Pendulum 328

Inverted Pendulum PID Demonstrator

Project Development Plan (PDP)

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Roles

Team Member	Primary Role	Secondary Role
Matt Handley	CAD	Calculations
Joe Sedutto	Electrical	Machining
Kat Swineford	Documentation	Assembly
Austin Cardosi	Coding	File Organization

Table 1.1.1

Abstract

A PID loop (Proportional, Integral, Derivative) loop is a very common error-reducing algorithm in our modern world. It can be implemented in many different ways, and controls everything from the heating cycle of your toaster to the cruise control in your car.

The PID loop seeks to reduce the “error” in a system. That error may be the speed you want to go, the target temperature of your toast or the upright position of a pendulum. PIDs are used extensively in many different applications and can be difficult to understand on a purely numeric basis. With that said, a PID demonstrator is a tool that allows users to interact with and gain a deeper understanding of the underlying control mechanisms.

Out PID demonstrator tackles this problem, it uses robust but minimalist construction to create a high quality and easy to maintain demonstrator. Users will interact with its front panel to tune and de-tune a system managed by PID. We will use a classic inverted pendulum which uses very similar principles to, balancing a baseball bat on your finger. Its high moment of inertia allows the pendulum to swing and waver when untuned, yet hold perfectly still when tuned correctly.

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The System Description

Problem Statement

The goal is to make a PID Demonstrator that teaches the operator how to use a PID loop. The operator will have control to adjust each individual variable and see how each effects a vertical standing pendulum.

Design Research

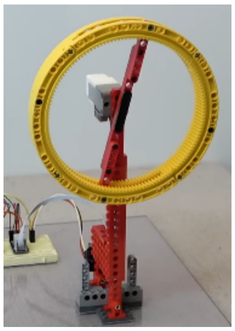
Rotary Inverted Pendulum

The rotary inverted pendulum spins about a fixed central axis. The arm that attaches to the fixed central axis holds the pendulum. The combination of the motor and sensors allow the pendulum to stand itself upright. Based on the pendulum's angle the motor can accelerate in both directions to counterbalance the falling rod. The assembly in Figure 1.2.1 below has an estimated cost of 200 to 500 dollars depending on its final configuration.

(Figure: 1.2.1)

Reaction Wheel Inverted Pendulum

The Reaction Wheel inverted pendulum functions off torque by a spinning wheel at the top of the pendulum. The torque and counter-torque used to move the pendulum left or right can allow for the pendulum to have the ability to stand vertically when the PID loop is corrected. This specific example was made with a variety of Lego parts and the builder in the video we observed demonstrates that his loop works with a variety of weights and modifications.



(Figure: 1.2.2)

Technical Challenges

One key challenge our team will face is trying to tune the pendulum to stay vertical as the PID loop works to correct things according to the variables chosen. In order to mitigate the above challenge the team will spend the right time perfecting the loop after construction. Another challenge could be getting the pendulum to swing up automatically without any outside assistance. A potential solution for this is to find examples of this kind of pendulum and see how to possibly code a startup sequence. Last potential challenge that might occur is troubleshooting the sensors to ensure accurate and precise readings for demonstrating the graphs of the PID loop. This can be mitigated by testing the sensors prior to mounting them to the system.

Customers/markets/economics/applications

Demonstrates control systems using a PID loop. Allows users to vary the control loop constants to change the behavior of the pendulum. Educational application for academia and industry.

Concept of Operations

Statements

Stakeholders: Southern New Hampshire University, Professor Carlstrom, Professor Husson, Professor Guo, educators and academics, industrial training, producers of parts and service.

Users: Pendulum team, educators and academia, industrial and software training, and producers of parts and service.

System Description: A PID system is a general method for a computer or intelligent system to reduce the error or deviation in a system. Examples include the thermostat in a stove, the cruise control in a car or the gain control on a phone microphone.

This system aims to help display the fundamentals of a PID system in the form of a machine dedicated to allowing the operator to experiment with the tuning and functions behind the algorithm.

It will be constructed from steel and wood, powered by a single motor and a small processor and power supply, portable but robust enough to be installed in semi-permanent use. Weighing between 30 and 50lb, with a TFT screen. The system will use a demo PID loop to balance an inverted pendulum. Users will have the ability to adjust the input rates while observing the response of the loop to course correct the pendulum.

Operational Environment: This demonstrator will be in an engineering lab setting that may be exposed to dust over time. This is an indoor device and can be powered on and off for demonstrations as necessary.

Support Environment: This demonstrator will be made from as many COTS (Common Off The Shelf) parts. This will allow for simple replacement when and if things break down. The environment the unit is in and the frequency of which the equipment is run will affect many parts' life cycles.

• Wearing components (belts, sliders)

Mitigation all wearable parts will be accessible and removable without major disassembly.

• Constant touching and interaction

Mitigation the demonstrator will be built from sturdy and easy to clean components.

• Constant uptime

Mitigation low power/sleep mode can prolong the life of electronics when not in use

Anything requiring major disassembly, prolonged repair or specialty parts will be built robust and within manufacturer spec with documentation for reference. All systems either self calibrating or not requiring calibration. The system will be designed with long life serviceability in mind.

Operating Modes:

• Off mode: the state in which the system is powered down and or unplugged.

