Pendulum 328

Inverted Pendulum PID Demonstrator

Critical Design Review (CDR)

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Concept of Operations Summary:

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.

Summary of Trade Studies:

All weights equal unless specified otherwise.	User Interaction Methods			
	Buttons Only	Buttons and LEDs	Buttons and TFT	Buttons, Buzzer, TFT
Demonstrates machine state effectively	--	-	*	+
Provides easy to use selection of mode	*	*	*	*
Provides meaningful feedback about PID Performance	--	*	*	+
Is an effective educational tool/in the spirit of the product	--	-	*	+

All weights equal unless specified otherwise.	Bearings		
	No Bearings	Dry Bearings	Ball Bearings
Conforms to minimum req' for **vibration**, **stiffness**, and **cost**.	--	+	*
Easily sourceable/ Requires lower maintenance	*	*	-
Operates silently	-	-	*
Requires little maintenance/ replacement	--	-	*

All weights equal unless specified otherwise.	Motor choice		
	DC Motor	Stepper Motor	Servo Motor
Low Noise	*	-	+

Ease of maintenance/ replacement	-	*	--
High Performance	--	-	+
Low cost	+	*	--

Requirements Compliance:

Functional:

Req ID or Section	Req. Title	Subject Statements	Req. Value	Performance	Margin	Notes / Basis
1.1	Low Power Mode	Provide low power mode in which all components are put into an idle state.	150 mA of current	50 mA of current	[10%]	
1.2	Autonomous Mode	Provide self-balancing autonomous mode.	30 minutes	Continuously	[15%]	
1.3	User-Control Mode	Provide user-control mode in which pendulum behavior is manipulated by variable resistors.	P Term is variable	P, I and D are variable	[N/A]	
1.4	Self-Tensioning	The system shall be self-tensioning.	Belt Always Taunt	[Comply / Does Not Comply]	[N/A]	
1.5	Mode Selection	System modes will be selectable by the user using a button.	Usage of Push Button	[Comply / Does Not Comply]	[N/A]	
1.6	User Control	The system shall have a display method capable of displaying the oscillations of the pendulum and the correction curve formed by the PID loop to the user.	Describe the error in the loop in a meaningful way.	Display the error in the loop as well as system state, score and PID values.	[5%]	
1.7	Capacitive E-stop	Provide a capacitive e-stop built into the circuit board.	E-Stop reacts when touched.	[Comply / Does Not Comply]	[N/A]	Sweaty skin vs. dry skin?

1.8	Manual E-stop	The system shall have a manual emergency stop.	E-Stop reacts when pressed.	[Comply / Does Not Comply]	[N/A]	
1.9	Warning Buzzer	The system shall have a buzzer to warn the user of the pendulum's harmonic oscillations into a ready state.	Buzzer functions on mode change.	[Comply / Does Not Comply]	[N/A]	
1.10	Fan for Power Supply	Provide an embedded fan for the power supply.	Fan is adequate for emitted heat.	Fan is more than adequate for emitted heat.	[10%]	
1.11	TFT Mode Display	The TFT screen shall display the system's current mode.	TFT displays current mode.	[Comply / Does Not Comply]	[N/A]	
1.12	TFT PID Constant Display	The TFT screen shall display the PID loops current Kp, Ki, and Kd values.	TFT displays constants	[Comply / Does Not Comply]	[N/A]	

Performance:

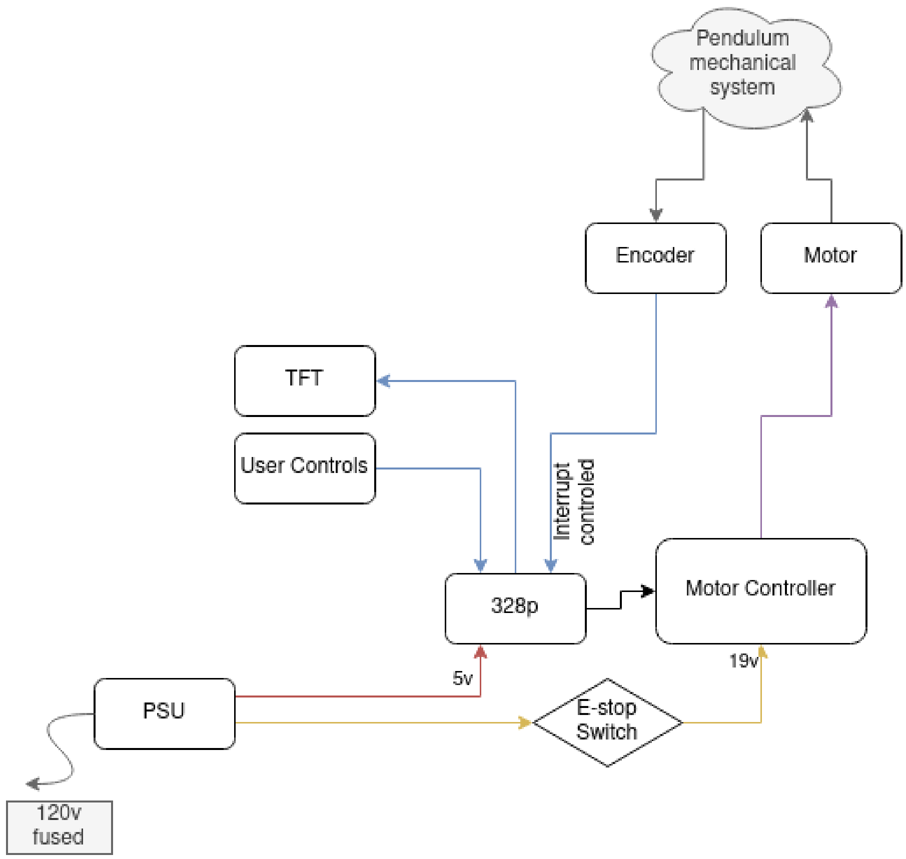
Req ID or Section	Req. Title	Subject Statements	Req. Value	Performance	Margi n	Notes / Basis
2.1	Power Required	Fully powered using a standard 120 V wall outlet.	120 V	[Comply / Does Not Comply]	[N/A]	
2.2	Spin-Up	The pendulum shall swing up into a start position in under 15 seconds.	20 s	15 s	[10%]	
2.3	Capacitive E-Stop	Capacitive estop shall cut current from the motor in under 200 ms	<= 200 ms	[Comply / Does Not Comply]	[N/A]	
2.4	Manual E-Stop	Upon the press of the estop, the system shall cut current from reaching the motor instantly	<= 30ms	<= 15 ms	[N/A]	
2.5	System Temp.	No component shall not exceed a temperature of 110 degrees Fahrenheit while in normal operation.	110 degrees F	90 degrees F	[20%]	

Interface, Design, Resource:

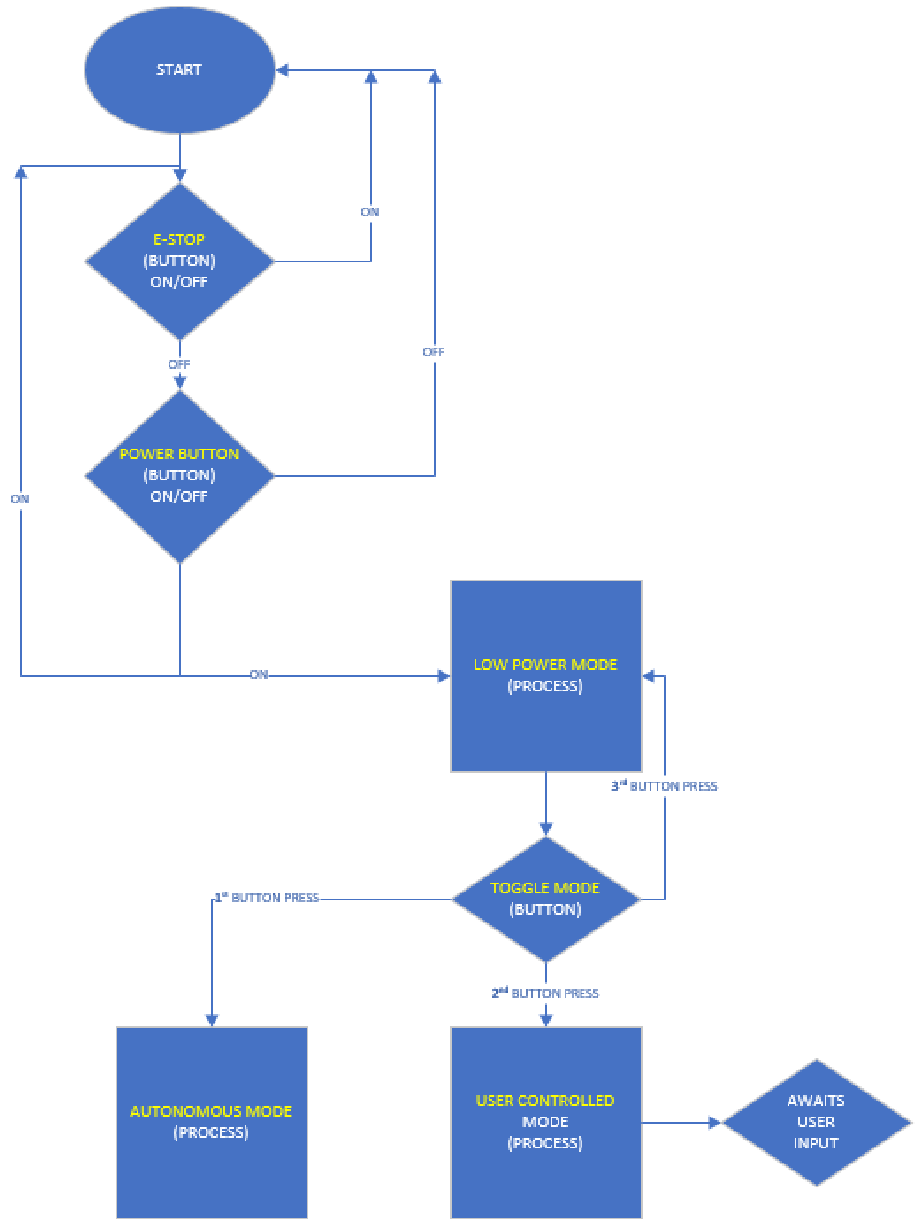
Req ID or Section	Req. Title	Subject Statements	Req. Value	Performance	Margin	Notes / Basis
3.1	Mass	The pendulum shall weigh between 8 to 13 grams	13 g	10 g	[10%]	
3.2	Span	The span of the linear track shall be no more than three feet long.	3 ft	2.5 ft	[N/A]	
3.3	Interface	The display screen shall have color to easily distinguish between the control loop, the current error in the system, and the target value for achieving balance.	Easily legible	[Comply / Does Not Comply]	[N/A]	
3.4	Weight	The system shall weigh no greater than 50 lbs with the removable legs attached.	50 lbf	40 lbf	[10%]	
3.5	Frame Material	The frame of the assembly shall be made with mild steel.	Mild Steel	[Comply / Does Not Comply]	[N/A]	
3.6	Design	All electrical components shall be grounded.	Grounded to meet Standards	[Comply / Does Not Comply]	[N/A]	
3.7	Length	The pendulum shall be no greater than 1.5 feet in length.	1.5 ft	1.4 ft	[N/A]	
3.8	Factor of Safety	All elements shall operate under their yield stresses and have a factor of safety of 1.5 or greater for embedded components.	1.5	[Comply / Does Not Comply]	[N/A]	
3.9	Design	All elements shall be under a fatigue strength that allows for a product lifetime of 20 years.	Appropriate σ	[Comply / Does Not Comply]	[N/A]	
3.10	Design	Wooden base shall have varnish applied.	Apply varnish	[Comply / Does Not Comply]	[N/A]	
3.11	Design	All fasteners shall be secured from vibration.	Apply loctite	[Comply / Does Not Comply]	[N/A]	

