ME 408 - MECHATRONICS SYSTEM DESIGN

FINAL REPORT

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Sabancı Üniversitesi

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Abstract

Inverted pendulum is a very useful mechanism for practicing the control of an unstable system. Moreover, there are different approaches to balance the pendulum which utilizes different control methods or mechanical components. In the design process, analyzing different approaches is essential considering the project requirements and real-life constraints. Determination of the objectives and tasks need to be done, are the second phase of the design process. In this context, the main objective is to balance the pendulum; furthermore, specific control performance should be satisfied. When the existing solutions in the literature has been evaluated, it was seen that there are two major designs for the inverted pendulum: a moving cart with that is connected to DC motor by a chain/belt and a wheeled cart that is stabilized by fixed sticks along the path. Each method has its own advantages and disadvantages in different aspects of the project. Conceptual designs eased to compare each design with other considering the resources that we have in this project because they show simple working mechanisms of the designs with the important components of the structure. Solidworks models are used to demonstrate the possible design options and to show the mechanical workload that is needed to be done. A rough project plan has also been made by assigning appropriate durations to major project objectives.

Introduction

In the Design and Implementation of an Inverted Pendulum project, it is aimed that an inverted pendulum mechanism should be designed such that pendulum is able to balance itself on top a moving cart. There are different approaches to the problem, the most common two design ideas are the railway cart approach and wheeled cart approach. For the first design idea, a pendulum base rides on a track or rail with the pendulum suspended in such a way that it is free to rotate more than a full revolution in two directions. The actuation is provided through either a DC motor driven cable, chain or ribbed belt connected to both ends of the pendulum base. For the second design idea, a wheeled cart that has four wheels, which spin together, restricts the cart to travel in a straight line. Overall, the control problem for both of the design ideas are similar to each other.

Even though there is a lot of research that has been done to solve this problem in a more efficient way, there are still some points to touch in an original way. Because we are asked to design the project under certain constraints and requirements, we will differ from the pre-found solutions in the literature.

Design and Implementation of an Inverted Pendulum project is a comprehensive project that includes several different engineering disciplines such as mechanics, statics, electronics, control. In the project, all of these areas should satisfy the minimum requirements; therefore, a solution methodology that considers these areas and has compatible parts between them, should be applied to the problem. Consequently, capstone design phases are the most useful approach to attack this kind of a comprehensive problem. In this context, each phase of the capstone design should be visited one by one and we should proceed after each completion. Within the context of the project, we have not to exceed a certain volume for the whole system. This is one of the fundamental constraints in the project since we should design the system and choose the components that are compatible with the given size. Another important constraint is that we cannot spend more than 200 TL for the project which restricts our component selections. We cannot afford for high quality electronic components and motors; thus, we should make a deeper analysis for the selection of materials. The evaluation of the preliminary design after considering the constraints and requirements while seeking for the best performance has been done and we made our design decision considering the possible design ideas. For the current phase of the project, we are working on finalizing the detailed design of the inverted pendulum system. There are still some undecided points in the detailed design which will be completed in the following week. Next phase will be starting implementation of the project by procuring the necessary components.

Project Requirements

In order to complete this project, there are some requirements that must be satisfied. It is better to clarify these before proceeding with further details. The requirements are:

- Size must fit within a domain of 100 cm x 100 cm x 30 cm. (WHD)
- The groups must build their own signal conditioning circuit

- The groups are required to use proper mechanical connectors
- Total additional cost must be less than 200 TL
- Available equipment kit includes:
  - Potentiometer
  - Power supply (12V 3A)
  - Op-Amp, power MOSFET, discrete components (R,C), screws nuts etc. are to be found at FENS1093.
  - Arduino Nano, cable and 1 Set each Male-Male Male-Female Female-Female pin connectors
  - Motor driver (L298)
  - Micro switch
  - Solderless breadboard
  - Screwdriver set
  - Nipper
  - Pliers

Bonus performance requirements are:

- Reduction in volume will be a bonus (will be quantified).
- Successful demonstration of the response to various disturbances in a predefined manner
- Having minimum total additional cost
- Swing up pole from rest position

Literature Survey

For the conceptual designs, 5 different design ideas were created to satisfy the general project requirements such as volume and available mechanical and electrical components. Those designs can be named as follows:

1. Railed cart with inelastic rope actuation

2. Railed cart with wheeled actuation

3. Railed cart with conveyor belt actuation

4. Rotary inverted pendulum

5. Wheeled car

These designs are listed preferred to non-preferred ideas according to their ease of implementation, manufacturability, cost and criteria which increase performance such as low and linear friction property for actuation platform, durability, torque and velocity transition. All of the designs can be produced relatively cheap components and can be analyzed properly to satisfy durability requirement. However, actuation type (torque and velocity transition) and friction properties are critical evaluation parameters. Since provided power supply is 12V 5A, it could not support huge motors which provide good range of instant torques. In addition, nonlinear friction is hard to model, and friction measurement becomes difficult. Additional non-linearity will introduce more challenge on control part of the project.

Railed cart with inelastic rope actuation

In this design, cart moves on rail and connection could be provided with linear bearings. Motor is fixed on the platform and power transmission is provided by inelastic rope. Ball bearing can be used as a pulley on the other side of the motor.

Advantages:

- Inelastic rope reduces backlash effect during high torque
- Cart is relatively light because motor is fixed at the end (good for instant acceleration)
- Rail limits side motion and increase durability
- Friction can be reduced with linear bearings

Disadvantages:

- Power is still transmitted by belt. Rope is inelastic but it may wriggle on pulley at the motor end

Railed cart with wheeled actuation

The difference between first design and this one, wheels are used for connections on rail.

Advantages:

- Backlash due to transmission belt is eliminated
- Friction is reduced with wheels

Disadvantages:

- Motor increases cart weight
- Wheels might cause slippage

Railed cart with conveyor belt actuation

In this design, we focused on conveyor belt transmission together with possible pneumatic actuation. However, our system should be small and light. Therefore, we do not need to accelerate heavy cart. In addition, pneumatic actuation works smaller frequency which harden the control implementation significantly.

Rotary inverted pendulum

This is completely different design and it uses angular motion to balance rod instead of linear motion. Since our motor will be small, heavy mechanics with rotation will be challenged both control and mechanical design parts.

Wheeled car

This design includes regular 4 wheeled car together with stick on top of it.

Advantages:

- Very easy to mechanically implement

Disadvantages:

- Car will be heavy since it carries motor
- Since car will move on different surface, it changes control performance significantly (not consistent).

Realistic Constraints

For the final choice of the design, we will consider several factors that are must and should be. For this analysis, we first listed the requirements of this project. After that, we listed constraints for this project even they are not given directly but can be deduced from the realistic limitations. In more details, we should design our inverted pendulum so that it is economically, environmentally, safety-wise, manufacturability-wise feasible.