• Idle mode: a power saving mode in which fans are turned off; the TFT screen is turned off; and the motor controller, CPU, and power supply will be swapped to their internal lower power consumption mode.

• Spin-up mode: a custom control procedure that self initializes (swing the pendulum up into a ready state using harmonic oscillation.

• Demo PID mode: a built-in PID procedure with lock Kp, Ki, and Kd values to demonstrate how the inverse pendulum is properly balanced.

• User PID mode: a control structure in which the user can manipulate the Kp, Ki, and Kd constants to witness the effects of their changes on the stability of the pendulum.

Use: This system will provide an excellent robust teaching tool for its users to grasp and deeply understand the function of a PID loop, which is an essential software and hardware algorithm for many industries.

Risks:

• Pinch Points and swinging pendulum

• Failure during demonstrations

• Damaged to the unit from normal use

• Short circuits and electrical malfunctions

• Heat accumulation

Impact Consideration: There are some considerations to think about with the implementation of this system:

• Being a hazard and risking misuse.

• Requiring physical space, either for storage or use.

• Producing a significant amount of pollutant to construct, deploy, and eventually recycle/throw away.

System Requirements (Top Level)

Functional Requirements: (what it does)

Number	Requirement	Verification
1.1	The system shall have a low power mode in which all components are put into an idle state.	Feature/Test/ Inspection
1.2	The system shall have an autonomous mode in which the pendulum will balance itself using an integrated PID loop.	Feature/ Demonstration
1.3	The system shall have a user-control mode in which the turning of potentiometers shall manipulate the constants of the PID loop	Feature/ Demonstration
1.4	The system shall be self-tensioning.	Feature/ Inspection/Test
1.5	System modes will be selectable by the user.	Feature/ Demonstration

1.6	The system shall have a screen capable of displaying the oscillations of the pendulum and the correction curve formed by the PID loop to the user.	Feature/ Inspection/ Demonstration
1.7	The system shall have a capacitive sensor that detects if the pendulum has come in contact with human skin.	Feature/Test
1.8	The system shall have an emergency stop.	Feature/Test/ Inspection
1.9	The system shall have a buzzer or noise making component to warn users of before the pendulum begins to harmonically oscillate into its balanced position.	Feature/ Demonstration
1.10	The system shall have an embedded fan in the electrical compartment to cool the circuit board and the power supply.	Feature/Test

Table 3.1.1

Performance Requirements: (how well it does)

Number	Requirement	Verification
2.1	System should be reasonably quiet.	Test/ Demonstration
2.2	The system shall be sufficiently powered using a standard 120 V wall outlet.	Test/Feature
2.3	The pendulum shall swing up into a start position in under 15 seconds.	Test/ Demonstration
2.4	Upon sensing a ground due to the touch of human skin, the capacitive sensor in the circuit board shall cut current from reaching the motor in under 200ms.	Test/ Demonstration/ Feature
2.5	Upon the press of the estop, the system shall cut current from reaching the motor instantly.	Test/Inspection
2.6	The autonomous mode shall balance the pendulum for the entirety of the duration that the system is in this mode (after the pendulum has been spun up to its starting position).	Test/ Demonstration

2.7	No component shall not exceed a temperature of 110 degrees Fahrenheit while in normal operation.	Test/Inspection

Table 3.2.1

Physical Requirements: (sizes, weight)

Number	Requirement	Verification
3.1	The pendulum shall weigh between 8 to 13 grams	Inspection
3.2	The span of the linear track for the pendulum shall be no more than three feet long.	Inspection
3.3	The display screen shall have color to easily distinguish between the control loop, the current error in the system, and the target value for achieving balance.	Test/ Demonstration/ Inspection
3.4	The system shall weigh no greater than 50 lbs with the removable legs attached.	Inspection
3.5	The frame of the assembly shall be made with mild steel.	Inspection/ Feature
3.6	All electrical components shall be grounded.	Inspection/ Test
3.7	The pendulum shall be 1.5 feet in length.	Inspection
3.8	All elements shall operate under their yield stresses and have a factor of safety of 1.5 or greater for embedded components.	Inspection/ Feature
3.9	All elements shall be under a fatigue strength that allows for a product lifetime of 20 years.	Inspection/ Feature

Table 3.3.1

Environmental and Safety Requirements:

Number	Requirement	Verification

4.1	The wooden base shall be given a varnish finish to improve the longevity of the wood and stop corrosion and thermal cycling damage.	Inspection
4.2	All fasteners shall be secured from vibration.	Inspection/ Feature
4.3	The system shall operate in a temperature range from 50 degrees Fahrenheit to 90 degrees Fahrenheit.	Inspection/ Test
4.4	The electrical compartment in the base shall be to open independently of the system in order to remove any dust that accumulates.	Test/ Demonstration

Table 3.4.1

Engineering Standards:

Number	Requirement	Verification
5.1	IEC TR 61923: IEC standards for instruments in household/indoor environments	Inspection/ Test
5.2	IEC 60745: IEC standard for power tools and similar motor controlled appliances	Inspection/ Test
5.3	IEC 60364-1: Rules for general design (fuses, proper grounding, insulation)	Inspection/ Test

Table 3.5.1

Risk Assessments

Risk Assessment

Risk	Likelihood	Consequence	Mitigation	Trigger

Statement		Tech	Cost Schedule		
Operators can have hair, fingers or extremities caught in pinch points.	5	Low	Low	Shields and guards keep hair and fingers away from dangerous areas. Capacitive and e-stop sensors deactivate loop when out of spec	On touch
Operators may become struck by falling pendulum	1	Low	Low	Pendulum has a very low weight and a low maximum jerk-speed.	On touch
Machine can become damaged by improper tuning	3	High	Low	When out of tune PID loops are prone to vibration and oscillation, to mitigate we will - Program min and max safe values - Build with the understanding that out of tune loops will produce known vibrations	When in use
Risk of fire, or total failure	1	Low	Low	Well documented internals and an electrical system robust and built to common standards.	All the time.