System Design and Properties:

System Functional Block Diagram:



System Operational Flowchart:



Subsystem Definition:

Subsystem Design Details:

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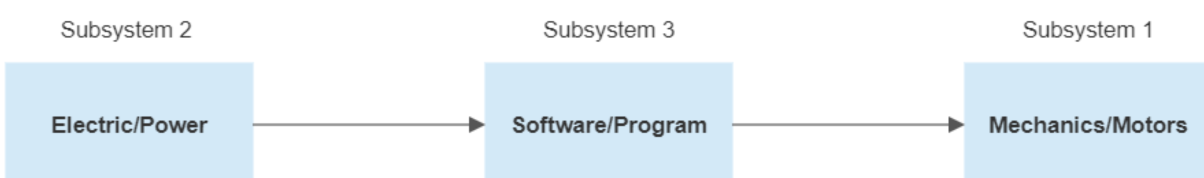
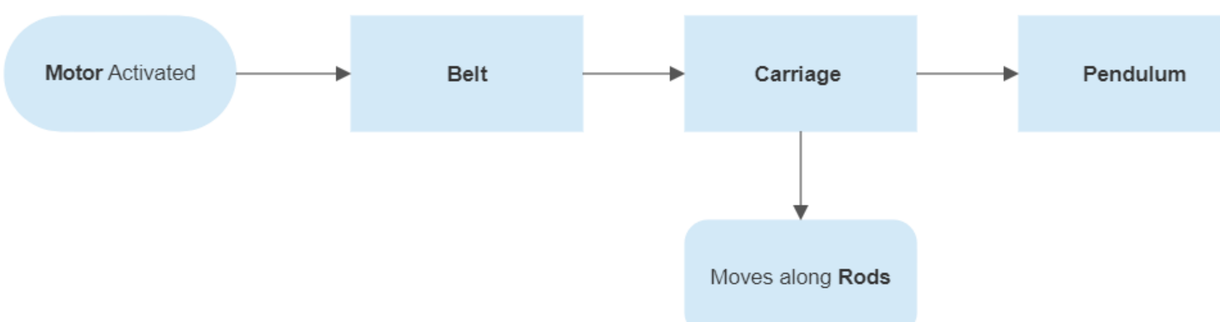
Our product consists of one main system that can be further expanded into three subsystems. The three subsystems are mechanical, electrical, and software. These subsystems are dependent on one another. In order for our system to successfully operate all subsystems must successfully communicate with one another. In the following sections we will describe each subsystem such as its functions, diagrams, etc.

Pendulum Subsystems Flowchart



Subsystem 1 or Mechanical

Our mechanical subsystem consists of the physical parts in our product such as rods, motors, pendulum, etc. Below is a basic overview of how the mechanical subsystem operates. :



1. **Motor**
    a. The motor is turned and is connected to the belt in which it can either accelerate or decelerate.
2. **Belt**
    a. Allows for the Movement of the carriage to allow for the PID loop to balance the pendulum
3. **Carriage**
    a. Connects to the belt, linear rails, and pendulum. Provides the ability to use the belt and motor to balance the pendulum.
4. **Pendulum**
    a. Rod attached to the carriage. Allows for movement in two directions along the same directions of the linear rails the carriage is attached to for the PID loop to balance it.

The software/program subsystem is what is used to activate the motor. The software subsystem is further described in the following sections

Subsystem 2 or Electrical

Our electrical subsystem consists of wires, outlets, switches, and all other electrical components in our product.

