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Design and Fabrication of an Inverted Pendulum Control System

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ABSTRACT

The inverted pendulum is a classical control problem, which involves developing a system to balance an inverted pendulum. For visualization purposes, this is similar to trying to balance a broomstick on a finger. This system incorporated a full system design including all of the mechanical, electronics, and aspect to the control system. There are three main subsystems that compose this design: The first is mechanical system, second is the feedback network which includes sensors and a method to read them, and final one is a controller which an interface to the mechanical system. After determining sets of requirements between the subsystems, each one was designed independent of the other two, simplifying the design process.The mechanical design involves building a fabriacted cart, pendulum, and drive mechanism. The cart and pendulum were developed out of primarily aluminum. The drive mechanism is a DC motor with bearings mounted onto its shaft to pull a cart, which the cart connects to it. The feedback network consisted of encoder, which were sampled by an analog-to-digital converter, to measure the angle of the pendulum and the displacement of the cart. The final system results in a cart that could balance a pendulum for a limited amount of time.

KEYWORDS: Inverted Pendulum, feedback network, Encoder

1. INTRODUCTION

The inverted pendulum (IP) control system design has become a common engineering challenge for researchers due to its important applications in practical life [1]. The problem is analogus to controlling a broomstick in the palm; most of the children do that in childhood aiming to make the stick stable in the vertical position. The IP stability and control has been a subject of research that attracts the attention of engineers and researchers since the last 50 years. IP model is used widely nowadays inrockets launching and missiles guidance.

An inverted pendulum is a pendulum which has its centre of mass above its pivot point. It is often implemented with the pivot point mounted on a cart that can move horizontally and may be called a cart and pole. Most applications limit the pendulum to 1 degree of freedom by affixing the pole to an axis of rotation. Whereas a normal pendulum is stable when hanging downwards, an inverted pendulum is inherently unstable, and must be actively balanced in order to remain upright; this can be done either by applying a torque at the pivot point, by moving the pivot point horizontally as part of a feedback system, changing the rate of rotation of a mass mounted on the pendulum on an axis parallel to the pivot axis and thereby generating a net torque on the pendulum, or by oscillating the pivot point vertically.

A simple demonstration of moving the pivot point in a feedback system is achieved by balancing an upturned broomstick on the end of one's finger. The inverted pendulum is a classic problem in dynamics and control theory and is used as a benchmark for testing control strategies. Can anyone balance a ruler upright on the palm of his hand? If he concentrates, he can just barely manage it by constantly reacting to the small wobbles of the ruler. This challenge is analogous to a classic problem in the field of control systems design: stabilizing an upside-down inverted pendulum.

2. RELATED WORK

2.1 LITERATURE REVIEW

The Inverted Pendulum System is a non-linear control systemthat is unstable as a training module of theoretical control system and various control system experiments. In the control system experiment of the Linear Inverted Pendulum, a pendulum with a center of mass above the pivot point is attached to a linear actuator and is moved to be in balanced condition [2]. Figure below is a general example in basic control system experiments with feedback especially in the design of control systems.

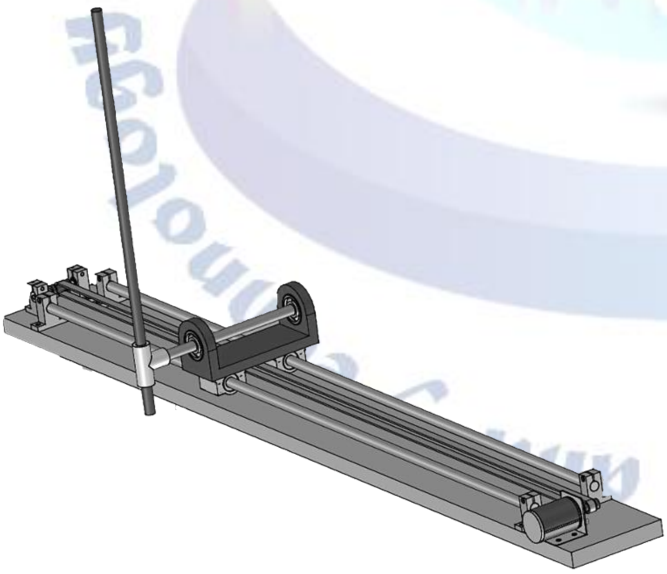

Figure 2.1.1 Inverted Pendulum

Inverted pendulum conditions that are unstable can be an interesting laboratory experimental objects and can be easily connected to real-world applications, such as rocket and missile control systems or electric vehicles with automatic balance systems.