Economic: We are given a kit that contains most of the must-have components for electronics. As explained in the project requirements, we must use most of the components given in the kit; however, we have more options for the construction (mechanical structure). Besides the given kit, we may use additional electrical components that we believe which increases the performance of the system. Because some of these high-performance components are expensive, we should not exceed the 200 TL budget. This is one of the most important limitations for this project since motors are the key component for inverted pendulum stabilization. Also, we may not use high-quality materials for the mechanical components because of the budget we have.

Safety: We should both think of human safety and the systems own safety when the system is operating. In the first case, any unstability should not result in the rod to fall over on a human with some speed. Therefore, we will implement our controller by taking this situation into account. For the second case, if we use a heavy stick and it falls over the system, it may harm the mechanical and electrical components on the system. Hence, we will try to use a stick as much as lighter.

Environmentally: We will be only using electrical and mechanical components for the inverted pendulum system which all can be recycled. There is no direct damage to the environment with our system.

Manufacturability: As we are asked to use specific electrical components, they are very accessible. For the mechanical structure, we will be designing our systems such that all the parts can be bought from pre-made shops or can be manufactured by simple machining. Using 3D printed components are also available in our resources.

Considering these realistic constraints plus the requirements, there is no absolute solution to this problem. So, we have developed different approaches to this problem and analyzed them roughly to compare each other. Going over the traditional solutions to this problem in the literature helps us to develop fundamental ideas of the project, yet we still have contradicting ideas with some of them considering the resources that we have. As the first step, we made an abstract thinking session and discussed the most relevant ideas to come up with an applicable model. Since there are several disciplines that should be taken into account, we have to come up with a satisfying solution for all of the fields [3].

Methodology

The introduction section describes briefly the latest improvements in the project. We can extend these improvements in the form of the phases of a capstone design process. We introduced the general procedure of the project, by now we have put solid developments in the context of the design process.

1) Problem Definition: We have clearly defined the problem in the Proposal Report and extended this definition by asking several questions about the concepts and requirements. After the first report, we faced some of these questions later while we were working on the project and gave more certain answers to them.

2) Conceptual Design: In the Proposal Report, we produced 5 different design ideas by only thinking of their basic working principles and component selections. At the end, we chose 2 most possible conceptual design ideas.

3) Preliminary Design: After we selected the possible two design ideas, we chose one of them and worked on its preliminary design (Number 1 in the Figure 1). First, we decided on the working principle of the system, and determined the necessary components and their locations in the system. Therefore, we prepared a CAD design of the design idea in Solidworks. Our CAD design was almost completed except the belt mechanism. We did not finalize the belt mechanism in the Proposal Report but we included it in this report.

4) Design Decision: We concluded that the preliminary design of our design idea mostly satisfies project requirements and constraints that are given to us. We may modify some details but overall, the detailed design will be done based on the developed design in the preliminary design phase.

5) Detailed Design: As we recently completed the preliminary design of the project, we are now deciding on the necessary electrical and mechanical components that are not included in the given kit. Because we have not finished some of the design decisions and therefore some calculations, we made some assumptions for the calculations. We used safety factors in order not to exceed any maximum limit that may cause significant problems in the implementation.

Proposed Solutions

In this project, we are aimed to design and build an inverted pendulum system. To solve this problem, we made comprehensive research for the existing solutions. After considering the multiple constraints and requirements, we finalized the discussion with two similar design ideas:

- A moving cart with that is connected to DC motor by a chain/belt. It moves on a rail which enables motion in only one axis. Rod is mounted at the top of the cart.
- A wheeled cart that is stabilized by fixed sticks along the path. Smaller DC motors are connected to the cart from inside. It moves on a rail which restricts the motion only in one direction. Rod is mounted at the top of the cart [5].

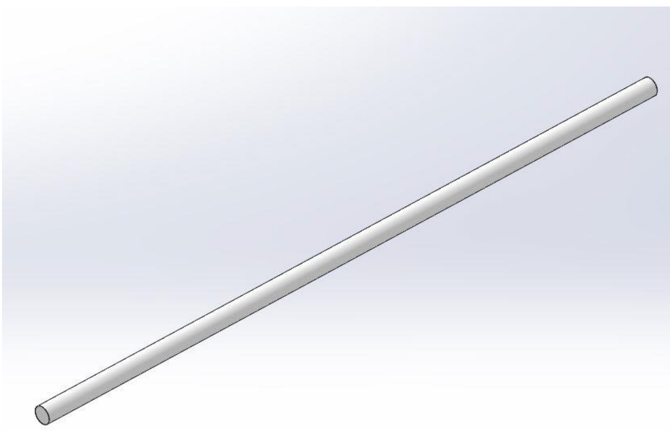
After we select the first design approach as our design, we started the advance this approach by our authentic methods. You can see the details of our design below. On the other hand, we changed this design in the implementation part of the project. We generally followed the same methodology; however, the main difference was we used a printer part as our base rail component. We added several mechanical components to construct our inverted pendulum system on that given part. This change increased our speed in the implementation part a lot.

1) Our Design

Rod

We selected our rod based on the literature surveys and previously done experiments by other people. We decided on the length of the rod as 0.4 m which is optimal in the most cases; however, after determination of the other components, we may review this value. The longer the rod, the easier it is to control the rod; nonetheless, increase in the weight causes a higher need of torque. We chose the material of it as Steel 304 at first but after several experiments, we decided to use a plastic rod (ABS or similar) in order to reduce the weight. We thought we can print it in a 3D printer or find similar material. When we model the rod that has the mentioned properties, we have:

- Mass = 0.190 kg
- I = 0.0025 kg.m2
- L = 0.4 m
- R = 0.007 m

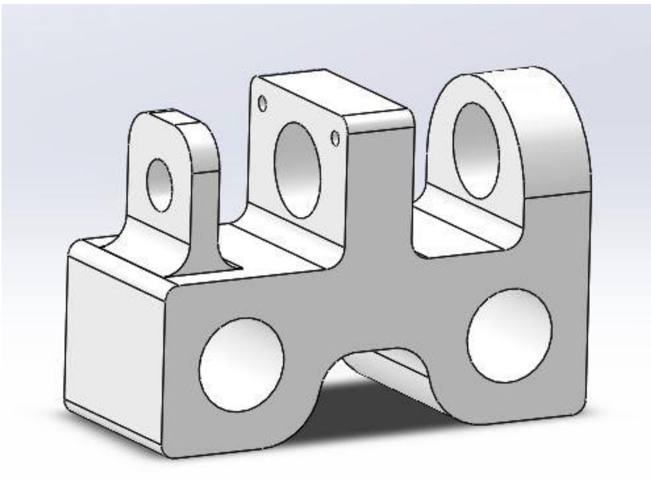


Cart

We designed the cart as it should as light as possible. We used two sticks to stabilize its motion in one axis. We connected these sticks with a linear bearing to decrease the friction. The friction coefficient of the linear bearings is approximately 0.001 which we neglected during the calculations. We decided to print this part from a high precision 3D printer using the ABS filament because we can give more details to the part and it will a lot lighter than the steel one. The cart also contains the pendulum mechanism which is a rotating stick. We measure the rotation angle with a 10k frequently-setting potentiometer [1].

