positioning.

# Mechanical Linkage Math

- **Angle Relation Equation:** Linear approximation relates  $\theta_2 \approx k\theta_1$ , derived from linkage geometry and small angle assumptions.
- **Linkage Geometry Details:** Mechanical linkage comprises fixed pivots, rods, forming angle  $\theta_1$  input and angle  $\theta_2$  output linkage arms.
- **Diagram Description:** Diagram labels  $\theta_1$  and  $\theta_2$  at joints highlighting pivot points and connecting rods illustrating angle transformation.

# Simulink Model

- **Input Signal Block:** Receives ball position data as input, initiating control system simulation with real-time feedback integration.
- **PID Controller Block:** Processes error signal between desired and actual ball position, outputting proportional, integral, and derivative actions.
- **Closed-Loop Feedback Path:** Ensures continuous correction by feeding motor-driven position changes back to the PID, stabilizing the ball on beam.



# PID Tuning

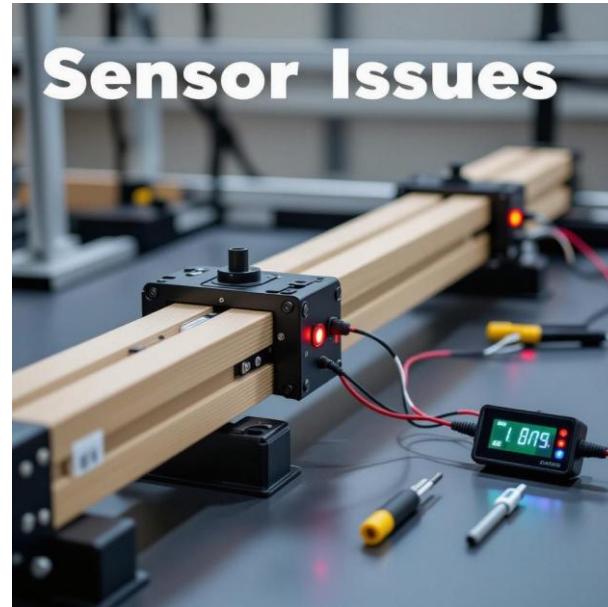
- **Tuned PID Parameters:** Final PID gains optimized as P=0.43, I=0.078, D=0.58 achieving stable beam control dynamics.
- **Improved System Response:** Tuning reduced overshoot and settling time, enhancing transient response to ball position disturbances effectively.
- **Scope Output Insights:** Scope graph illustrates smooth setpoint tracking with minimal steady-state error and oscillation in beam angle.

# C++ Code & Sensor Testing

- **Code Structure Overview:** Modular C++ architecture separates sensor reading, PID control, and motor actuation for maintainability and clarity.
- **Sensor Testing Procedure:** Conducted iterative sensor output validation using static and dynamic ball positions to calibrate distance measurements.
- **Pseudocode Snippet:** Loop reads sensor data, computes PID output, sends PWM signals to servo motor for real-time beam adjustment.

# Sensor Problems

- **Echo Cancellation Issue:** Ultrasonic sensor reads constant 40cm due to sound wave echo reflecting off metallic beam surface.
- **Misleading Distance Data:** Persistent echo interferes with accurate ball distance measurement, causing unreliable feedback for control loop.
- **Impact on PID Control:** False sensor readings disrupt PID calculations, leading to incorrect motor commands and unstable beam behavior.



# Troubleshooting

- **Sensor Mounting Angle Adjustments:** Variations of sensor angles attempted to reduce echo effect and improve accuracy of distance readings.
- **Ball Size Experiments:** Different ball diameters tested to evaluate influence on sensor reflection patterns and measurement reliability.
- **Alternative Sensor Positions:** Mounting sensor at various beam locations analyzed to minimize interference and optimize echo signal quality.

# Motor Hardware Problems

- **Stepper Motor Limitation:** Initial stepper motor exhibited unidirectional rotation due to faulty driver circuit and control signal issues.
- **Servo Motor Replacement:** Selected servo motor offering bidirectional rotation with integrated feedback, improving beam angle control precision.
- **Implementation Process:** Rewired control signals, adjusted PID parameters, and calibrated servo response for seamless integration and performance.

# Final Results

- **Prototype Demonstration:** Photos exhibit ball stably balanced on beam, validating effective PID feedback and hardware integration.
- **Scope Output Analysis:** Oscilloscope captures confirm system stability with smooth ball position tracking and minimal oscillatory deviation.
- **Visual Confirmation:** Screenshots highlight real-time control response confirming rapid corrections maintaining ball at setpoint under disturbances.



## Group Reflection & Future Work

- **Team Collaboration Insights:** Coordination challenges improved through iterative communication, fostering problem-solving and knowledge sharing effectively.
- **Sensor Accuracy Enhancements:** Future work includes integrating advanced sensors with noise filtering to reduce echo interference and improve feedback reliability.
- **Motor & Software Refinements:** Enhance motor control algorithms using adaptive tuning and optimize software for faster real-time response and stability.