There are several studies related to an inverted pendulum that has been done, by designing an inverted pendulum with a linear path. In this study, the Inverted Pendulum was designed as a linear inverted pendulum to eliminate the length limit of the path contained in the pendulum inverted with the transverse path.

2.2 PRINCIPLE OF INVERTED PENDULUM

The system involves cart, able to move backwards and forwards. And a pendulum hinged to the cart at the bottom of its length such that the pendulum can move in the plane as the cart moves. That is the pendulum mounted on the cart is free to fall along the cart's axis of rotation [1]. The system is to be controlled so that the pendulum remains balanced and upright. If the pendulum starts off-center, it will begin to fall. The pendulum will move to opposite direction of the cart movement. It is a complicated control system because any change to a part will cause change to another part. We only take feedback from the angle of the pendulum relative to vertical axis other than state of being carriage position, carriage velocity and pendulum angular velocity. The cart undergoes linear translation and the link is unstable at the inverted position. So, briefly the inverted pendulum is made up of a cart and a pendulum. The goal of the controller is to move the cart to its commanded

3. PROPOSED WORK

3.1 MATHEMATICAL MODELING

3.1.1 Nonlinear Equation of Motion:

The first thing we do is derive the nonlinear equations of motion. Although the Lagrange formulation is more elegant, this video uses the conceptually simpler Newtonian formulation that anyone who has successfully completed an engineering dynamics should be able to understand.

Let Mass of Cart= M_C

Mass of Pendulum= M_P

Length of Pendulum=L

Position of Cart=X

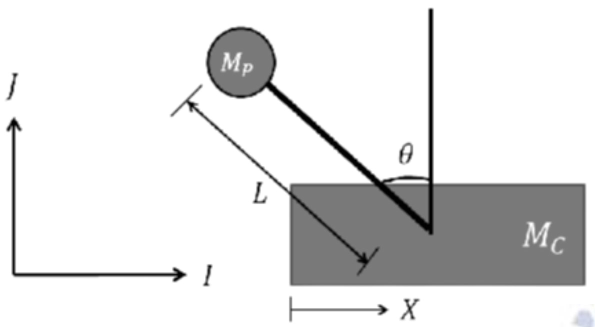

Figure 3.1.1 Free Body Diagram of Inverted Pendulum.

3.1.2 Free Body Diagram of Cart :

- Weight of the cart itself so this is -McgJ in J direction.
- Normal force pushing upward.so, this is an N in the J direction.
- And there's the tension (or) compression in this massless rod.
- Imagine the pushing the cart to the left or right in order.
- To keep the pendulum balanced.
- So, that control force that force pushing the cart left and right.
- Just going to call "F" going to the horizontal of course.
- So "F" in the "I" direction.

"F" can be positive or negative.it can be changing in time.

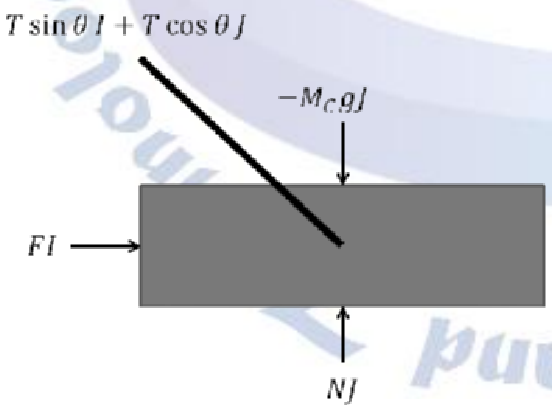

Figure 3.1.2Free Body diagram of Cart

3.1.3 Free Body Diagram of Pendulum :

- This Circular mass up here.
- Assuming that the rod is massless.so we do need a free body diagram of the rod.
- Weight of the pendulum.it's -MpgJ in the J direction.

So,there's the weight of the pendulum acting down on its and also feel the tension in the rod again exact same rod so its exact same tension but it's the other end of the rod on it's a force equal in magnitude opposte direction of the tension acting on the cart.