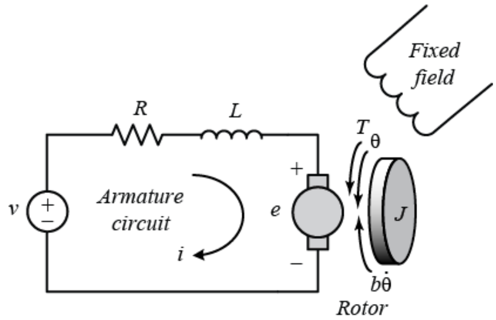
As we said in the previous sections, we used a belt mechanism to move the cart. Therefore, we put the connection station of the belt on top of the cart. Although there are several details in the part, because we 3D print it, we can easily manufacture it and it does not weight very much. The final mass of the cart is approximately 0.150 kg. When we model the cart that has the mentioned properties, we have:

- Mass = 0,34 kg
- Viscous Friction = 6 N.s/m



DC Motor

When choosing the DC motor, there are several specifications that should be paid attention. These are the maximum current value, nominal current value, voltage value, angular velocity value, maximum torque value. We can make connections with the electrical specifications and the mechanical specifications by following the below model.



We can write the electrical and mechanical equations of the DC motor as:

$$T = K_i * \quad (1)$$

$$e = K_e * \dot{\emptyset} \quad (2)$$

$$j\ddot{\emptyset} + b\dot{\emptyset} = K * i \quad (3)$$

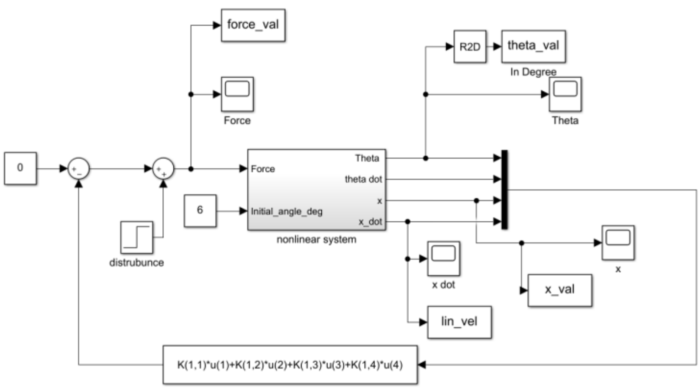
$$l\frac{di}{dt} + R * i = V - K\dot{\emptyset} \quad (4)$$

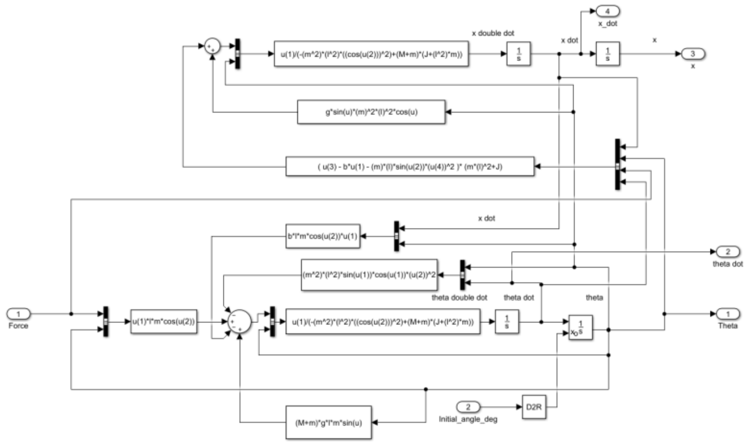
$$s(js + b)\emptyset(s) = K * I(s) \quad (5)$$

$$(Ls + R)I(s) = V(s) - ks\,\emptyset(s) \quad (6)$$

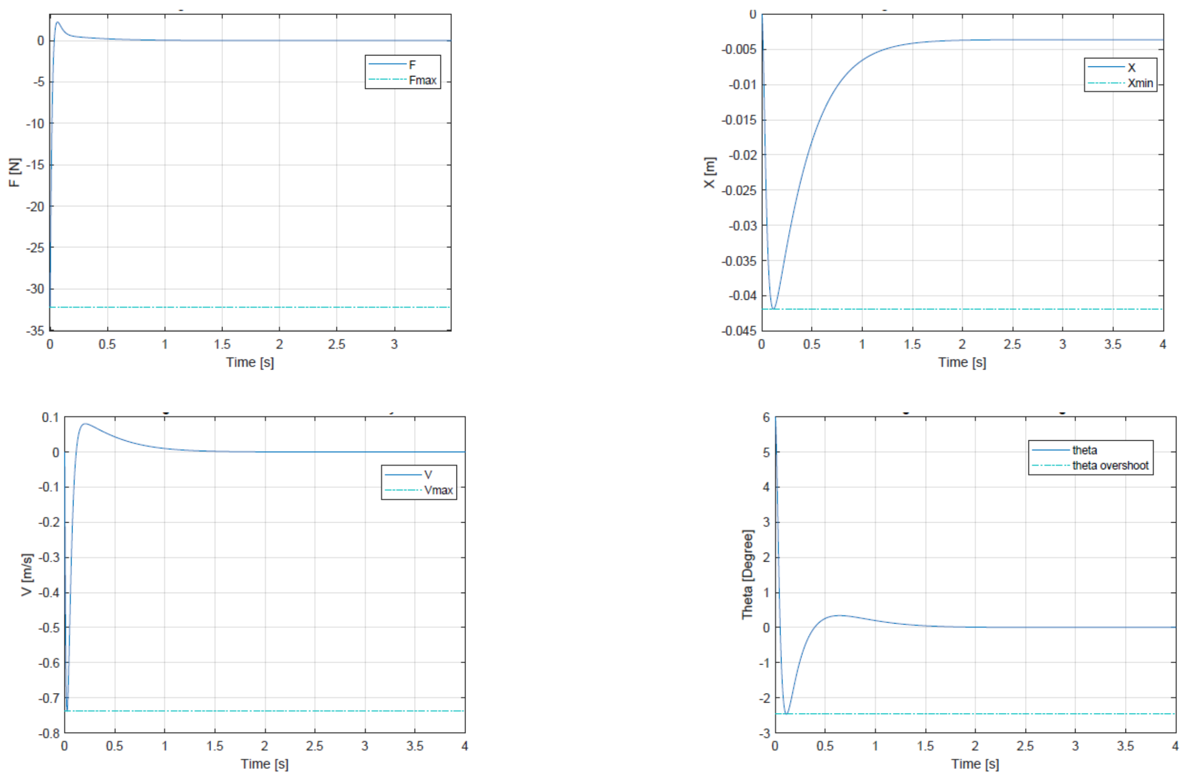
$$p(s) = \frac{\dot{\emptyset}(s)}{V(s)} = \frac{K}{(js + b)(Ls + R) + k^2} \quad (7)$$

Note that, because the effect of the inductor is very small, we neglected it in the mathematical model. Therefore, we ended up with the 4 important specifications of the motor which are: torque, rotational speed, current and voltage. We have to pay attention all of them in our design. In order to select our DC motor, we first modeled our system as an inverted pendulum which we used nonlinear model as State Feedback model. You can see the model in figure.





