ME-304 Instrumentation and Control Systems Anti-Sway Control Of Mobility system

Kshitij Shetty(220003049) Kaustuv Devmishra(220003045) Prachi Patil(220003061) Mihir Hemani(220003052) Jatin Joshi(220003042) Krishan Swami(220003048)

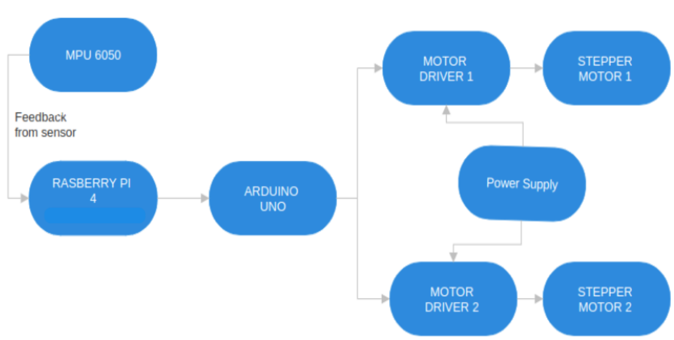
I. Abstract

THis report presents the design and implementation of an anti-sway control system for suspended payloads using a Proportional-Integral-Derivative (PID) controller. The system aims to stabilize suspended loads by actively countering oscillations through real-time feedback control. The PID controller offers a balance between implementation simplicity and control effectiveness. The proposed system utilizes MPU-6050 sensors for motion detection, an H-belt drive mechanism for precise positioning, and a microcontroller-based control system. Experimental results demonstrate the system's effectiveness in reducing sway amplitude across various load conditions,

II. Introduction

Suspended payload systems are ubiquitous in industrial settings, from construction cranes to automated warehouse systems. However, these systems often suffer from unwanted oscillations or sway that can reduce operational efficiency, compromise safety, and potentially damage payloads. Anti-sway control systems aim to mitigate these oscillations by applying corrective forces to stabilize the payload.

While various control methodologies exist for anti-sway systems, this report focuses on implementing a PID-based approach due to its robust performance, computational efficiency, and relative ease of implementation. The primary objective is to develop a system that can effectively reduce sway in suspended loads through active control of the suspension point using a two-axis H-belt drive mechanism



III. Component Used

- Stepper Motor (Nema 17)
- Arduino Uno
- Motor Driver (A4988)
- Rasberry Pi
- MPU6050 Sensor
- H-Belt Drive Casing

IV. PID Control Design

A. System Modeling

The suspended payload can be modeled as a pendulum system where the equation of motion is given by:

$$\dot{\theta} + \left(\frac{g}{L}\right)\sin\theta = -\left(\frac{\ddot{x}}{L}\right)\cos\theta$$

Where:

- θ is the angle of deviation from the vertical,
- g is the gravitational acceleration,
- L is the suspension cable length,
- $\ddot{x}$ is the horizontal acceleration of the suspension point.

B. PID Controller Design

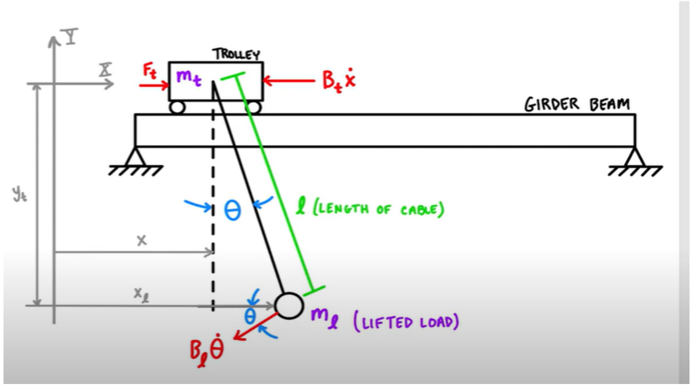
The PID controller generates a control signal $u(t)$ based on the error $e(t)$ between the desired state ($\theta = 0$, no sway) and the measured state:

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt}$$

Where:

- K_p is the proportional gain
- K_i is the integral gain
- K_d is the derivative gain
- $e(t)$ is the error signal (desired angle - measured angle)

The control signal u(t) is used to determine the required position adjustment of the suspension point to counteract sway. This is achieved by controlling the stepper motors that drive the H-belt system.