Table 4.1.1

Design Concepts

Sketches

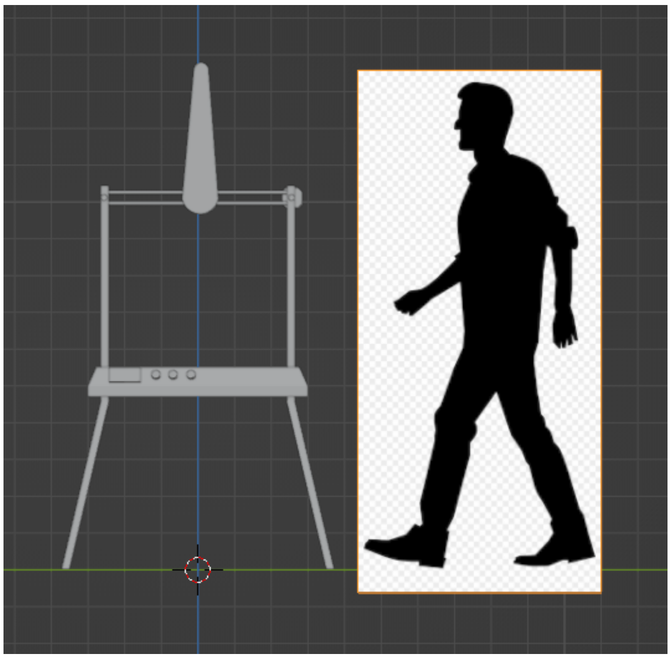


Fig 5.1.1

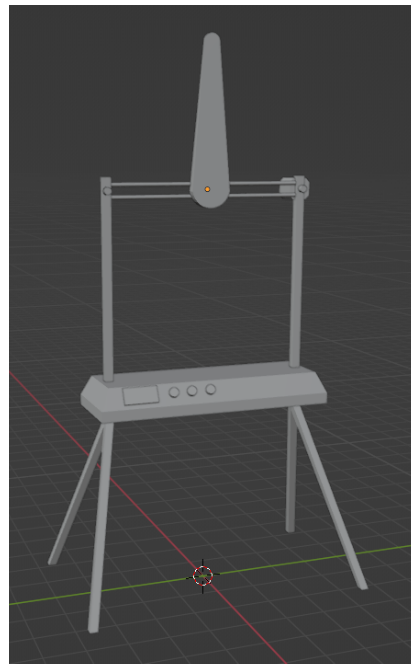


Fig 5.1.2

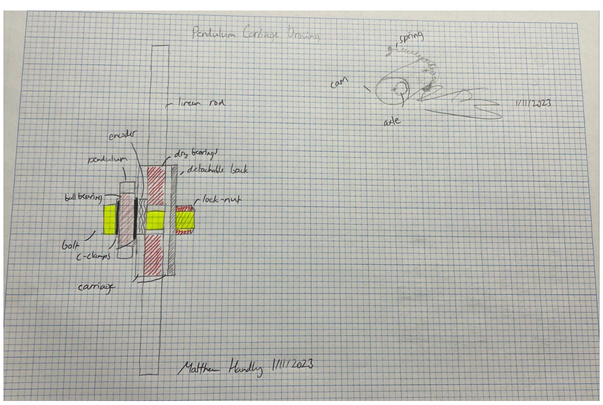


Fig 5.1.3

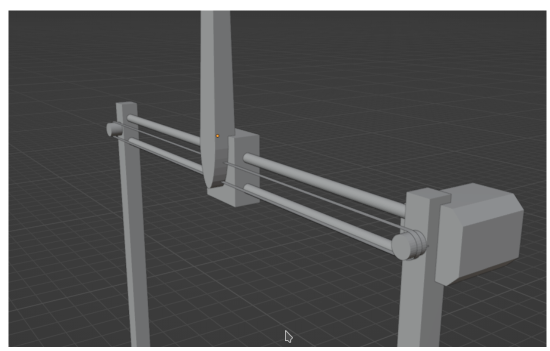


Fig 5.1.4

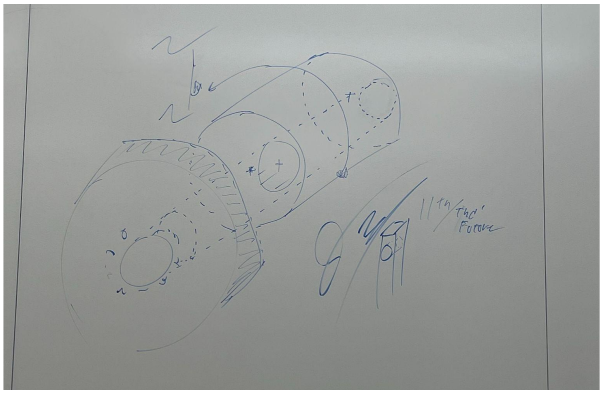


Fig 5.1.5

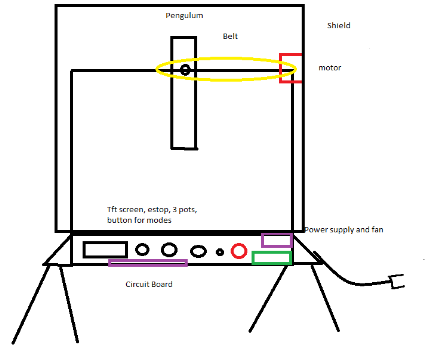