We simulated out model with a 6 degrees of initial theta values and aimed at reaching 0 degree as fast as possible. We save the required maximum force value, as a result the position change, velocity change and theta angle change. You can see the results in figure.



As a result of the shown simulations, the measured maximum values for the force, velocity, position and theta angle are:

- F_{max} = 32 N
- V_{max} = 0.7 m/s
- X_{max} = 40 cm
- $Theta_{max}$ = 6 degrees

This information provides the vital information to calculate the important concepts in the inverted pendulum system. First, the system length should be more than 40 cm as only for 6 degree of initial theta value needs 40 cm space to balance the rod. Second, because we choose theta to be small, it smoothly approaches to 0-degree desired angular position. On the other hand, force and linear velocity values determine the DC motor specifications that we have to consider while we are choosing. For the torque of the motor, we can calculate it using the required maximum force and radius of the power arm. In this case, our power arm is the belt mechanism; therefore, we use the radius of the belt bearing. The radius is 15 mm, so the torque is:

- T = F * R
- T = 32 * 0.015
- T = 0.48 Nm

Also, for the angular velocity, we can calculate it by dividing the linear velocity to the power arm which was mentioned above. Therefore, the angular velocity is:

- V = W * R W = V / R
- W = 0.7 / 0.015
- W = 46.67 rad/s

Because most of the angular velocity specifications are in revolution per minute:

- W = 445.67 rpm

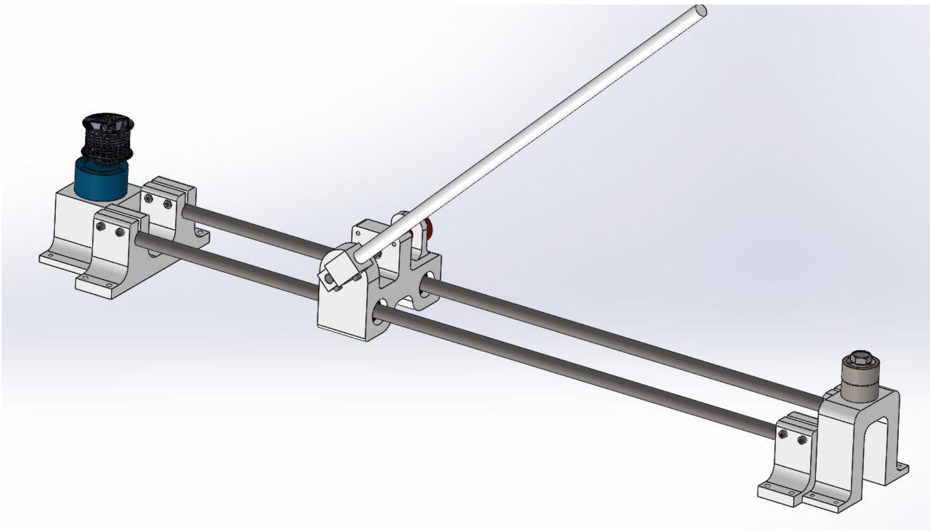
So far, we decided the mechanical speci_cations of our motor; however, we still need to decide on the electrical speci_cations. To do that, we also have to consider the motor driver that we use in our system. When we check for the datasheet of the Motor Driver L298, we see that it gives the current in range of 2-3 A. We know that from the DC motor equations, current is directly related with the torque; thus, we should consider the maximum torque corresponding to 3 A for the torque speci_cations. In the end, without exceeding our budget, we chose the motor that has a 37 mm diameter with a 19:1 reduction rate [6]. This motor's specifications are:

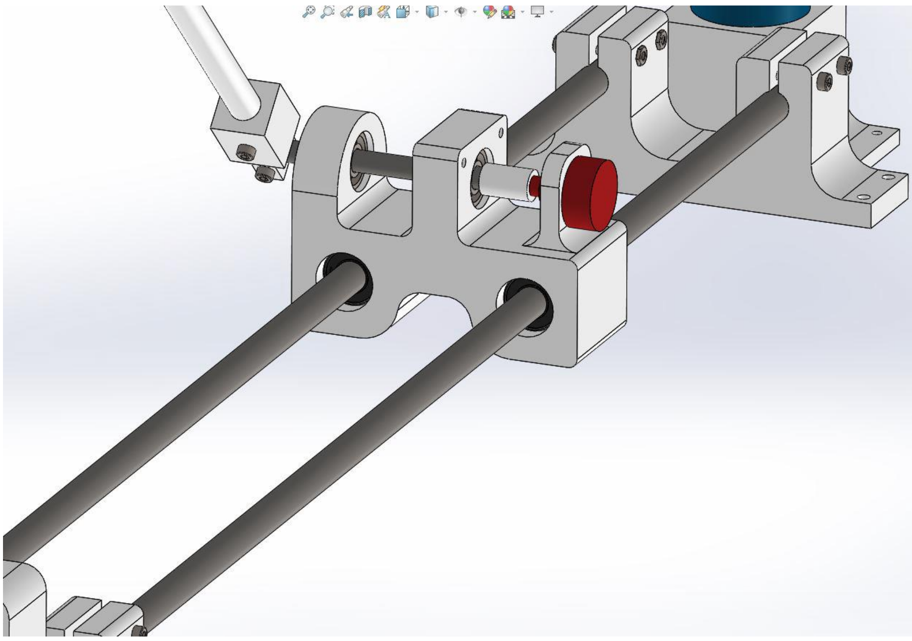
- W_{max} = 500 rpm
- $Torque_{max}$ = 0.49 Nm
- I_{max} = 5 A

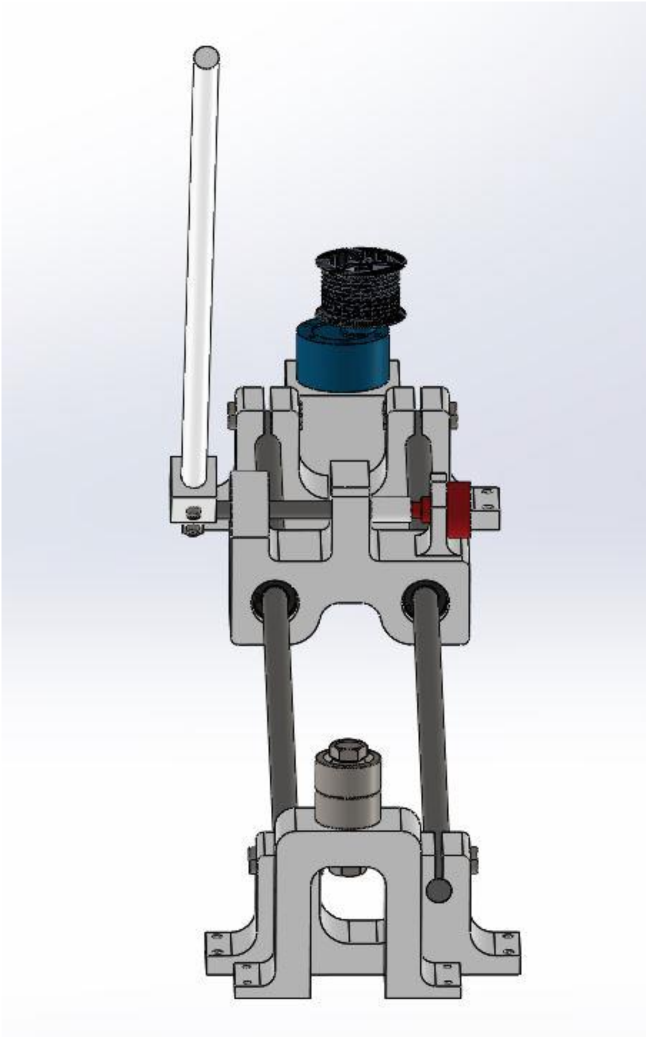
The motor is not chosen certainly because we are making our calculations and there may be additional changes in the system which require some re-calculations in the process. Considering our limited budget, we chose this motorin our design; however, our primary intention is to use a larger motor that has higher torque and angular velocity capabilities.