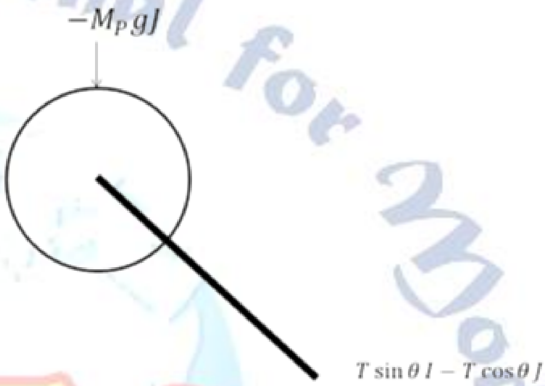

Figure 3.1.3 Free Body Diagram of Pendulum

3.1.4 Newton's 2nd Law :

$$F = m.a$$

- F = Force
- m = Mass of an object
- a = Accleration

Cart :

I direction : $F - T\sin\theta = M_C\ddot{X}$ ---------------(0)

J direction : In the vertical, the cart does not accelerate.vertically, nothing will be moving the horizontal.

Pendulum :

I direction: $T\sin\theta = M_P a_{P_X}$ ------------------(1)

J direction: $-T\cos\theta - M_P g = M_P a_{P_Y}$--------(2)

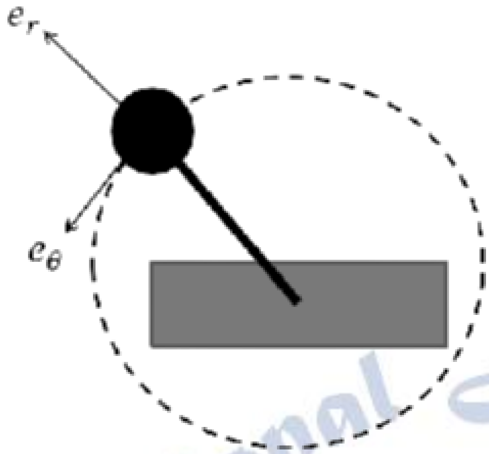

Figure 3.1.4 Forces Resolved on the Pendulum.

$$a_P = a_C + a_{P/C}$$

$$a_P = \ddot{X}I[-\cos\theta\, I - \sin\theta\, J] - L\dot{\theta}^2[-\sin\theta\, I + \cos\theta\, J]$$

To solve these expression for accleration into equation of motion of the equation(1)and equation(2),

From Equation (1)

$$T\sin\theta = M_P - M_P L\ddot{\theta}\cos\theta + \cos\theta\, J \quad \text{-------------(3)}$$

From Equation (2)

$$-T\cos\theta - M_P g = -M_P L\ddot{\theta}\sin\theta - M_P L\dot{\theta}^2\cos\theta \text{----------(4)}$$

I have got equation(3)and equation(4)here and they are differential equation in other words $\ddot{X}$ that will $\ddot{\theta}, \dot{\theta}$ in here so it's a relationship between X and θ and their various derivatives.

We have 3 differential equation right ,that are equation 3,equation 4 and equation 0.

But we also have a tension. We can keep that tension ther but if we can weid like to eliminate it right, because it's going to save a bit of a hassle later on and this problem is actually quiteesay to rid of the tension.

$$(3)\ \cos\theta + (4)\ \sin\theta$$

Equation (3)

$$T\sin\theta\cos\theta = M_P\ddot{X}\cos^2\theta + M_P L\dot{\theta}^2\sin\theta\cos\theta$$

Equation (4)

$$-T\cos\theta\sin\theta - M_P g\sin\theta$$
$$= -M_P L\ddot{\theta}\sin^2\theta - M_P L\dot{\theta}^2\cos\theta\sin\theta$$

Final equation of(3)$\cos\theta$ +(4)$\sin\theta$

$$-M_P g\sin\theta = M_P\ddot{X}\cos\theta - M_P L\ddot{\theta}(\cos^2\theta + \sin^2\theta)$$

$$-M_P g\sin\theta = M_P\ddot{X}\cos\theta - M_P L\ddot{\theta} \quad \text{---------------(5)}$$