Fig 5.1.6

System Composition Block Diagram

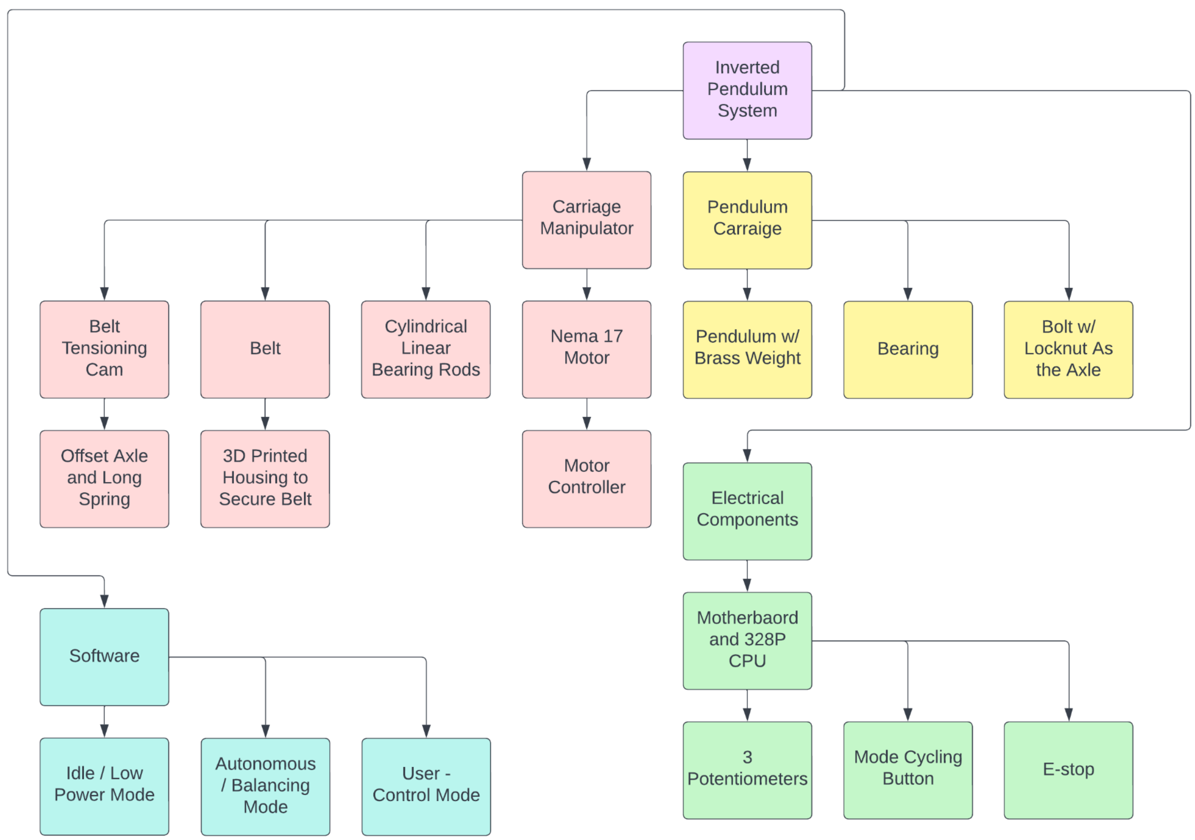


Figure 6.1.1

Flow Chart of Operations

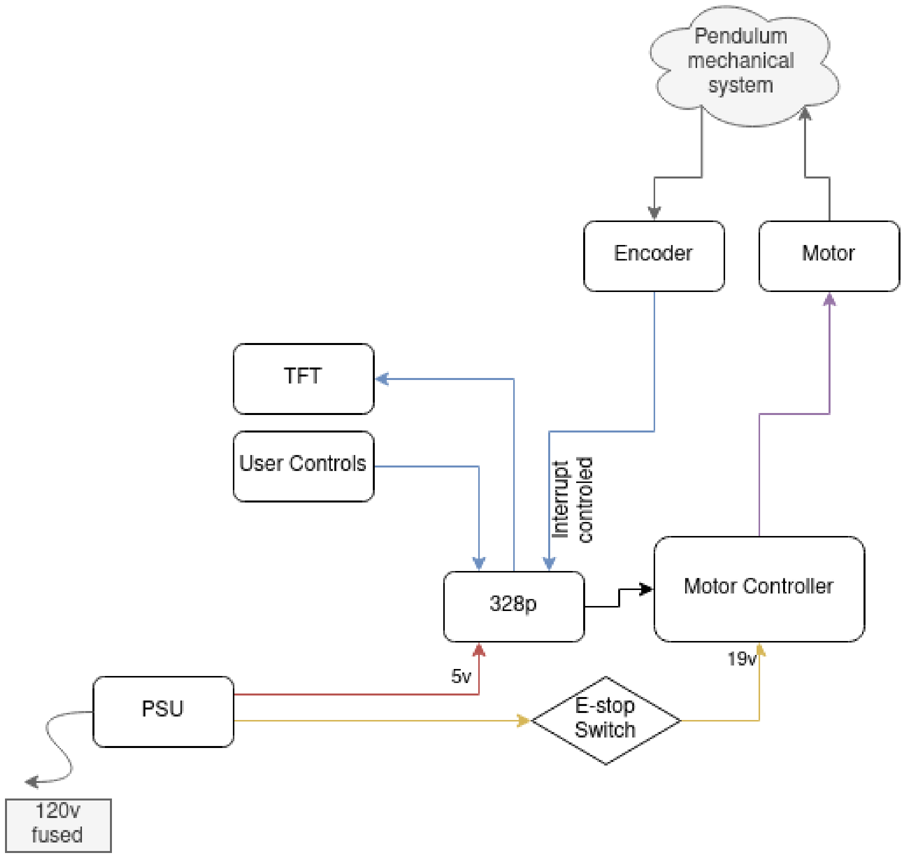


Figure 6.2.1

Software Flow Chart

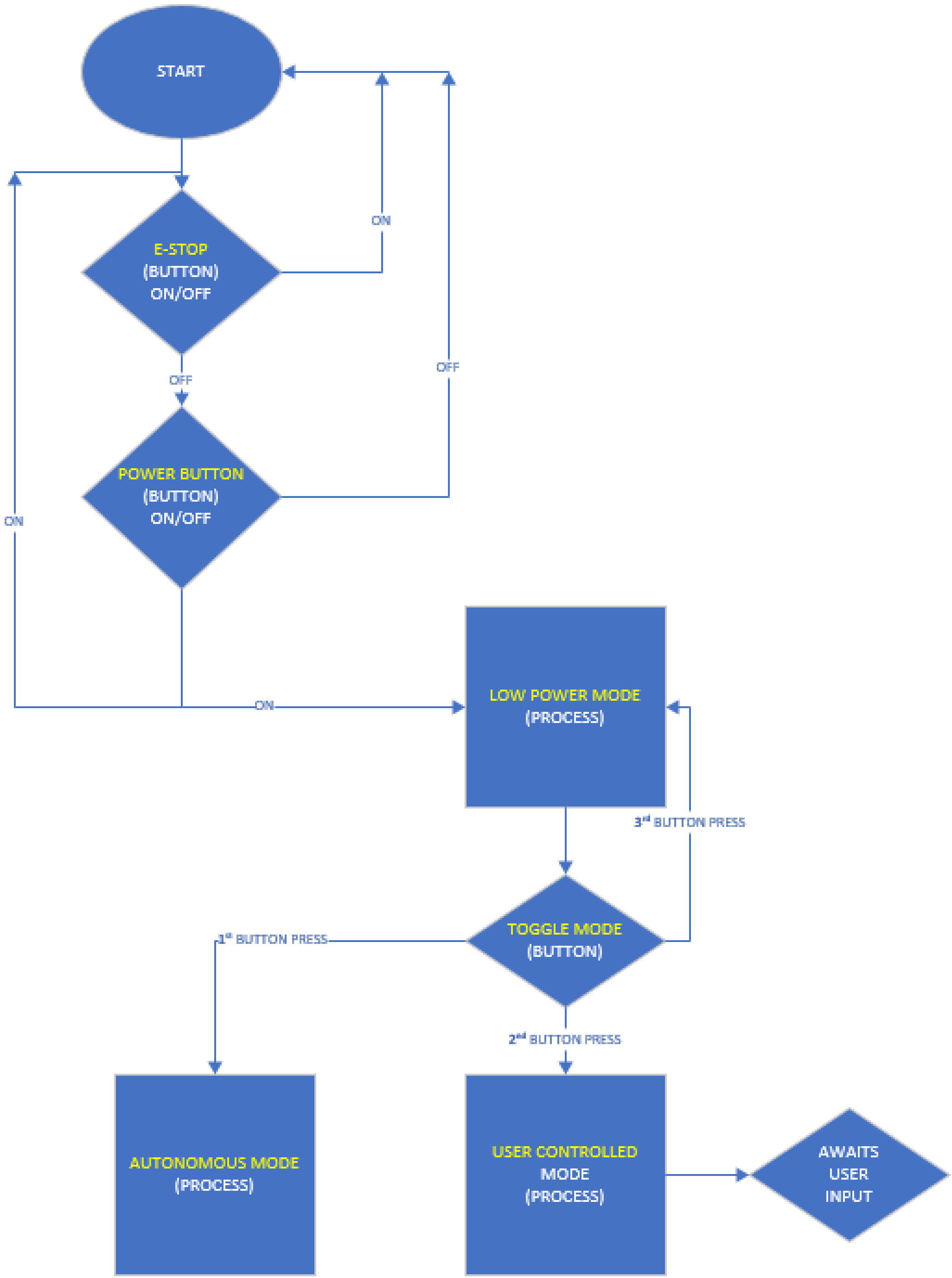


Figure 6.3.1

Health and Safety Design Features:

- Protective shielding around the pendulum’s range of motion to avoid pinch points and physical contact.
- Capacitive e-stop and manual e-stop in case of emergency.
- All electrical components are grounded to prevent dangerous discharge.
- All components shall be ventilated and fan cooled to regulate temperatures.
- Access to embedded components shall be easy to clean the machine and remove dust and debris.