CAD Design

We draw our model in Solidworks. Belt mechanism was designed with rope and pulley system. Rope will be rotated around double rotational bearing and pulley on motor. Linear bearings are used to slide cart on the rod. Balanced rod mount was designed to strength joint and avoid direct physical load on potentiometer. Slide rods mounts and motor mount will be fixed on a straight plate.







COMSOL Analysis

We tested our cart rod connection with modeling the joint as hinge joint with friction. Relative rotation, angular velocity, displacement and joint forces were obtained under free fall of the rod. Since COMSOL is a new environment for us, it took a lot of time to import CAD file correctly for the analysis. We will extend this analysis such as stress and bending.

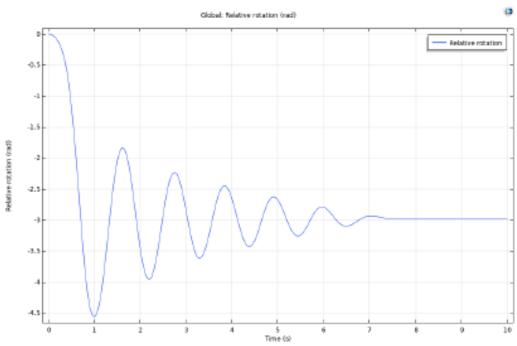


Figure 12

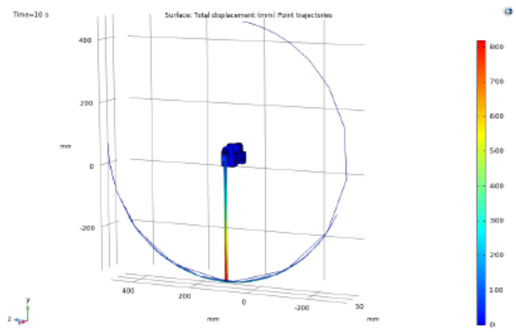


Figure 14

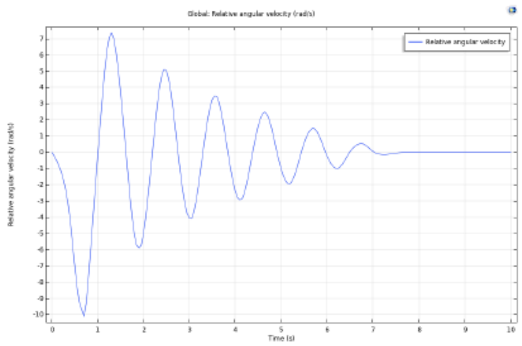


Figure 13

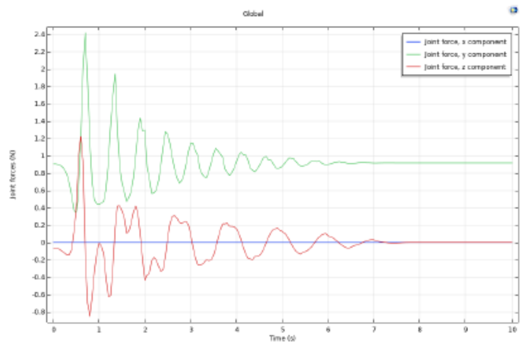
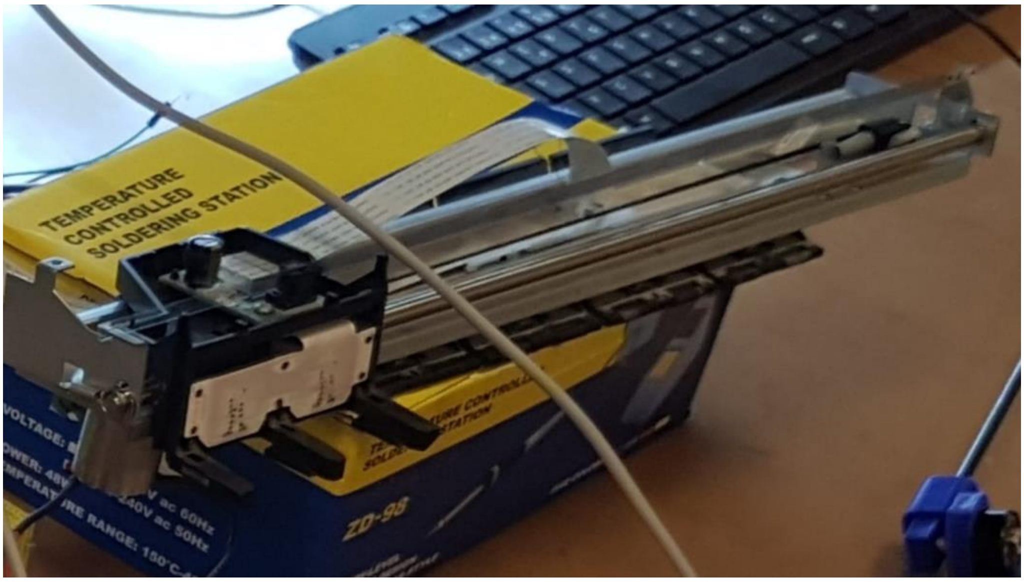


Figure 15

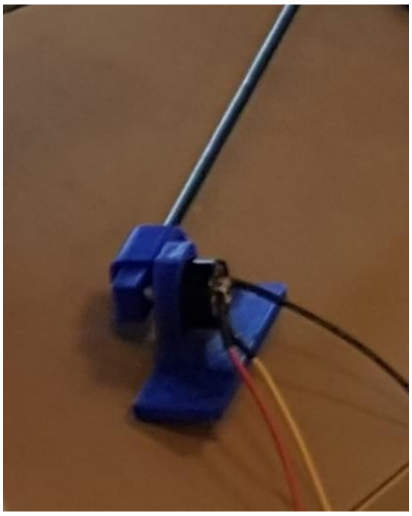
Joint forces, velocity and rotation were obtained in our expected range. There was no force exerted in the x direction since it is rotation axis of the rod.