Equation(5) is the equation of motion of pendulum

In the equation(0) also have tension force. In this equation also we can eliminate tension force by substitution of "$T\ sin\theta$" value in the equation.

$$F - T\sin\theta = M_C\ddot{X} \quad \text{---------------(0)}$$

$$F - M_P L\ddot{\theta}\cos\theta - M_P L\ddot{\theta}\cos\theta - M_P L\dot{\theta}^2\sin\theta = M_C\ddot{X}$$

$$F + M_P L\ddot{\theta}\cos\theta - M_P L\dot{\theta}^2\sin\theta = (M_P + M_C)\ddot{X} \quad \text{---------(6)}$$

Finally we got equation of motion of body; Equation of motion of body in form of the equation,that is equation(6).

3.2.COMPONENTS

Following is the list the components used in the assembly.

List of the components	Description
Linear Bearing.	Linear bearings carry a load on a rail that does not have to be in a straight line using a pad, bushing, or roller system. Although the actuator limits the length of the rail, it can be any length. The load and the required speed determine the bearing's durability.
Roller Bearing.	The cart was fitted with a roller bearing. The pendulum oscillates in a clockwise and anticlockwise motion at 360 degrees using roller bearings.
Shaft Rods.	Shaft rods are used to propel the cart forward and backward. The shaft rods are attached to the linear bearing. The shaft rods have a diameter of 12mm and a length of 1 metre.
Aluminium Sheets.	Aluminium sheets are useful for organising the design of the cart since they are lightweight, and we utilise them.
Gt2 Belt.	"Gates Tooth" is abbreviated as "GT." GT2 belts are comprised of Neoprene rubber with a fibreglass core and measure 1.38mm in thickness, 1 metre in length, and 10mm in width. The GT2 belt is used to propel the cart forward or backward.
Pendulum and Shaft Rods.	Aluminium is used for the pendulum and shaft rods. since aluminium is a light metal .The pendulum and shaft rods have a diameter of 12mm and a length of 450mm.
Idler Pulley.	Pulleys are mechanical devices that direct applied force in a rotational or linear motion system. A belt system's idler pulley is crucial to its functionality. The

	idler pulley is one of several pulleys that drive a cart's belt system. The idler pulley controls the belts that attach to the cart and are used to propel it forward.
Shaft Bracket.	Shaft brackets have a high friction resistance and can achieve high precision rotating in a smooth movement, as well as corrosion resistance, acid resistance, ease of installation and use, and a linear reciprocating motion for a variety of mechanical systems, as the role of the support or drive, often with the support shaft rods.
Motor Pulley.	A motor pulley is a pulley that is permanently attached to a DC motor. A timing belt is guided by this motor pulley.
DC Motor.	A DC motor, also known as a direct current motor, is an electrical machine that uses direct current to convert electrical energy into mechanical energy. A magnetic field is formed in the stator of a DC motor when it is turned on. Magnets on the rotor are attracted and repelled by the field. The rotor rotates as a result of this. To keep the rotor spinning continually. DC motors are chosen over other types of motors because they allow for exact speed control. DC motors can start, stop, and reverse quickly, which is critical for managing the operation of manufacturing equipment.
DC Motor Mounting Brackets.	The mounting brackets are intended to be used as an additional support or as an alternate mounting option for your DC motors.
Ultrasonic Sensor.	An ultrasonic sensor is an electronic device that uses ultrasonic sound waves to detect the distance between a target item and converts the reflected sound into an electrical signal. Ultrasonic waves move quicker than audible sound waves. The transmitter and receiver are the two primary components of ultrasonic sensors.
Arduino Mega 2560.	The Arduino Mega 2560 is an ATmega2560-based microcontroller board. It contains 54 digital input/output pins, 16 analogue inputs, a 16 MHz crystal oscillator, USB, power, an ICSP header, and a reset button. It comes with everything you need to get started with the microcontroller; simply plug it into a computer via USB or power it with an AC-to-DC converter or battery. Most shields produced for the Arduino Duemilanove or Diecimila are compatible with the Mega. The Arduino Mega 2560 is a successor to the Arduino Mega.
Encoder.	At each point of rotation, an absolute encoder delivers a unique position value or data word that represents the encoder's "absolute" location. An absolute encoder can give you the precise location of the spinning shaft it is monitoring from the moment it is turned on.
L298N Dual H Bridge.	The L298N is a dual H-Bridge motor driver that allows for simultaneous speed and direction control of two DC motors. The module can power DC motors with voltages ranging from 5 to 35V and peak currents of up to 2A.
Bread Board.	The breadboard is a circuit assembly approach that allows for quick circuit fabrication without the need for soldering or permanent connections. Breadboards almost often feature common rows, where the holes in a row are electrically linked. Leaded components are placed into holes with metal grips that gently clamp onto the lead.
Jumper Wires.	Jumper wires are simple cables having connector pins on both ends that may be used to connect two places without the use of solder. Jumper wires are commonly used with breadboards and other prototyping tools to allow for quick circuit changes as needed.
24Volts Power supply.	A power supply is an electrical device that transforms electric current from a power source, such as the mains, into the voltage and current values required to power a load, such as a motor or electronic equipment. Electronic circuits