Used Engineering Standards:

- EC TR 61923: IEC standards for instruments in household/indoor environments
- IEC 60745: IEC standard for power tools and similar motor controlled appliances
- IEC 60364-1: Rules for general design (fuses, proper grounding, insulation)

Task Plan

	Name	Duration	Start	Finish	Predecessors	Resource Names
	Start	0 days	1/3/22 8:00 AM	1/3/22 8:00 AM		
	⊟Proj Dev Plan (PDP)	39 days	**1/3/22 8:00 AM**	**2/24/22 5:00 PM**	**1**	
	Research	2 days	1/3/22 8:00 AM	1/4/22 5:00 PM	1	
	CDR report due	0 days	2/24/22 11:00 PM	2/24/22 5:00 PM	19;20;21	
	ConOps	5 days	1/5/22 8:00 AM	1/11/22 5:00 PM	3	
	Design concepts	2 days	1/3/22 8:00 AM	1/4/22 5:00 PM	3SS	
	Report writing	6 days	1/5/22 8:00 AM	1/12/22 5:00 PM	6	
	PDP Draft/SRR	0 days	1/21/22 8:00 AM	1/21/22 8:00 AM	7;5;22	
	PDP report	3 days	1/21/22 8:00 AM	1/25/22 5:00 PM	8	
	PDP Due	0 days	1/25/22 5:00 PM	1/25/22 5:00 PM	9	
	PDP Presentation	0 days	2/24/22 5:00 PM	2/24/22 5:00 PM	2	
	⊟Design	15 days	**1/3/22 8:00 AM**	**1/21/22 5:00 PM**		
	⊟Preliminary design	14 days	**1/3/22 8:00 AM**	**1/20/22 5:00 PM**		
	Mechanical	7 days	1/3/22 8:00 AM	1/11/22 5:00 PM		
	Electrical	5 days	1/3/22 8:00 AM	1/7/22 5:00 PM		
	Programming	14 days	1/3/22 8:00 AM	1/20/22 5:00 PM		
	Func Proto Build/Test	3 days	1/10/22 8:00 AM	1/12/22 5:00 PM	15	
	⊟Detailed design	8 days	**1/12/22 8:00 AM**	**1/21/22 5:00 PM**		
	Mechanical	5 days	1/12/22 8:00 AM	1/18/22 5:00 PM	14	
	Electrical	5 days	1/13/22 8:00 AM	1/19/22 5:00 PM	17	
	Programming	7 days	1/13/22 8:00 AM	1/21/22 5:00 PM	17	
	System Requirements	5 days	1/3/22 8:00 AM	1/7/22 5:00 PM		
	Critical Design Review	0 days	1/21/22 5:00 PM	1/21/22 5:00 PM	18	
	Spring Break	5 days	2/25/22 8:00 AM	3/3/22 5:00 PM	23;4	
	⊟Fabrication and Integrat	14 days	**3/4/22 8:00 AM**	**3/23/22 5:00 PM**	**24**	
	Build	7 days	3/4/22 8:00 AM	3/14/22 5:00 PM		
	Assembly	7 days	3/15/22 8:00 AM	3/23/22 5:00 PM	26	
	Functioning Prototype Milest	0 days	3/23/22 5:00 PM	3/23/22 5:00 PM	25	
	Test Readiness Review	0 days	3/23/22 5:00 PM	3/23/22 5:00 PM	28	
	⊟Testing	8 days	**3/23/22 5:00 PM**	**4/4/22 5:00 PM**	**28**	

	Name	Duration	Start	Finish	Predecessors	Resource Names
	⊟Testing	8 days	**3/23/22 5:00 PM**	**4/4/22 5:00 PM**	**28**	
	Testing plan	0 days	3/23/22 5:00 PM	3/23/22 5:00 PM		
	Subsystem testing	4 days	3/24/22 8:00 AM	3/29/22 5:00 PM	31	
	Integrated testing	4 days	3/30/22 8:00 AM	4/4/22 5:00 PM	32	
	⊟Final phase	10 days	**4/5/22 8:00 AM**	**4/18/22 5:00 PM**	**29;30**	
	Parts order	1 day	4/5/22 8:00 AM	4/5/22 5:00 PM	18	
	Final Report Draft	10 days	4/5/22 8:00 AM	4/18/22 5:00 PM		
	⊟Final Report Due	5 days	**4/19/22 8:00 AM**	**4/25/22 5:00 PM**	**34**	
	Final iteration	5 days	4/19/22 8:00 AM	4/25/22 5:00 PM		
	⊟Final presentations	5 days	**4/26/22 8:00 AM**	**5/2/22 5:00 PM**	**34**	
	Final demonstration	5 days	4/26/22 8:00 AM	5/2/22 5:00 PM	38	
	Finish	0 days	4/18/22 5:00 PM	4/18/22 5:00 PM	34	