2) Our Implementation

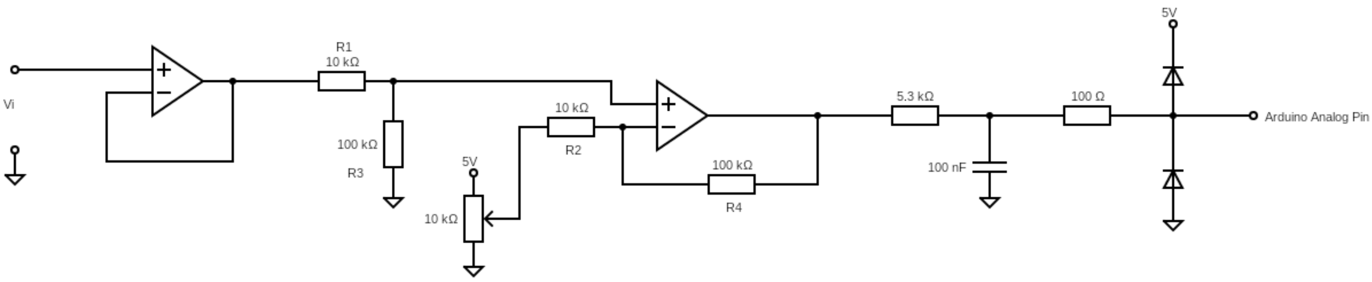
We have designed an inverted pendulum system to balance the rod using a moving cart. We have searched for the all of the necessary components in the design, and the cost does not exceed the limit. When we moved to the procurement process, we had some difficulties at ordering some of the components. After several discussions, we changed our design and decided to use the components that are already available in our lab. There are major changes in the design, the first change was at the mechanical base which we took an old printer set up that has a rail and a simple cart on it. The system also has a small motor and shorter path to move the cart along it. We also changed the pulley mechanism to a belt mechanism which also can satisfy the needs of the system. Besides its disadvantages in terms of control, the mechanical parts are almost ready to use which speeds up the assembly process.



First, we made several experiments with the given motor as we were not sure whether it has enough torque and speed to balance the rod on the cart. We decided to use a carbon fiber tube on the cart because it is lighter. We then designed the connection parts of the rod and potentiometer to the system so that we can measure the angle changes properly. We 3D printed the connection parts and assembled them to the mechanism.



Second, we worked on the electronic circuitry of the system. We used signal conditioning circuit to measure +/-25 degree range more precisely and accurately.



Basic Schematic of Signal Conditioning Circuit

Potentiometer output is connected to voltage follower to transfer voltage as much as possible without drawing current from potentiometer. Since voltage follower has high input impedance and 1 gain, nearly all voltage transferred to the rest of the circuit with small current value.

Output of voltage follower is connected to differential amplifier part. Offset voltage which is 2.5V removed with voltage divider potentiometer. Since R1 equals to R2 and R3 equals to R4, gain is $\frac{R4}{R2}$ ($V_+ - V_-$). Gain of the signal conditioning circuit is 10.

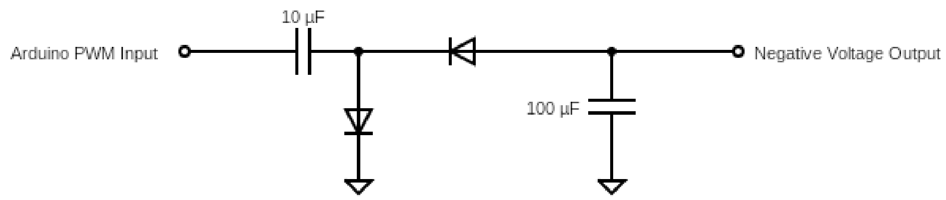
The amplified signal is passed into the first order low pass filter. The cutoff frequency is set to 300Hz. 100nF capacitor and 5.3kΩ resistor are used.

$$f cutoff = \frac{1}{2\pi RC}$$

We calculated the natural frequency of the system around 5Hz and we designed our smallest low pass filter cutoff frequency to 20Hz. However, a large capacitor is required to set the cutoff to 20Hz and large capacitor value causes large time constant which increases time delay in the system. Time delay in the control system is one of the most undesired properties. Therefore, physical low pass filter cutoff frequency is set to 300Hz. Second low pass filter is designed with software to obtain second-order lower cutoff frequency.

Since the signal conditioning circuit aims to amplify small angle changes, large degree in potentiometer causes negative voltage or voltage that is larger than 5V. To limit output voltage, two diodes is connected to 5V and ground together with 100Ω. Schottky diode is used due to their typical low forward voltage values.

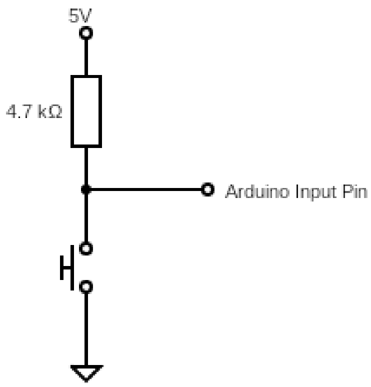
Op-amp packages require a power supply to amplify the input signal. Since we might move the setup outside the lab, we used differential amplifier design instead of summing amplifier due to not required negative voltage supply. However, the power supply range cannot be used completely by the op-amp (LM324N). Our measurement demonstrates that there are 0.7V losses. Therefore, we designed a charge pump to generate a negative voltage.



Charge Pump Circuit

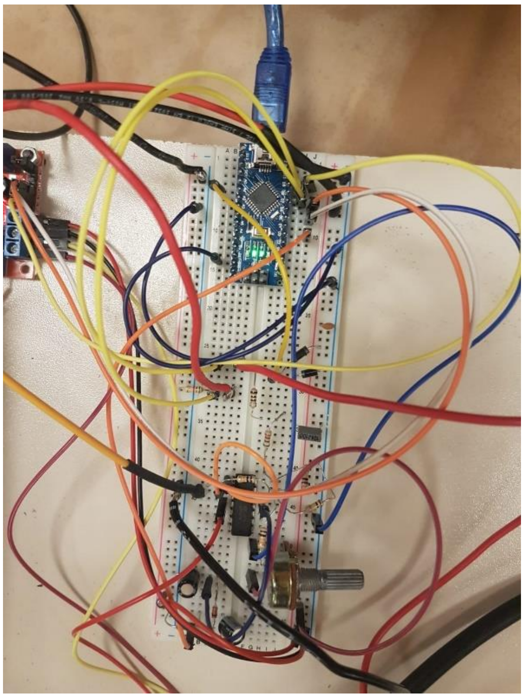
Arduino PWM output is used to generate square wave input for negative voltage generation. Fast switching diodes are used in D1 and D2. C2 capacitor is 100 µF and C1 is 10 µF. Output voltage was measured around -3.5V

Limit switches are used to stop motor when cart hits the end of the rail. In the circuit, we connected them with pull-up resistors.



Limit Switches Connection (Pull-up)

Arduino digital pins are used to get input from limit switches. When limit switches are triggered, current passes through circuit.