	that convert alternating current (AC) input to direct current (DC) output are known as ac to dc power supply. Ractifiers are a type of ac to dc power supply. They convert the input ac voltage to a variable dc voltage, then filter it to get an unregulated DC voltage.

3.3Drawings of the other components

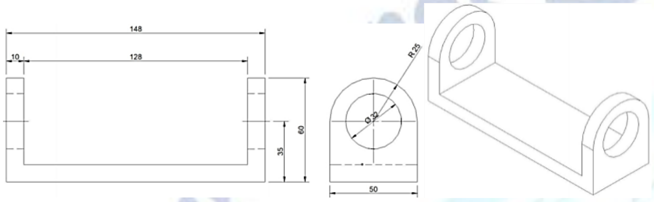

Figure 3.3.1 Carrier.

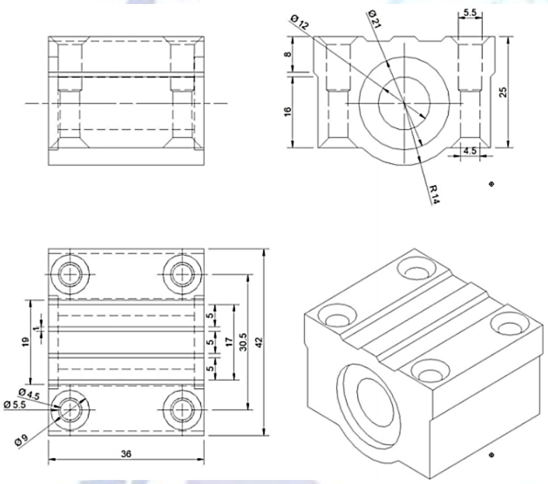

Figure 3.3.2 Liner Bearning.

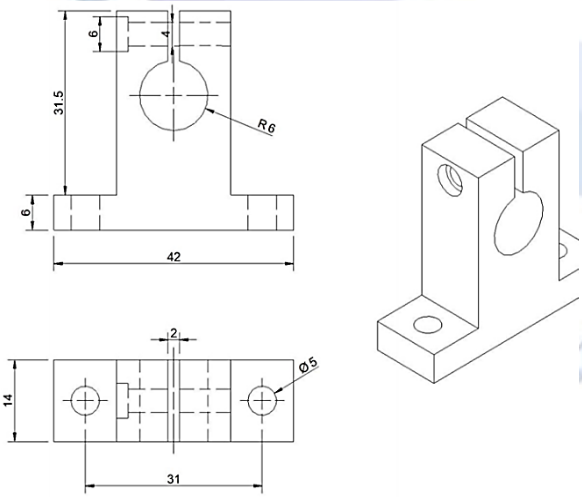

Figure 3.3.3 Shaft end support.