Figure 7.1.1

Budget/BOM

Item	Qty	Reference(s)	Value	LibPart	Cost
1	1	A101	A4988	Driver_Motor:Pololu_Breakout_A4988	$1.99
2	1	C101	10uf	Device:C_Polarized	$0.00
3	2	C201, C202	100nf	Device:C_Small	$0.00
4	2	C203, C204	22pf	Device:C_Small	$0.00
5	1	C301	10uf	Device:C_Polarized_Small	$0.00
6	6	C302, C303, C401, C402, C403, C404	100nF	Device:C_Small	$0.00
7	1	C304	1uF	Device:C_Small	$0.00
8	1	D101	1.8TFT	KenwoodFox:1.8TFT	$2.30
9	1	D201	STAT	Device:LED	$0.00
10	1	D301	PWR	Device:LED	$0.00
11	1	D401	RX	Device:LED	$0.00
12	1	D402	TX	Device:LED	$0.00
13	6	H101, H102, H103, H104, H105, H106	PiMountingHole	Mechanical:MountingHole	$0.00
14	1	J101	MOTOR	Connector:Conn_01x04_Male	$0.00
15	1	J102	ENCODER	Connector:Conn_01x04_Male	$0.00
16	1	J201	ICSP	Connector_Generic:Conn_02x05_Odd_Even	$0.00
17	1	J301	19V Input	Connector:Barrel_Jack	$0.00
18	1	J401	USB_B_Micro	Connector:USB_B_Micro	$0.00
19	1	J402	PROG	Connector:Conn_01x06_Female	$0.00
20	1	JP101	SolderJumper_2_Bridged	Jumper:SolderJumper_2_Bridged	$0.00
21	1	JP201	RSTBridge	Jumper:SolderJumper_2_Bridged	$0.00
22	1	JP401	SolderJumper_2_Open	Jumper:SolderJumper_2_Open	$0.00
23	7	R201, R202, R203, R206, R301, R403, R404	1K	Device:R_Small	$0.00
24	3	R207, R208, R402	10K	Device:R_Small	$0.00
25	1	R401	4K7	Device:R_Small	$0.00
26	1	RV201	P_Pot	Device:R_Potentiometer	$0.00
27	1	RV202	I_Pot	Device:R_Potentiometer	$0.00
28	1	RV203	D_Pot	Device:R_Potentiometer	$0.00
29	1	SW201	RESET	Switch:SW_Push	$0.00
30	1	SW202	START_SW	Switch:SW_Push	$0.00
31	1	SW203	STOP/MODE_SW	Switch:SW_Push	$0.00
32	1	U201	ATmega328P	MCU_Microchip_ATmega:ATmega328P-A	$4.30
33	1	U301	NCV1117ST50T3G	Regulator_Linear:LM1117-5.0	$0.10
34	1	U401	FT232RL	Interface_USB:FT232RL	$0.05
35	1	Y201	16mHz	Device:Crystal	$0.00
36	?	N/A	10ft Tube Stock Steel	N/A	$100.00
37	?	N/A	Wood Paneling	N/A	$35.00
38	?	N/A	3D Printer Fillament	N/A	$10.00
39	?	N/A	Stepper Motor	N/A	$7.99
40	?	N/A	Bearings and Timing Belt	N/A	$20.00
41	?	N/A	Finishing Products	N/A	$15.00
42	?	N/A	Welding Gas and Consumables	N/A	$30.00
					$226.73

Figure 8.1.1

References

Figure (1.2.1) (n.d.). *Rotary Inverted Pendulum*. Quanser. Retrieved January 22, 2023, from https://www.quanser.com/wp-content/uploads/2017/03/ROTPEN-graphics.jpg

Figure (1.2.2) (n.d.). *Lego, Raspberry and Python Project - Reaction Wheel Inverted Pendulum*.

(2022, April 16). YouTube. Retrieved January 22, 2023, from

https://youtu.be/WObG2LoSEwQ

Appendixes:

Appendix A: Calculations / Model

```
# Model from here:
# https://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling


M = 0.5;   # Mass of cart
m = 0.02;   # Mass of pendulum (tip)
b = 0.1;    # Fricition
I = 0.016; # Pendulum moment
g = 9.8;
l = 0.3;
q = (M+m)*(I+m*l^2)-(m*l)^2;
s = tf('s');

P_cart = (((I+m*l^2)/q)*s^2 - (m*g*l/q))/(s^4 + (b*(I + m*l^2))*s^3/q - ((M + m)*m*g*l)*s^2/q - b*m*g*l*s/q);

P_pend = (m*l*s/q)/(s^3 + (b*(I + m*l^2))*s^2/q - ((M + m)*m*g*l)*s/q - b*m*g*l/q);

sys_tf = [P_cart ; P_pend];

inputs = {'u'};
outputs = {'x'; 'phi'};

set(sys_tf,'InputName',inputs)
set(sys_tf,'OutputName',outputs)

sys_tf