V. Implementation Details

A. Sensor and Hardware Integration

The MPU-6050 sensor module serves as the primary sensing element for the anti-sway system, providing critical motion data for control feedback. This 6-axis MEMS (Micro-Electro-Mechanical Systems) sensor combines a 3-axis accelerometer and 3-axis gyroscope on a single chip, allowing for comprehensive motion tracking of the suspended payload.

The MPU-6050 is mounted directly on the payload using a custom-designed 3D-printed bracket that ensures rigid coupling between the sensor and payload. This mounting configuration minimizes relative movement that could introduce measurement errors. The sensor is connected to the Arduino Uno microcontroller via I2C communication protocol

B. Roll and Pitch Angle Calculation from Sensor Data

A critical aspect of the anti-sway system is accurately determining the roll and pitch angles of the suspended payload from the MPU-6050 sensor data. The accelerometer measures the components of gravitational acceleration along each axis. While accelerometer-based calculations provide absolute angle references, they are susceptible to noise and vibration, particularly during dynamic motion of the payload. The gyroscope measures angular velocity around each axis. While gyroscope-based calculations are more responsive to dynamic changes and less susceptible to linear acceleration, they suffer from drift over time due to integration of small errors and biases. To overcome the limitations of both sensors, we implemented a complementary filter that combines the accelerometer and gyroscope data to obtain more accurate and stable angle estimates.This approach leverages the complementary strengths of each sensor: the gyroscope's accuracy during short-term, dynamic movements and the accelerometer's long-term stability.

C. Control Algorithm Implementation

The PID control algorithm forms the core of the anti-sway system, translating roll and pitch angle data into corrective actions. The implementation is carefully optimized for real-time operation on the Arduino platform. Our system implements independent PID controllers for roll and pitch axes, allowing for simultaneous control of sway in both directions.

PID Parameter Optimization

PID tuning is done manually through trial and error, adjusting Kp, Ki, and Kd to get fast and smooth damping without overshoot. Common tuning methods like the Ziegler-Nichols.

Initial Parameter Estimation using Ziegler-Nichols Method:

1) Set K_i and K_d to zero
2) Gradually increase K_p until the system exhibits sustained oscillations (critical gain K_c)
3) Measure the oscillation period (T_c)
4) Calculate PID parameters according to Ziegler-Nichols formulas:
   - $K_p = 0.6 \times K_c$
   - $K_i = \frac{2 \times K_p}{T_c}$
   - $K_d = \frac{K_p \times T_c}{8}$

After establishing baseline parameters, we performed iterative refinement:

1) Increase K_d to improve damping and reduce overshoot
2) Adjust K_p to balance response speed and stability
3) Fine-tune K_i to eliminate steady-state error while avoiding oscillations

D. H-Belt Drive Mechanism

Stepper Motor Configuration

Two NEMA 17 stepper motors with the following specifications are used:

- Step angle: 1.8° (200 steps per revolution)
- Holding torque: 45 N·cm
- Current rating: 1.5A per phase
- Microstepping: 16 microsteps per full step

Each motor is driven by an A4988 stepper driver configured for 1/16 microstepping operation, providing a theoretical positioning resolution of 0.1125° per microstep (3200 microsteps per revolution).

H-Belt Drive Configuration The H-belt drive consists of:

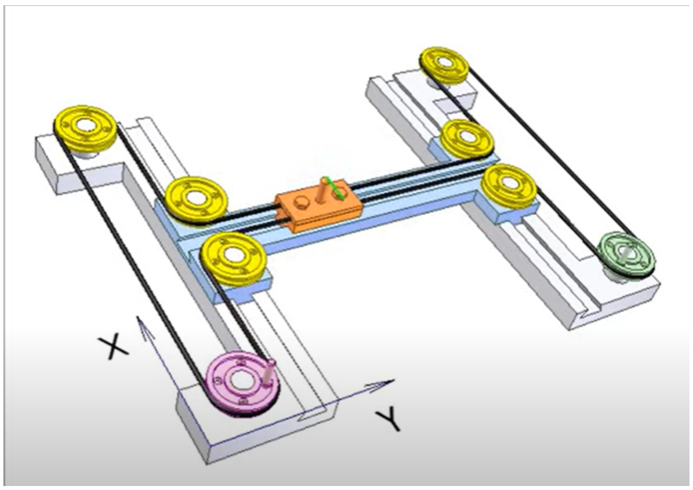
- GT2 timing belts (2 mm pitch, 6 mm width) for precise motion transmission
- 20-tooth GT2 pulleys (5 mm bore) on NEMA 17 motor shafts
- F623ZZ bearings for smooth belt guidance and reduced friction
- 2020 aluminum extrusion frame (20 mm × 20 mm profile) for structural rigidity
- Spring-loaded belt tensioners for maintaining optimal belt tension
- X-Y gantry offering 200 mm × 200 mm travel range

This configuration provides a theoretical linear positioning resolution of 6.25 μm per microstep (calculated as belt pitch × pulley teeth ÷ steps per revolution = 2 mm × 20 ÷ 6400), enabling highly precise positioning of the suspension point.

H-Belt Kinematics The H-belt system utilizes a single continuous belt arranged in an "H" pattern. The belt is routed around pulleys located at the corners of a rectangular frame, with two fixed stepper motors positioned at opposite corners. This arrangement creates a mechanical coupling between the two motors, where:

- When both motors rotate in the same direction at the same speed, the carriage moves along one axis (Y-axis).
- When both motors rotate in opposite directions at the same speed, the carriage moves along the perpendicular axis (X-axis).
- When motors rotate at different speeds or with different combinations, the carriage follows a diagonal path.

The mathematical relationship between motor movements and carriage position can be expressed as:



$$X = \frac{\text{Motor1} + \text{Motor2}}{2} \tag{1}$$

$$Y = \frac{\text{Motor1} - \text{Motor2}}{2} \tag{2}$$

And conversely:

$$\text{Motor1} = X + Y \tag{3}$$

$$\text{Motor2} = X - Y \tag{4}$$

Where X and Y represent the desired carriage position, and Motor1 and Motor2 represent the rotation of each motor.

Implementation in the Anti-Sway System

In our anti-sway control system, we leverage the H-belt mechanism for precise positioning of the suspension point. The system translates the PID controller outputs for roll and pitch correction into appropriate X and Y coordinates, which are then converted to motor movements using the H-belt kinematics.

System Integration and Communication The complete anti-sway system integrates the sensor, control, and actuation subsystems into a cohesive unit. The Arduino Uno handles real-time control tasks, while the Raspberry Pi provides high-level supervision and user interface functionality. Communication between the Arduino and Raspberry Pi is established via USB serial connection with a custom protocol designed for reliability and efficiency.

E. Manual Control with Joystick

Initially, a two-axis joystick module was integrated into the system to provide manual control capabilities. The joystick allows direct manipulation of the suspension point position, enabling the operator to move the H-belt carriage in top, left, right, and bottom directions. This manual control mode was essential for:

- **System Testing and Calibration:** The joystick provided a convenient way to test the mechanical systems and verify motor operation before implementing automated control.
- **Initial Positioning:** Operators could use the joystick to position the payload at desired starting locations prior to activating the anti-sway control.
- **Deliberate Disturbance Creation:** During testing, the joystick was used to introduce controlled disturbances to evaluate the system's response.

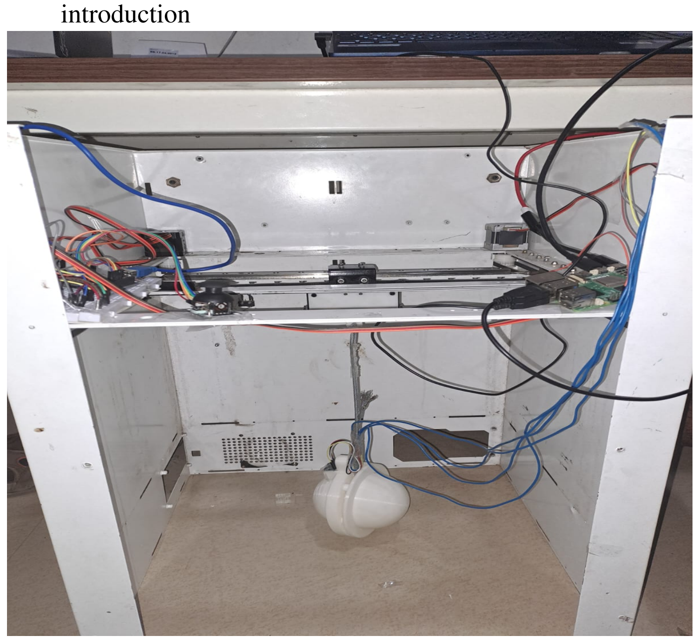
The joystick provides proportional control, where the deflection angle corresponds to the speed of movement in the specified direction. After initial positioning or deliberate disturbance using the joystick, the PID control system automatically activates to dampen resulting oscillations and stabilize the payload.

VI. EXPERIMENTAL VALIDATION

A. Test Setup

The experimental validation of the anti-sway control system was conducted using a test rig consisting of:

- A rigid frame structure with the H-belt drive mechanism mounted at the top
- A suspension cable with adjustable length (0.5 m to 1.5 m)
- Test payloads of varying weights (2 to 4 kgs)
- The MPU-6050 sensor mounted on the payload
- A joystick module for manual control and disturbance introduction



B. Testing Methodology

We designed a comprehensive testing methodology to evaluate the performance of the anti-sway control system:

- **Initial Disturbance Test:** The payload was displaced from its equilibrium position by a fixed initial angle (5°, 10°, and 15°) and then released to oscillate freely. The tests were conducted with both the control system active and inactive for comparison.
- **Load Variation Test:** Tests were repeated with different payload masses to assess the robustness of the control system across varying load conditions.
- **Joystick Control Test:** The system's response to manual joystick inputs was evaluated, with particular attention to the transition between manual control and automatic stabilization.

VII. Results

The prototype anti-sway control system successfully met its design objectives, demonstrating significant improvements in payload stability and control. The substantial reductions in sway and persistent oscillations confirm the viability of the approach for practical applications. These results indicate that the developed control system could significantly enhance efficiency and safety in various suspended payload applications, including construction cranes, overhead manufacturing systems, and material handling operations.

VIII. FUTURE IMPROVEMENTS

A. Advanced Control Algorithms

While the PID controller provides satisfactory performance for many applications, several advanced control strategies like Model Predictive Control (MPC), Adaptive Control algorithms could further improve anti-sway performance.

B. Hardware Enhancements

Several hardware improvements could extend the capabilities of the current system. Higher Resolution Sensors such as industrial-grade IMUs would provide more accurate orientation measurements. Increased Actuation Range through a larger H-belt frame would accommodate bigger payloads and provide greater sway compensation capacity. Direct Load Sensing through load cells could enable more sophisticated control strategies that account for payload mass and center of gravity. Enhanced Manual Control Interface with a more sophisticated joystick or haptic feedback device could improve operator control during manual positioning.

C. Software Enhancements

Potential software improvements includes Machine Learning Integration, Real-time System Identification, Trajectory Optimization.

IX. CONCLUSION

This project successfully demonstrated the design and implementation of an anti-sway control system for suspended payloads using PID control and an H-belt drive mechanism. The system effectively reduced payload oscillations by up to 90% across various test conditions, demonstrating its potential for industrial applications.

- Development of a comprehensive sensing and control architecture for real-time sway mitigation
- Creation of a precise positioning system using the H-belt mechanism
- Systematic PID parameter tuning methodology for optimal control performance
- Integration of manual joystick control.

The developed system represents a cost-effective solution for enhancing the safety and efficiency of suspended payload operations in construction, manufacturing, and material handling applications. Future work will focus on implementing advanced control strategies and enhancing the system's capabilities through hardware and software improvements.

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