3.4 Solid model of the Assembly

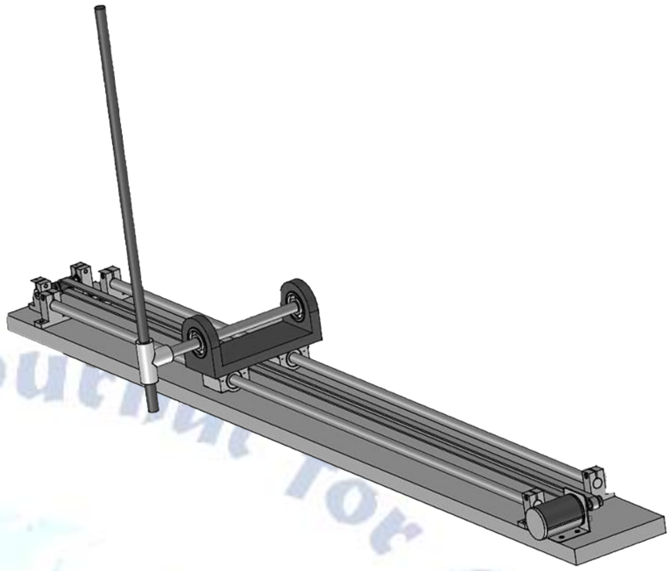

Figure 3.4.1 Assembly of Inverted pendulum control setup.

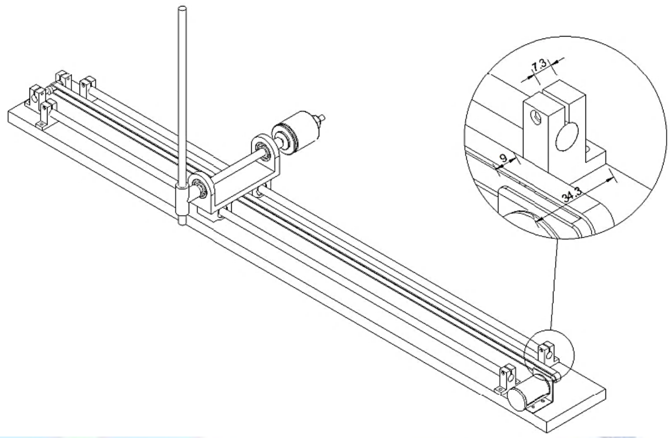

Figure 3.4.2 Assembly drawing of the setup.

3.5CIRCUIT DIAGRAM

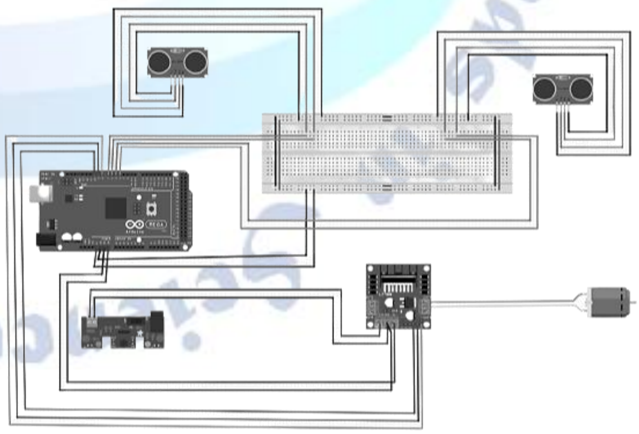

Figure 3.5.1 Circuit Diagram.

4. RESULTS

As a result of this, the inverted pendulum controller was designed in a way that satisfies the high response requirement. The control system's purpose is to balance the stick vertically on the cart by applying a control signal (force) on the cart.

Considering the initial requirements, the full-state feedback system meets them widely. This controller works as intended and it is easily modified once the linearized model has been obtained. The system responds well to perturbations and the cart can be controlled without losing pendulum stability. Therefore, the requirements have been met since the pendulum can be stabilized in its upright position while keeping the control of the position of the cart.

Many requirements were met such that a working mechanical system was developed along with a control circuit and an accurate feedback network. An interface was also created through hardware and software to integrate the Arduino Mega 2560 as the main processing unit for the controller.

From this, it seems that with the right modifications, it would be quite feasible to balance a pendulum for an extended period of time.

Co-ordination between the ultrasonic sensor and motor direction is more desirable and movement of cart and pendulum also more effectively.Encoder dedicated the angle accurately and most pleasant to the control system.

The most beneficial aspect of this project was that it gave exposure to a full system design. The experience gained from developing each of the subsystems given the constraints they imposed on each other and then integrating them together proved to be invaluable.

5. CONCLUSION

Finally, the objectives of the work were achived. The work considered developved successfull model and the main goal of the project was successfully achieved.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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