```

Figure 9.1.1

Appendix B: LibreOffice Schedule

		Name	Duration	Start	Finish	Predecessors	Resource Names
1		Start	0 days	1/3/22 8:00 AM	1/3/22 8:00 AM		
2		**Proj Dev Plan (PDP)**	**39 days**	**1/3/22 8:00 AM**	**2/24/22 5:00 PM**	**1**	
3		Research	2 days	1/3/22 8:00 AM	1/4/22 5:00 PM	1	
4		CDR report due	0 days	2/24/22 11:00 PM	2/24/22 5:00 PM	19;20;21	
5		ConOps	5 days	1/5/22 8:00 AM	1/11/22 5:00 PM	3	
6		Design concepts	2 days	1/3/22 8:00 AM	1/4/22 5:00 PM	3SS	
7		Report writing	6 days	1/5/22 8:00 AM	1/12/22 5:00 PM	6	
8		PDP Draft/SRR	0 days	1/21/22 8:00 AM	1/21/22 8:00 AM	7;5;22	
9		PDP report	3 days	1/21/22 8:00 AM	1/25/22 5:00 PM	8	
10		PDP Due	0 days	1/25/22 5:00 PM	1/25/22 5:00 PM	9	
11		PDP Presentation	0 days	2/24/22 5:00 PM	2/24/22 5:00 PM	2	
12		**Design**	**15 days**	**1/3/22 8:00 AM**	**1/21/22 5:00 PM**		
13		**Preliminary design**	**14 days**	**1/3/22 8:00 AM**	**1/20/22 5:00 PM**		
14		Mechanical	7 days	1/3/22 8:00 AM	1/11/22 5:00 PM		
15		Electrical	5 days	1/3/22 8:00 AM	1/7/22 5:00 PM		
16		Programming	14 days	1/3/22 8:00 AM	1/20/22 5:00 PM		
17		Func Proto Build/Test	3 days	1/10/22 8:00 AM	1/12/22 5:00 PM	15	
18		**Detailed design**	**8 days**	**1/12/22 8:00 AM**	**1/21/22 5:00 PM**		
19		Mechanical	5 days	1/12/22 8:00 AM	1/18/22 5:00 PM	14	
20		Electrical	5 days	1/13/22 8:00 AM	1/19/22 5:00 PM	17	
21		Programming	7 days	1/13/22 8:00 AM	1/21/22 5:00 PM	17	
22		System Requirements	5 days	1/3/22 8:00 AM	1/7/22 5:00 PM		
23		Critical Design Review	0 days	1/21/22 5:00 PM	1/21/22 5:00 PM	18	
24		Spring Break	5 days	2/25/22 8:00 AM	3/3/22 5:00 PM	23;4	
25		**Fabrication and Integr...**	**14 days**	**3/4/22 8:00 AM**	**3/23/22 5:00 PM**	**24**	
26		Build	7 days	3/4/22 8:00 AM	3/14/22 5:00 PM		
27		Assembly	7 days	3/15/22 8:00 AM	3/23/22 5:00 PM	26	
28		Functioning Prototype Mile...	0 days	3/23/22 5:00 PM	3/23/22 5:00 PM	25	
29		Test Readiness Review	0 days	3/23/22 5:00 PM	3/23/22 5:00 PM	28	

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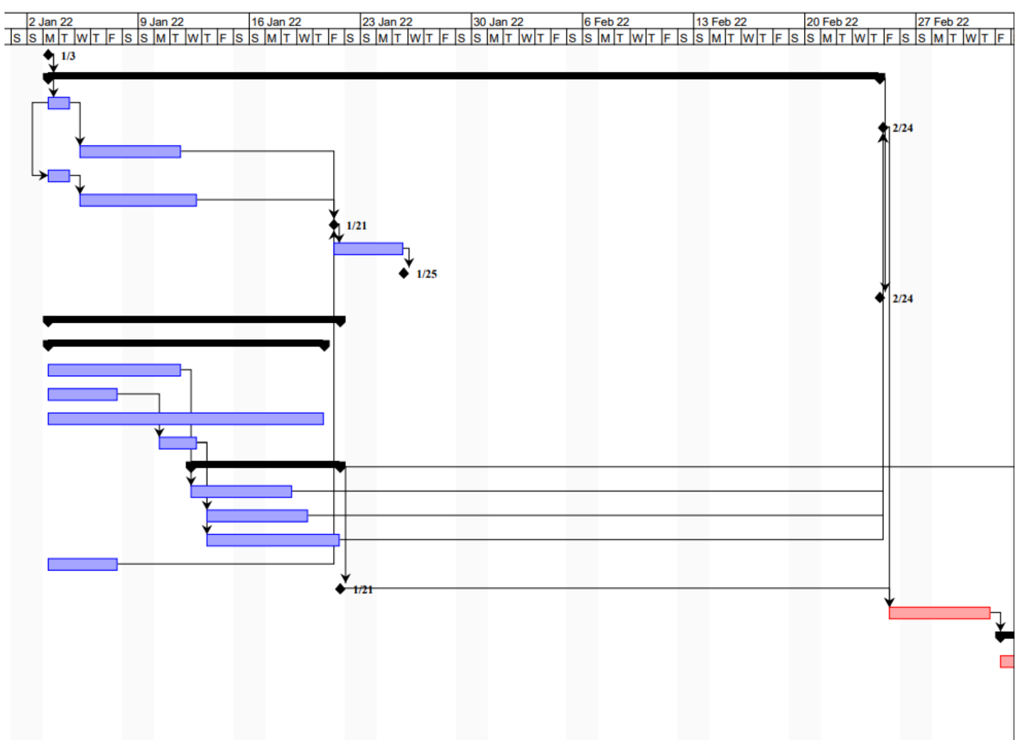

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