Implementation on Breadboard

Implemented circuit gain is 9.81. Since there are small ripples that come from the power supply, it causes small fluctuation in the circuit. Therefore, we use 470pF capacitor between 5V and ground line to smooth signals.

Materials for Circuit Design:

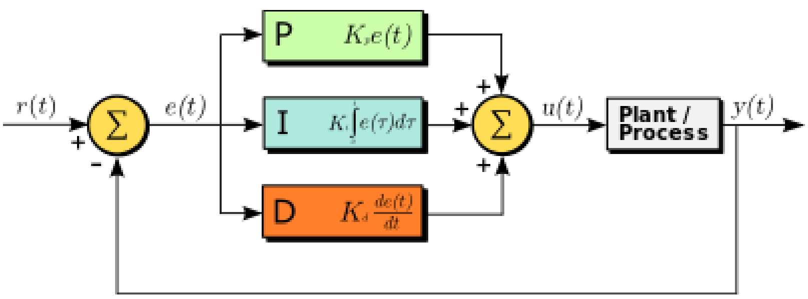
- 2 x N5819 Schottky diode
- 1 x LM324N Op-Amp
- 1 x 104J100 capacitor
- 1 x 10 µF capacitor
- 1 x 100 µF capacitor
- 1 x 10k potentiometer
- 2 x 1N4148 fast switching diode
- 1 x 470pF capacitor
- 1 x 100nF
- 1 x 5.3kΩ
- 2 x 4.7kΩ
- 2 x 10kΩ
- 2 x 100kΩ
- 1 x 100Ω

Next, we worked on our code that reads the potentiometer value, applies a PID control to the signal in order to balance the rod and gives power to the motor. We implemented our code step by step by being sure that each part works as desired. We used a low pass filter (Exponential Moving Average Filter [EMA]) in the code as well in order to eliminate high frequency signals and smooth the signal.

$$f_{3dB} = \frac{f_s}{2\pi} cos^{-1}(1 - \frac{\alpha^2}{2(1-\alpha)})$$

Sampling frequency was set to 200Hz and α was picked as 0.5. The cutoff point is chosen 23Hz as it is explained in previously.

Also, we put two end switch sensors to two ends of the mechanism so that the cart will stop when it touches end points. We used the Arduino Nano microprocessor and Arduino environment to bridge the gap between mechanical components and electronics. We controlled the pendulum with PID (proportional–integral–derivative) control theory which multiplies the error signal with three different control terms.



Mathematically, the formulation is as follows:

$$u(t) = K_\mathrm{p} e(t) + K_\mathrm{i} \int_0^t e(t')\,dt' + K_\mathrm{d} \frac{de(t)}{dt}$$

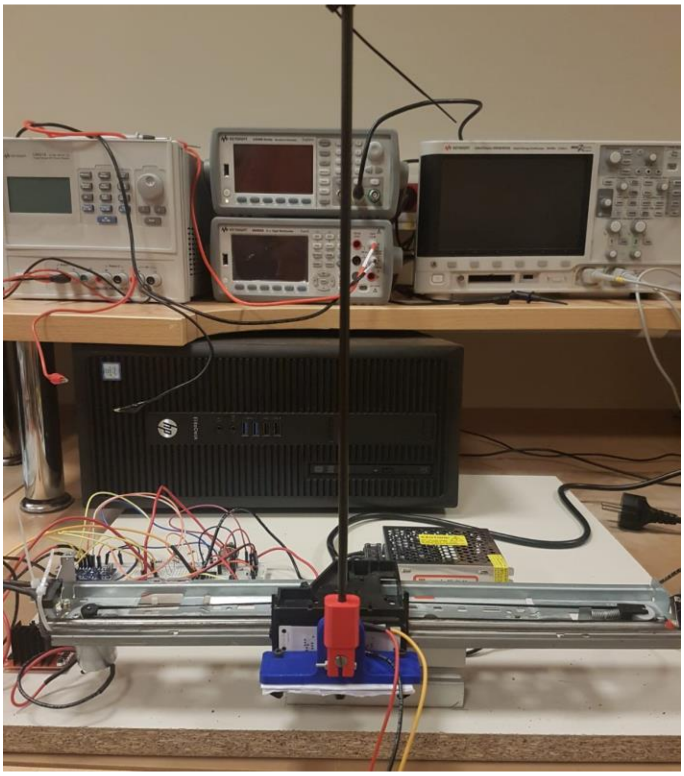
We started the algorithm with introducing a negative PWM signal to Arduino at 1 kHz with 50% duty cycle. Then we convert the incoming signal from a voltage value to an angle value and apply the digital low pass filter. We want to hold the rod at 0 degree so, we enter the PID parameters and compute the required PWM signal that is for the motor. The computed PWM value is given for two different cases where the rod angle is grater than zero or smaller than zero. We change the direction of the motor signal by adding the minimum threshold value that is necessary to start working the motor because of the static friction forces.

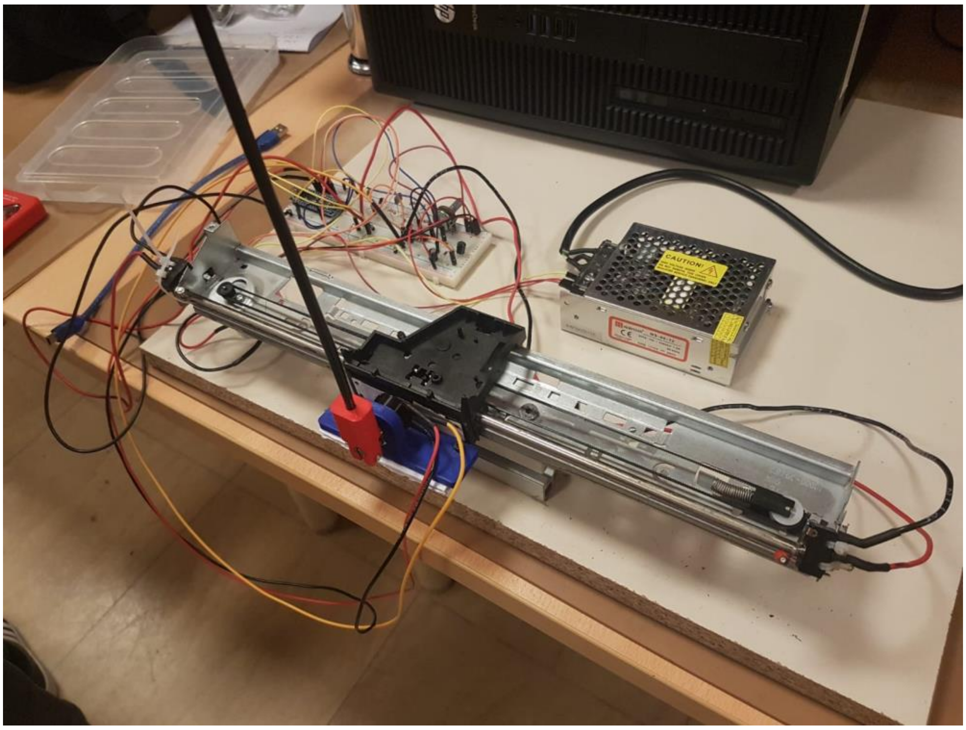
Next, we constructed our platform by assembling the mechanism, electronic circuitry and power supply to a wooden plate. We used proper mechanics which has a base of a relatively heavy plate so that the system can stand still even if put it at the end of the table. We put the pendulum mechanism on a sigma profile which provides the enough freedom for more advanced control techniques such as swinging up the pole. We also used countersunk bolts to stabilize the system which block any kind of motion of the mechanism.

Lastly, we started making experiments with the PID parameters that we initialized. After many trials, we found out that in order to tune the PID parameters in the best way, we should increase the integral term more than the other terms because it prevents the backlash in the system which provides a smoother motion. The final PID parameters are:

$K_p = 70$ $K_i = 250$ $K_d = 0.25$

Overall, our final design can be seen in the following figures:





After tuning the PID parameters, we made several experiments with the system. We observed that we are able to balance the pendulum in static situations. On the other hand, if we apply a force to the rod, cart can balance it up to a limit-force. When a force that it smaller than the threshold force is applied, cart can recover the vertical position of the stick in the short rail, whereas, if the force is larger than the threshold force, cart cannot control the pendulum because it needs more space to move. Our rail is short; therefore, we should apply a more advanced control technique by also controlling the position of the cart. To do that, we should track the position of the cart which means we need an additional sensor. This idea can be applied to the future work of this project.

Conclusion

At the end, we have faced several problems during the design and implementation of the project. We modelled the system as much as similar to the real system by entering the important system characteristics to identify the relevant control terms such as the maximum force and torque that we need. However, we neglect the nonlinear dynamics of the system and we assume the rod can move in an angular range of 12 degrees. We understood that this model does not fully satisfy the dynamics of the system. Also, we designed a new, optimum inverted pendulum mechanism from scratch in order to reduce the required weight and friction in the system. We made several changes during design phase for a more efficient design. Other criteria in the design phase was to select the mechanical components that we can procure easily which also must be cheap so that we do not exceed out 200 TL budget.

In the implementation part of the project, we used lots of machinery tools to construct the mechanism using the given printer part. After we look over the given part in detail, we removed the unnecessary parts carefully. We made a simpler design for the new mechanism so that we can find enough space on the given part. We put additional elements into the mechanism to make the system more stable. As an example, there was a problem about the angle of the rod, and we solved it by putting a piece of paper. Also, we attached the end switches with plastic cable ties to the two ends of the mechanism. Moreover, the belt got off the cart, we had to stabilize the belt to the cart using plastic cable tie.

As a result, this project showed that there are multiple aspects of building a system that contains electrical components, mechanical components and programming workload. We should work in an order so that each part is improved concurrently. It is essential to check each phase whether it is working or not. We should always have a backup plan for any case, some mechanical components can be broken, or some electrical components can be burnt. We are now aware that there are priorities for making changes in the system. For example, the first thing that we should try is to solve the problem by changing the program of the system which is the easiest way for most of the cases. Changes in the mechanics are generally the hardest and most time-consuming changes. Even if we are done with everything in the project, some fine adjustments may be misaligned or broken; thus, it is better to check the system before each operation.

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Appendix

Our code:

```
#include <PID_v1.h>


#define negPWM 3


int potPin = A1;
double potVal = 0.0;
double angle = 0.0;
double EMA_a = 0.5; //initalization of EMA alpha  // 0.5, 200Hz ->  23Hz cutoff point!
double filt_angle = 0.0;   //initialization of EMA output (low pass)


int left_switch = 7; // end swtich left
int right_switch = 8; // end swtich right


#define in1 5 //PWM output to L298n
#define in2 6 //PWM output to L298n
#define enA 9 //Pin to enable/disable H bridge


double Kp = 70.0;
double Ki = 250.0;
double Kd = 0.25;


double a_in, a_out, a_setp, pwmin; //PID parameters
PID angPID(&a_in, &a_out, &a_setp, Kp, Ki, Kd, DIRECT); // PID loop for controlling the motor



void setup() {
  pinMode(negPWM, OUTPUT);


  pinMode(enA, OUTPUT);
  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);
```

```
  digitalWrite(in1, LOW);
  digitalWrite(in2, HIGH);

  angPID.SetSampleTime(5);
  angPID.SetMode(AUTOMATIC);
  angPID.SetOutputLimits(-255, 255);

  pinMode(left_switch, INPUT);
  pinMode(right_switch, INPUT);

  Serial.begin(115200);
}

void negVoltPWM() {
  digitalWrite(negPWM, HIGH);
  delayMicroseconds(500);  //Approx 50% duty cycle @ 1kHz
  digitalWrite(negPWM, LOW);
  delayMicroseconds(1000 - 500);
}

void lowPassFilt() {
  filt_angle = (EMA_a * angle) + ((1 - EMA_a) * filt_angle);
}

void DEBUG_potVal() {
  //Serial.println(potVal);
  Serial.println(filt_angle);
}

String readStr;
int serialCount = 0;
double tuneParam = 0.0;

void setPIDParams() {
  Serial.println("Enter PID parameters (Kp, Ki, Kd): ");
```

```
 while (Serial.available()){
   char c = Serial.read();
   if (c == ','){
      tuneParam = readStr.toDouble();
      readStr = "";
      if (serialCount % 3 == 0){
        Kp = tuneParam;
      }
      else if (serialCount % 3 == 1){
        Ki = tuneParam;
      }
      else if (serialCount % 3 == 2){
        Kd = tuneParam;
      }
      serialCount = serialCount + 1;
   }
   else{
     readStr = readStr + c;
   }
 }
 Serial.print("Received parameters: ");
 Serial.print(Kp);
 Serial.print(", ");
 Serial.print(Ki);
 Serial.print(", ");
 Serial.println(Kd);
 angPID.SetTunings(Kp, Ki, Kd);
}

void loop() {
 negVoltPWM();

 if (digitalRead(left_switch) == true && digitalRead(right_switch) == true){
   potVal = analogRead(potPin);
   angle = potVal * 50 / (1023.0 - 16.0) - 25.79;
```

```
    lowPassFilt();
    //DEBUG_potVal();

    a_setp = 0.0;
    a_in = filt_angle; //filt_angle
    setPIDParams();
    angPID.Compute();

    if (a_out < 0)
    {
     pwmin = (-1 * a_out) + 70;
     digitalWrite(in1, HIGH);
     digitalWrite(in2, LOW);
     pwmin = min(pwmin, 255);
     analogWrite(enA, pwmin);
    }
    else if (a_out >= 0)
    {
     pwmin = (a_out) + 70;
     digitalWrite(in1, LOW);
     digitalWrite(in2, HIGH);
     pwmin = min(pwmin, 255);
     analogWrite(enA, pwmin);
    }

  } else {
     analogWrite(enA, 0); //Stop motor!
  }
}
```