Subsystem 3 or Software

The software subsystem is how the electrical subsystem communicates to the mechanical subsystem. It consists of all the code we will be implementing in our product. The way the software subsystem operates is it is able to take data based on which switches are activated and can control the motor speed and mode accordingly. The software can be further broken down into three modes, described below. The modes are controlled by a button.

- Low Power Mode
    - This mode is the default mode when the system is first turned on.
    - Designed to draw little power while the system is not physically moving

- Autonomous Mode
- User Controlled Mode

Describe what design features consider, contribute, impact or affected by

Public health, safety, and welfare

One concern for public health in our design is the swinging pendulum itself which can hit and hurt someone if not used properly or tamper with the safety mechanisms in place on the system. The safety mechanism in place is a hard stop button if the system malfunctions. It serves to stop the system cold as well as a mechanism to detect if the pendulum hits something such that it will stop the system as well. In addition to those we plan to implement a screen between the user and the swinging pendulum. Another concern is the electronics inside overheating and causing fire. This is presented by the operation conditions to be placed in a lab room. To combat this the system has very low voltage running it such that overheating causing damage or fire is unlikely even with constant use.

Global, cultural, social, environmental, and economic factors

Since the system does use electricity, depending where that power comes from it contributes to the cost of fossil fuels or other environmental power hazards potentially if left constantly on. It is to note however this system draws very little electricity compared to other things in the building it is placed in but nonetheless does draw power. When the system is scrapped, if not ethically recycled can cause environmental hazards such as releasing toxic chemicals including lead, mercury, cadmium, and chromium where heavy metals like those can do a great deal of harm.

Summary of Prototype Activities:

Prototype Mainboard

Mainboard requires several important features:

- E-Stop
- Button Inputs
- Potentiometers
- Encoder
- Motor output
- Limit Switch
- TFT Screen

The prototype board implements all these features as well as…

- USB Programming/debugging
- Status lights
- Mode and start select buttons
- Onboard VRM

Prototype Activity #	**Prototype Activity Description**	**Data Gathered**	**Performed By**
1	USB Debugging	Usb debugging and auto-reset works on the devboard	Joe is the best
2	Encoder Limit Detection	Both chosen interrupts trigger on the rising edge without issue on the devboard	Joe
3	TFT Screen	TBD	Joe
4	Buttons and debouncing	Button debouncing works in software and hardware on the devboard	Joe

Prototype Bearings

See Summary of Trade Studies for specific details and weights.

Each bearing is tested and evaluated with the above chart, with specific attention to:

- Cost of bearing (4 needed for every pendulum)
- Noise (Minimize sliding grinding noises)
- Performance (How well does it slide and protect the carriage shafts)
- Longevity (How long does it last without service or lube?)

Prototype Activity #	Prototype Activity Description	Data Gathered	Performed By
1	Characterize relative sound levels under operation and gauge their change over time.		
2	Evaulate heat, overall slop, noise and other performance metrics (defined above)		
3	Weight		

Summary of Analyses: (Feasibility Tests)

Bearings

Results from experimentation with different 8mm bearings.

Board Design

Results from preliminary board design

Calibration Plan:

Phase-D Readiness (Go Over Data Package List):

Ethical and Professional Responsibilities:

Honesty and integrity are two paramount traits in the engineering profession. Without good intentions and truthfulness we would not have reliable trustworthy products. In our design, we have different mechanical parts that are moving and rotating while the system is operating. We have an ethical and professional responsibility to ensure that nobody using our product is prone to injury. We are also accountable for any damage caused by our product. Our pendulum design will not be released to the public for demonstration until we can fully trust and rely on our system to operate without risking the health of others. Another ethical responsibility that is related to safety is to only work in areas of understanding or competence. Working in areas with little understanding is not efficient as well as not safe. It is a responsibility of our team to educate and familiarize ourselves with the topic we have chosen to ensure that we are performing efficiently and safely.

References:

https://www.nspe.org/resources/ethics/code-ethics

Appendix: