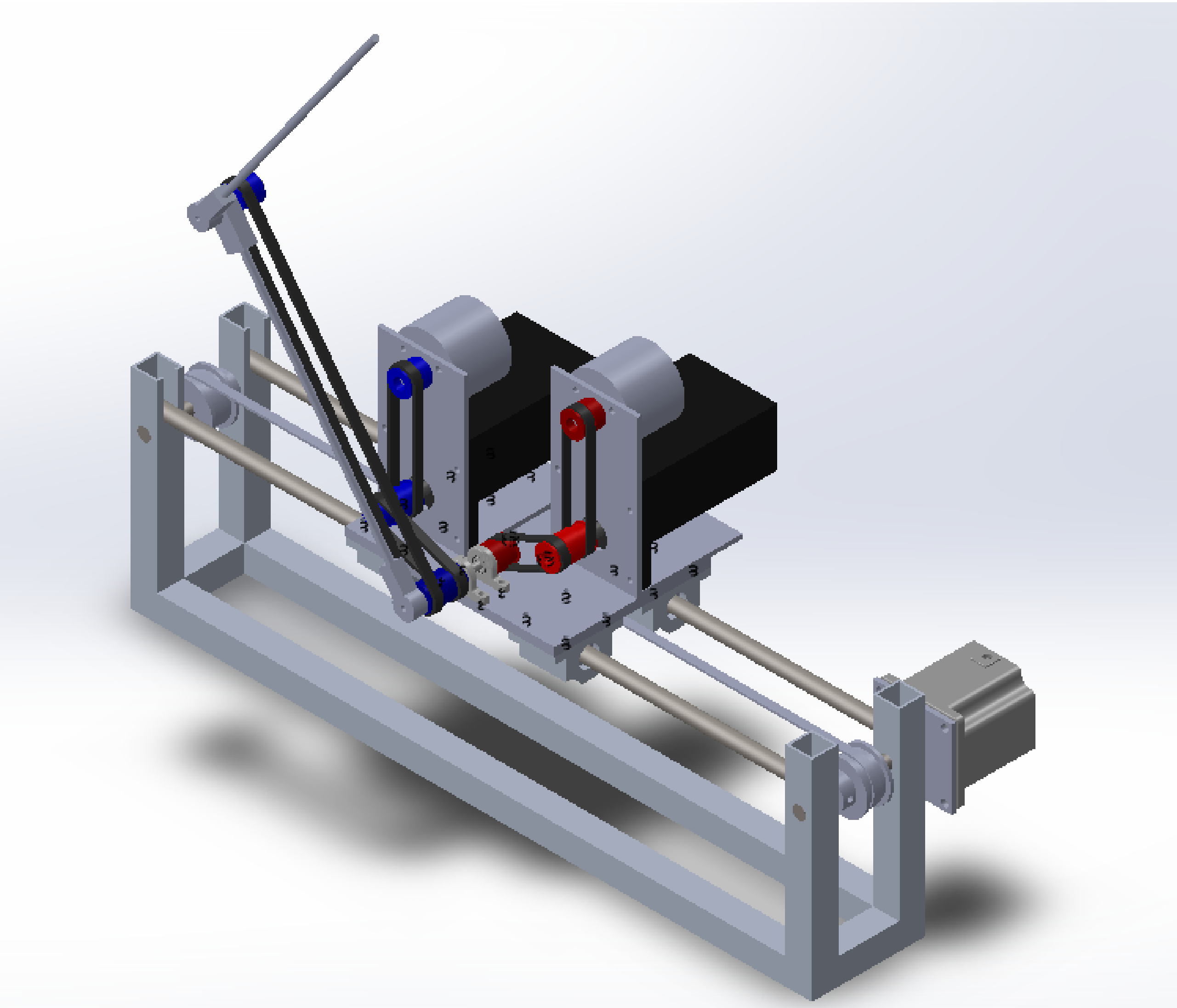
Preliminary Design Report

A Double-Pendulum Robotic Platform to Understand Human Balance



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Abstract:
The purpose of this report is to present the preliminary design of an actuated double-pendulum robot to be used for researching human balance and teaching high school students. An analysis on the design shows the feasibility of double pendulum robot capable of being accelerated $9.8m/s^2$, with the ability to apply $2-5Nm$ torques at each joint. Based on the current design and bill of materials the total projected cost of the system is $870 which includes all mechanical and electrical components of the project.

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1 INTRODUCTION

1.1 PROJECT MOTIVATION

Professor Kong is a mechatronics professor at U.C. Davis who teaches UC Davis's high school COSMOS program participants how control systems work. The current demonstration that he uses is a single pendulum simulation programmed in Matlab. Students change different parameters within the program to generate different pendulum reactions with respect to the parameters. Professor Kong would like to take this to the next level by showing a physical control system working in the real world. He needs a compact and easy to setup demonstration device that can be used to teach his students how control systems work. He would like the students to be able to directly interact with the model by taking the resulting parameters from the simulation and testing it on the physical model.

Dr. Moore is a mechanical engineering lecturer and researcher at UC Davis. Dr. Moore is researching controllers in humans and answering whether there is a governing control equation that humans follow. He would like to test control equations that researchers have found from various studies like *Postural feedback responses scale with biomechanical constraints in human standing* (Park 2004). Park simplified the human model by excluding the knee joint, only observing the torques at the ankle and hip joints, shown in Figure 16 in Appendix H. Dr. Moore would like to test this data on a double pendulum robot to determine its validity.

1.2 NEEDS AND SPECIFICATIONS

Starting with Professor Kong's needs, the double pendulum robot needs to be able to demonstrate a control system. The pendulum should also take parameters acquired from Matlab simulations for usage. It needs to be portable moving from a storage to the front of a classroom. It needs to be large enough that it is visible even to students in the back of the class. It also needs to be able to operate safely, so no student or researcher has a chance of getting injured.

Dr. Moore's primary target is the ability to conduct his research which consists of having an easily robust mechanical system, having an easy method of uploading various control algorithms, being able to run multiple trials repeatedly in a timely fashion, and being able to record and gather substantial data from each run. The robot must be able to have similar dynamic characteristics.

To sum up the two sponsors' needs, Prof. Kong requires a simple demonstration device while Dr. Moore requires flexibility. The double pendulum robot should be a small size, roughly contained within a 3x3x3 ft box to ensure portability. However, it should be large enough to be easily visible, thus the pendulum arms should be approximately 1 ft in length each. On the software side, there should be a simple and attractive interactive Graphical User Interface (GUI) to appeal to students and make them want to use the program to learn about control systems. The pendulum controller should contain a pre-determined control system that functions with the gains being the parameters that can be changed, ensuring the control system will work properly. Returning to the hardware side, the robot will require a method of changing its weight distribution to match a human's distribution. The motors of the robot will need to be able to hold a 1.5 feet tall double pendulum in place when an acceleration similar to a bus' acceleration - approximately 0.7 m/s^2 - acts on the pendulum. There also needs to be a motor that can drive the robot with a bus' acceleration. Each of the robot arms' joints and the motor to drive the robot needs to have sensors that will relay important information, such as the torque applied, back to the user. Finally, the software of the double pendulum robot becomes more complex as it needs to be a more complex GUI, which allows for a user to easily enter a new control algorithm, setup a new trial, and run the trial quickly. The controller will also be required to run multiple feedback systems as well as convert angular data from rotary encoders into torque data. A complete list of needs and specifications can be found in Appendix B Table 4 5.

1.3 MISSION STATEMENT

Inverted double pendulums are often used to teach control systems however these units typically balance by a moving cart rather than applied torques at the pivot points. The goal of this project is to create a double pendulum robotic platform that be perturbed by a specified motion and react by applying specific moments at the pendulum pivots according to the implemented control system. These controllers should be easy to change so researchers can run various tests.

A system physically capable of doing this, with limited modifications, will also be able to demonstrate control system to high school students. A robot with the functionality will have fair market interest amongst researchers trying to understand human balance and teachers that require a simple device for demonstrations. The robot is designed under the assumptions that it is a stand-alone product - meaning it does not require users to buy any other product besides the robot to operate - it is capable of interfacing with a computer, and it is safe to operate.

This problem has been broken down into several sub-problems. The first is a platform that can perturb the robot in a defined and repeatable manner. Second is an actuated double pendulum robot that can apply torques at each joint to simulate a human using their muscles located in the hip and ankle. This same pendulum being actuated upon must freely rotate when the motors are not engaged. Lastly, a system of electronic components that can interface with a controller and carry out the appropriate control equation reactions while recording data for users.

2 CONCEPT DESCRIPTION

An overall concept design has been finalized in order to solve the problem of learning human balance by testing control algorithms and the problem of demonstrating a control system to a high school class. This section is split up into four sections, the three main subsystems, perturbation unit, double pendulum robot arm, and electronics, with a final section on the interaction of the various subsystems. The factors that were considered in choosing the concepts includes cost, ease of manufacturing, feasibility, and simplicity. The overall concept is desired to be low cost, easy to disassemble and reassemble, works properly for a long period of time, and easy to understand and use. The details of these criteria are detailed in the Appendix.

2.1 PERTURBATION UNIT

The perturbation unit consists of a frame to support electronics and hold the overall structure, a platform to hold the pendulum arm, and pulley and drive belt system. The frame's dimensions are 82.5 mm x 495.3 mm x 152.4 mm. These dimensions were chosen to minimize the footprint of the robot, lower costs, increase portability, and provide a large enough structure that is easy to see from afar. The frame is constructed out of square aluminum tubes with an outer edge length of 19 mm and a thickness of 1.5875 mm. The linear rails are hardened precision shafts with a diameter of 10 mm. They are fitted into holes on the frames during assembly to lock them in place and minimize vibrations during runs. The entire of the weight from the cart and the pendulum will be supported by these two linear rails. The platform is 152.4 mm x 114.3 mm

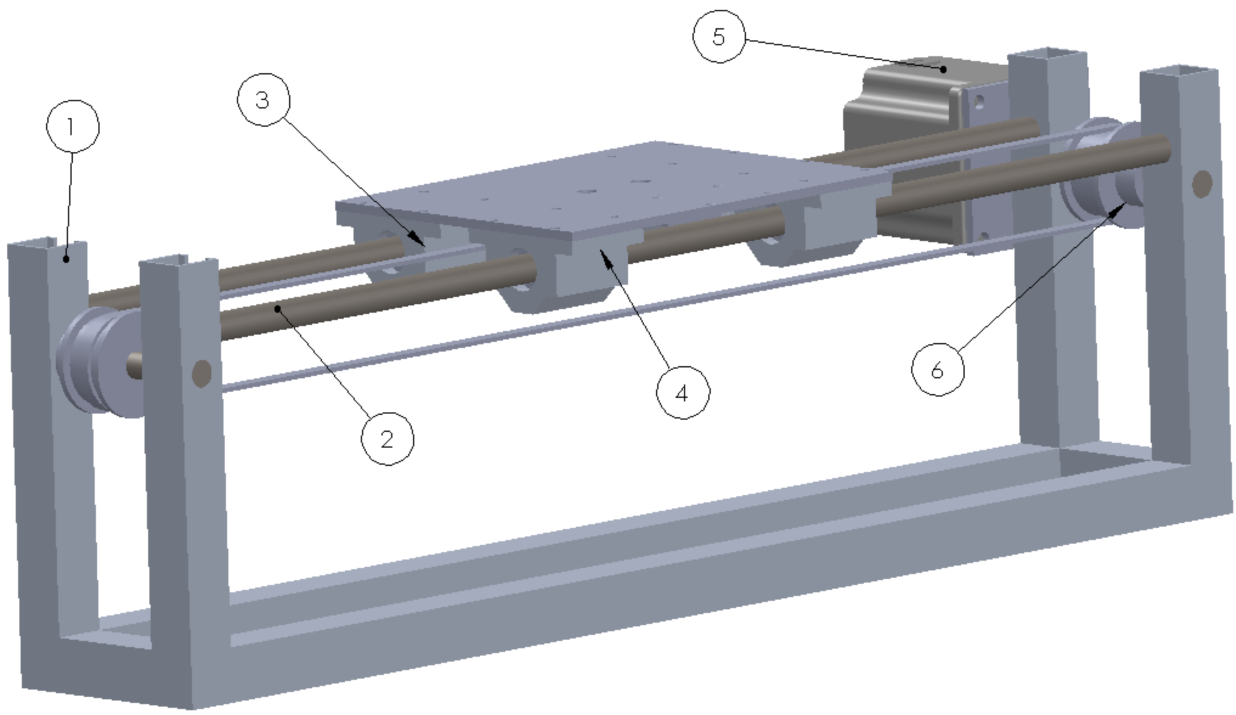

FIGURE 1: PERTUBATION UNIT: (1) ALUMINUM FRAME (2) LINEAR ROD (3) GT2 TIMING BELT (4) LINEAR BEARING (5) STEPPER MOTOR (6) GT2 PULLEY

with a thickness of 6.35 mm and is made out of 6061 aluminum. There are four ball bearing attached to the platform that minimize the friction on the linear rails. There are a set of end plates to lock the belt tightly to the platform allowing it to transfer its linear momentum to the platform. The belt end plates have grooves cut using a laser that matches the pitch of the belt.

A pair of pulleys with an approximate diameter of 30 mm will be used to transfer the motion from a motor to the drive belt. The pulley attached on the motor shaft will be fixed using a setscrew to the shaft. The other pulley is an idler meant to guide the belt and maintain tension. The selected belt to drive the cart is the GT2 timing belt, which has seen application in precision 3D printers and CNC machines. It is 6 mm wide, 1.5 mm thick with a pitch diameter of 2 mm. This is enough to ensure the cart will be supplied with a maximum linear acceleration of $1m/s^2$. Because the weight of the cart is supported mostly by the linear rails and the distance from pulley to pulley is not too long, the belt does not sag significantly enough to affect the motion of the cart. Finally, the belt is driven by a NEMA 23 rated with a maximum rpm of 600 and continuous operating torque of 120 mN-m.

2.2 DOUBLE PENDULUM ROBOT ARM

The actuated double pendulum robot arm is the key component that will determine the success of failure of the project and is the most complex electro-mechanical system in the entire project. After many long hours of research, simulation, and thought experiments a preliminary design has been decided on. In addition, significant improvements and changes have been made to the design as a result of the design review that occurred on February 30th 2017.

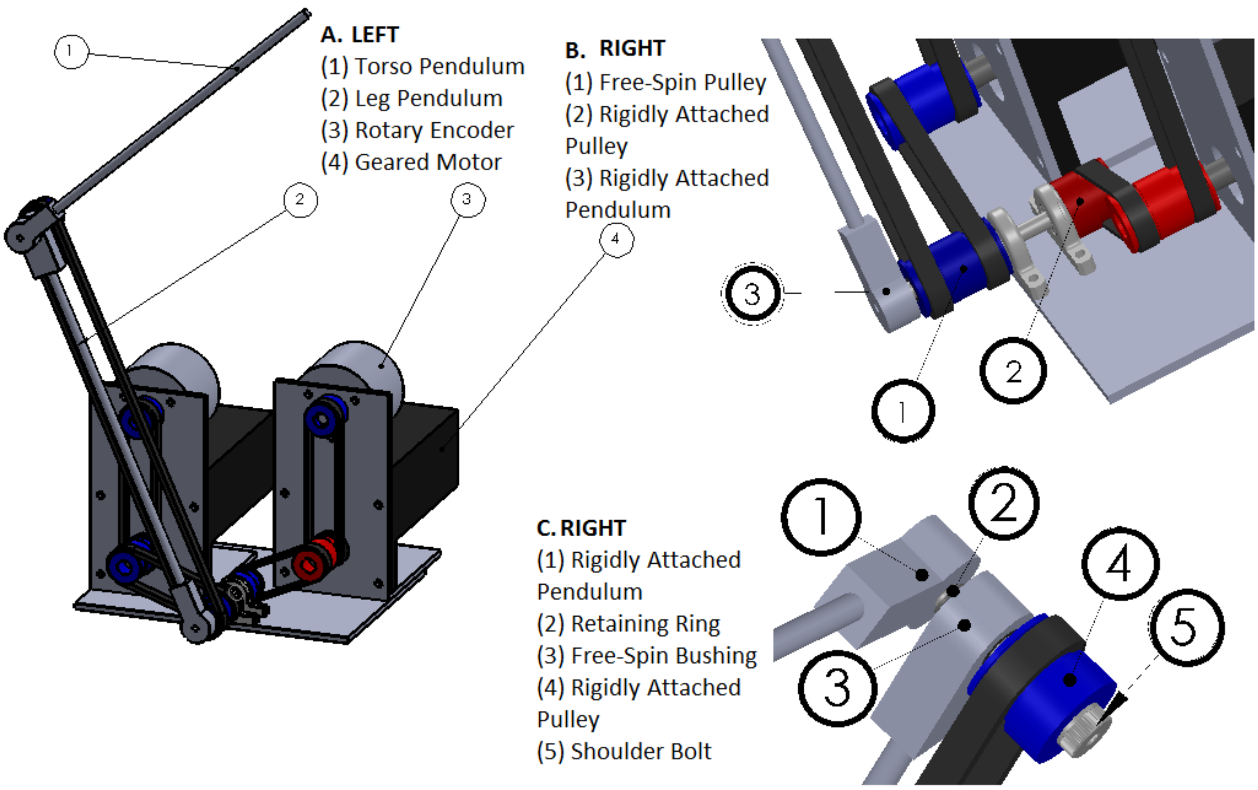

FIGURE 2: KEY COMPONENTS OF THE ACTUATED DOUBLE-PENDULUM ROBOT ARM.

2.3 ACTUATION

The overall design Figure 2 A shows the basic structure of the robot. The robot pendulums are made by two rods. There are two geared motors that are used for the actuation of the pendulum arms. The analysis and sizing of motors is discussed in detail in the A pulley transmission is used to apply the torques from the motors at their designated pivot points. In addition, there are two rotary encoders that will track the position of the arm during tests each of these are coupled to their respective motors by a pulley.

2.4 PULLEY TRANSMISSION SYSTEM

The pulley system is color coded, red pulleys are pulleys that are controlling the leg pendulum and blue pulleys indicate that they are controlling the torso arm. Figure 2B and 2C details the transmission from the motors. Starting from the bottom the pulley labeled 1 in Figure 2B has bearings inside to prevent interaction with the shoulder bolt shaft while sharing the same radial axis. This design allows the belt connecting the torso pendulum to its motor to have a constant distance regardless of the path of the leg pendulum. The pulley labeled 2 is rigidly attached to the shoulder bolt shaft effectively couping the leg pendulum to its motor. All pulleys use set screws to rigidly attach them to their respective shafts allowing quick removal and changing of gear ratios if needed.

2.5 SINGLE PENDULUM SIMPLIFICATION

A double pendulum is too complex for high school student to actively engage with. The current design allows for the pendulum to be simplified in two ways. The easiest is by unscrewing the top pendulum from the arm. The second solution is a software solution where a predetermined controller can be used to control the bottom pendulum with the high school students only controlling the parameters for the top pendulum.

2.6 ELECTRONICS

The electronics subsystem consists of the power supplies and controls for the robot. This system is by far the most expensive but most important. For safety reasons DC converted from standard 110VAC is going to be used. A single dual-channel 10A PWM motor driver board will be used to control the voltage to control the torque. The perturbation unit will use a stepper motor connected to stepper motor driver to command specific positional changes.

The Beaglebone Green, an embedded Linux device, was selected as the controller because of its embedded Linux environment and PRUs (Programmable Realtime Units) that will be used to insure system reliability. The embedded Linux environment enables faster transferring of data and a local storage system. The current design is to use the Beaglebone Black with a lightweight server so that computers can easily interface with the machine. All tests would run through the PRU's and have safety conditions that could stop the system in the event of a timeout or disconnect. The Beaglebone will have all inputs and outputs directly connected to its general input and output connectors.

2.6.1 CONTROL SYSTEM IMPLEMENTATION

Accurate control of the robot's accelerations and torques are extremely important for research purposes. Dr. Moore is designing a controller that can be used to accurately translate give inputs into real outputs. This will then be used in conjunction with the Beaglebone to get the robot to follow the requested dynamics parameters.

2.6.2 USER INTERFACE

The User Interface (UI) is an important aspect that will make the double-pendulum robot a versatile machine. The UI is simply an interface that can be as complex or simple as it needs to be. Two UI designs will be created, one for students and one for researchers. The only feature researchers need is a way to program their control system and collect the data results of the test which can be as simple as a console interface. To make things easier a GUI will additionally be created for researchers with additional tools to help run tests. The most important user interface is the one for students since this is how the students will interact with their robot. The GUI will need to be simple and engaging. It will consist of a few parameters the students can change and a button to save the experiment data.

2.7 COMPOUND SYSTEM

An image of the mechanical sub assemblies is shown on the cover. The new pendulum design allows the entire pendulum to swing down to the ground without interference from the base. This modification was made for two reasons. The first was to prevent impact forces from a falling pendulum damaging the pendulum or any part of the system. The second reason is that a swing up demonstration for high school students could be used to engage high school students. Appendix F has several images of the various sub components and assembly.

3 SIZING, ANALYSIS, AND JUSTIFICATION

The following provides the data that supports many of the sizing and design decisions. Many methods were used to determine appropriate sizing including statics analysis, simulation and experiments. Due to the various interactions of the subsystems the design process was iterative and these analyses only validate the concepts that are currently being implemented.

3.1 STATICS ANALYSIS

A number of statics analyses were completed on critical components on load bearing elements within the subsystems. Summarizing the results no yielding will occur under static conditions with large factors of safety.

TABLE 1: SUMMARIZED RESULT OF STATICS ANALYSES

Component	F_s	δ_y
Lower Pendulum Shoulder Bolt Shaft	6.4	-
Linear Guide Rail	32.6	-0.0015
Structural Frame	400	-

The detailed analyses can be found in Appendix G.

3.2 TIMING BELTS ANALYSIS

One of the concerns that was brought up during the design review was the deflection of the belts for the cart. An analysis was done on the belts for an acceleration of 9.81 m/s^2 of the 4.5kg cart, which would create a tension of 41N. The manufacturer, SDP/SI, recommends a maximum working tension of 111N which is significantly larger than the force generated from the max acceleration that is specified for the system.

3.3 SCALING PARAMETERS

The initial design was to create a 1:3 scale model of a human. This proved to be difficult because of the weight of the model. The scaling factors were derived in Appendix I equation 1 and 2 show that a small decrease in the length dimension greatly reduce the mass/inertial properties. A scale of 1:4 was chosen as a reasonable size with a total mass of about 1.25 kg.

3.4 MOTOR SIZING ANALYSIS

The biggest challenge for this project has been appropriately specifying motors for the double pendulum arm. The main reason is that the arms must be able to be perturbed and not remain static when perturbations are applied. The team must find the motor with the minimum resistance when not powered. Two methods have been studied yielding two different motor requirements the team has worked to resolve this issue by using easily interchangeable pulleys that can provide different gear ratios.

3.4.1 TORQUE SCALING USING BIO-MECHANICAL DATA

The first method for determining the appropriate motor torques and powers uses the relations found in Appendix I. Relation 4 shows that given any torque value the dominating factor is the static torque. An overestimate can be made when scaling if the torque that is being scaled is assumed to be completely static Equation 5. Using this relation torque values were obtained from the paper (Anderson 2007) paper on voluntary joint torques. The maximum of flexion and extension were taken and divided by the factor. This value then must be multiplied by two because humans have two legs and this data only measures one. Powers were additionally calculated using the maximum angular speed regardless of the plots $P_{max} = T_{max} * \omega_{max}$ again this would result in an overestimate. The results from scaling 1:3 and 1:4 are in Appendix J. This data can then be used to determine that a motor with a 2Nm torque and at least 6W of Power will be sufficient for both joints. The motors in the Bill of Materials in Appendix L reflect these design choices with 17W 2Nm motors.

3.4.2 DOUBLE PENDULUM PYTHON SIMULATION

A second approach was taken using a python script derived from the (Park 2004) paper on postural responses of standing humans.Scaling is not fully understood in terms of torques and gains which has impeded progress. Current progress in the simulation has given viable values in the power and torques, which can be used to select motors tentatively, even if the selections are subject to change in the further study. The assumption in the current simulation is that if unscaled model and scaled system exhibit similar motions under the same input, two systems are equivalent. Thus, torques and power values produced in the scaled model can be reference values in selecting motors.

A simple experiment was conducted to understand the acceleration and frequencies in the human perturbation. The result was in Figure 17 in Appendix H. From the result, it can be seen that the maximum acceleration is about 1 g, and the maximum frequency is approximately 25 rad/s. So, it is assumed that perturbation frequency ranges from 1 rad/s to 25 rad/s and a small frequency corresponds to a larger displacement. Then, a sum of sine wave, which resembles a general input to the system, is constructed. The scaling factor in dimensions and weights chosen currently is a quarter, and the total mass of double pendulum is 1.25 kg. The controller of the original model is therefore adjusted to produce the similar motion in terms of angle displacements and angular velocities. Through trial and error, the optimal scaling factor for numerical gains of the original model is 80, and comparison plots between scaled and unscaled model are shown in 18, 19, 20 and 21 in Appendix H.

The plots of motion, torques and powers for the scaled model under the sum of sine inputs are then generated. They can be found in Figure 22, 23, and 24 in Appendix H. It can be seen that powers required at two joints are not large. However, the torques, which should be the top priority in the motor selection, are. The maximum torque for ankle joint and hip joint are 3 N*M and 0.5 N*m respectively.

Besides the motors at two joints, another motor is also needed to drive the system (cart and double pendulum) over the platform. Since the linear bearing will not produce large friction, the friction coefficient is assumed to 0.25. The input is applied to systems with different total masses, and with a specific total mass of the system, the plot of the power can be the reference value in select that motor. In this case, the mass of cart is close to 1 kg, which requires roughly

5 W power alone.

To account for factors that have not been considered in the simulation, higher values of torques and power are expected in the motor selection. The criterion for each motor is shown in Table 27 in Appendix H.

	Ankle Torque	Hip Torque	Whole System
Digi-Key Part Number	966-1727-ND	966-1721-ND	966-1684-ND
Vendor	Crouzet	Crouzet	Crouzet
Price ($)	153.16	84.79	74.88
Torque (N*m)	5	2	0.05
Power (W)	33	17	15

TABLE 2: MOTOR SELECTION

4 LOGISTICS

4.1 PLANNING

This plan details tasks, milestones, duration, due dates and assignees of our project to finish by the Senior Design Showcase. A Gantt chart is provided in Appendix K. Many of the major tasks during this quarter can be done in parrallel. In order to maximize throughput, Stanley and Ruoxi will form a team to construct the robot and Kendall and Chen will form another team to program the robot.

4.1.1 CONSTRUCTION OF ROBOT

The construction part can be divided into 5 steps: the CAD drawings, cart and pendulum construction, frame constructions, assembly, and electronics and circuitry. All detailed drawings will be created based on our model, so that machining and construction can begin. 11 days have been allocated ending on April 7th for the drawings. After that, one month is given to actual construction, which includes component manufacturing, prototyping, cart and pendulum assembly, frame assembly, electronics setup. This session consists of many manufacturing processes, such as cutting, facing, milling, threading, tapping, dying and welding, therefore more time is allocated for construction. This is completed, ideally, by May 5th so testing can proceed shortly afterwards.

4.1.2 PROGRAMMING

Programming will start simultaneously with the construction. There are 4 sub tasks in this assignment: control diagram creating, motor software developing, user interface establishing, and data recording. Control diagram will be created as a guide for the feedback, user interfacing, and data recording. This task is given a week and needs to be done on April 8. After that, all other programming parts are able to start. The motor software developing is assigned to

Kendall; meanwhile, the user interface establishing and data recording tasks are assigned to Chen. These should finish at the same time as construction, on May 5th.

4.1.3 PROJECT PACKAGE

Necessary project documentation is required throughout and after construction and programming. This task consists of CAD packaging, software packaging, and writing documentation. There is no specific time period for documentation. However, we are required to have all materials ready around May 20 to set aside enough time for showcase preparation.

4.1.4 TESTING

Testing session will be conducted after programming and construction. We set 20 days for testing in order to avoid any emergency and delay. Debugging should be completed by May 25.

4.2 FINANCES

The section details a accurate budget for the preliminary design. Appendix L shows that the bulk of the cost for the double pendulum robot is due to the electronics and actuators. Due to the high torque and power requirements specified, the actuators increased in size, power, and cost. Furthermore, the increased motor power and sizes changed the selected drivers and other electronic components required for normal operation, additionally increasing the cost. Also, due to the need of precisely reading angular values over a large range of possible pendulum configurations, three rotary encoders were required.

Compared to the high costs of the actuators and electronics components, the mechanical components of this project were significantly cheaper. This is due to the fact that a majority of mechanical components are bought in bulk and then fabricated slightly to meet our needs and also the fact that mechanical components are less costly in general.

Overall, the subtotal of the perturbation unit, the double pendulum robot arms, the actuation, and electronics and controllers is $133.25, $110.15, $240.31, and $318.08, which combined with the $68.15 tax leads to a grand total of $869.94.

Appendices

A STAKEHOLDERS

The following details some of the possible stakeholders for this project and what their impact/interaction with the project will be.

TABLE 3: STAKEHOLDERS

Stakeholder	**Relation to Project**
Sponsors	Primary funders and supporters of the project.
High School Students	Will benefit from learning about control systems.
COSMOS Instructor	Be able to effectively engage and teach students about control systems.
Robotics Researchers	Verify controllers that define human balance and use data in robotics.
Prosthetics Industry	Understand balance better and develop better prosthetics.
Programmers	Have to be able to control and provide interface for robot to users.
Manufacturers	Robot must be manufacturable.

B NEEDS AND SPECIFICATIONS

TABLE 4: NEEDS FROM STAKEHOLDERS AND BRAINSTORM SESSIONS.

Number	Needs
1	**Controller must be easy to make modifications to.**
a	Controller must allow for different controllers to be inputted.
b	Allow for various gains and parameter changes.
c	Easy upload of simulations data.
2	**Robot must be able to represent human physiology**
a	The pendulum should be able to bend like a human.
b	The pendulum weight distribution should be easy to change.
3	**The robot should be easy to setup.**
a	Will not break when moving.
b	Easy to interface with.
c	Be portable and easy to move.
d	Be convenient to power.
4	**Robot should be easy to maintain**
a	Should be able to withstand daily wear and tear.
b	Have a maintenance guide.
c	Use as many off the shelf and easy to replace parts.
5	**Collect data in a way that can be used for analysis**
a	Easy to download data.
b	Provide readings of each sensor in appropriate intervals
c	Provide data on robot reactions.
d	Have sensors on each linkage.
6	**Easy to interface with.**
a	Easy to use interactive interface
b	Simpler model that will interface with the robot.
7	**Must be safe to use**
a	Limit damage caused by arm
b	Be electrically safe
8	**Pendulum should be able to recover from tipping over.**
a	A steady state position should be able to be established.
b	Should react to relatively controlled perturbations.
9	**Tests should be repeatable.**
a	Robot should be able to reset itself after each test.
b	Perturbations should be able to be repeatable.
10	**Must be easy to manufacture**
a	Custom parts easy to make.
b	Easy to assemble
c	As many off the shelf parts as possible

TABLE 5: CONCEPT SPECIFICATIONS ESTABLISHED FROM NEEDS.

Number	Description of Specification	Units
1	Connect with a single click.	clicks
2	Interface with a windows PC.	N/A
3	Process a human readable control equation.	N/A
4	Robot must be 2ft tall.	ft
5	Robot must have 3 different weight configurations.	lbf/in
6	1st pendulum should have 180 degree motion.	degree
7	2nd pendulum should have 270 degree motion.	degree
8	Minimum Torques should be the maximum joint torques of a human.	lbf-in
9	Use less than 150 parts.	parts
10	Maintenance Manual no bigger than 5 pages.	pages
11	Use less than 20 custom parts.	parts
12	Cart should record velocity.	in/s
13	Distance traveled accuracy +/- 0.125 inches.	in
14	Sensors accuracy +/- 0.125 inches.	c
15	Max Travel Distance of 5 inches.	in
16	Min velocity 50 in/sec.	in/s
17	Min Acceleration 80 in/sec^2	in/s^2
18	3 steps to download data files.	steps
19	Have at least one sensor per linkage.	sensors
20	Store data to csv file.	format
21	Take readings of all sensors at least every 10ms.	ms
22	Sensors accuracy 0.5 degrees.	degrees
23	HMI with less than 10 inputs.	inputs
24	Graphically Appealing.	subj
25	Defined control equation that parameters can be changed.	equation
26	Pad robotic arm with Shore 40 or less.	Shore
27	Ground Robot.	N/A
28	Use 24 VDC.	V
29	Have E-Stop.	N/A
30	Default control equation.	equation
31	Cart should record velocity.	in/s
32	Distance traveled accuracy +/- 0.125 inches.	in
33	Max Travel Distance of 5 inches.	in
34	Min velocity 50 in/sec.	in/s
35	Min Acceleration 80 in/sec^2	in/s^2
36	Sensors accuracy +/- 0.125 inches.	inches

C GENERATED CONCEPTS

Many concepts were generated during the concept generation phase of the project. This appendix details the most prominent concepts that were further evaluated.

TABLE 6: BRIEF DESCRIPTIONS OF VARIOUS CONCEPTS CONSIDERED FOR SELECTION

Concept Description	
Concept	**Description**
Trackless(RC)	Use of an RC car without any linear guide
Tracked(Guided Rails)	Use of a cart on guide linear guide rails
Floating(Boat)	Having the cart platform float in a rectangular pool.
motor	Electrical motor attached to an outlet or other power source
Pneumatic	Using air from a compressor to generate rotary motion.
Solenoid	Metal piston actuated by electromagnetic force for linear motion.
Hydraulic	Using another fluid from a compressor to generate linear motion.
Timing Belt	Using a timing belt to transmit rotary motion into linear motion.
Ball Screw	Using a ball screw to transmit from rotary motion into linear motion.
Lead Screw	Using a screw without ball bearings to go from rotary to linear.
Base Mount	Attaching the pendulum motors to the cart at the base of the arms.
Direct Mount	Attaching the motors to each arm directly.
Threaded Rods	Using threaded rods as the pendulum arms.
Holes	Drilling holes into rectangular pendulum arms.
Detachable Arm	Making the upper arm removeable.
Holding Pin	Locking the upper arm and lower arm into a single one with a pin.
Software	Using code to hold the relative angle between the two arms to be 0.
DC	Using a direct current voltage supply.
AC	Using an alternating current voltage supply.
Arduino	Using Arduino as the microcontroller for the robot control.
Raspberry Pi	Using Raspberry Pi as an onboard computer control.
PLC	Using a programmable logic board to control robot functions.
Beaglebone	Using a BeagleBone as an onboard computer control.

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D CONCEPT EVALUATION CRITERIA

The following tables are a refined list of criteria that the various designs were evaluated on.

TABLE 8: DESCRIPTION OF CRITERIA FOR THE CART

Perturbation Unit Design	
Criterion	**Description**
Cost	The cost of materials and electronics.
Dynamic predictability	The ability to make accurate accelerations and hold positions.
Ease of setup	How simple it is to put all the components of the cart together.
Ease of use	How simple it is to make the cart behave in the desired manner.
Manufacturability	The ease of which all the individual components can be made and minimal use of custom parts.
Power transmission	The ability to transmit high power from the actuator to the cart.
Total Size	Dimensions of entire setup.
Total weight	Weight of the entire setup.

TABLE 9: DESCRIPTION OF CRITERIA FOR THE CART ACTUATION

Perturbation Actuation Selection	
Criterion	**Description**
Accuracy	The ability to generate the desired power and torque.
Additional hardware	The ability to provide motion without the use of extra parts.
Cost	The total cost of each part of the actuation mechanism.
Ease of setup	The ease of integrating the actuation with the robot.
Manufacturability	The ease of making each component of the actuation.
Power transmission	The ease of transmitting the power from actuation to other parts of the robot.

TABLE 10: DESCRIPTION OF CRITERIA FOR THE CART TRANSMISSION SYSTEM.

Rotary to Linear Transmission Selection	
Criterion	**Description**
Accuracy	How closely to the desired displacement the transmission can attain.
Cost	The price of the transmission and accessories.
Power Transmission	The efficiency of the power transmission from rotary to linear.
Robustness	The ability to function properly under different conditions.
Speed	How fast the system can make the cart travel linearly.
Weight	Weight of the transmission system.

TABLE 11: DESCRIPTION OF CRITERIA FOR THE MASS DISTRIBUTION ARRANGEMENT

Mass Distribution Arranger	
Criterion	**Description**
Cost	The cost of construction and all materials.
Distribution Variation	The precision of the distribution range available.
Ease of Installation	The ease of attaching the masses to the pendulum arms.
Ease of Manufacturing	The ease of constructing the arranger.

TABLE 12: DESCRIPTION OF CRITERIA FOR THE SIMPLE PENDULUM CONVERSION.

Single Pendulum Simplification (For use with HS students)	
Criterion	**Description**
Cost	The cost of the simplification mechanism and accessories.
Ease of Conversion	The ease of changing from a double pendulum to a single pendulum and back.
Ease of Manufacturing	The ease of making the conversion mechanism or software.

TABLE 13: DESCRIPTION OF CRITERIA FOR PENDULUM JOINT ACTUATION.

Pendulum Joint Actuation	
Criterion	**Description**
Additional Hardware	Use of additional components other than the actuation device.
Cost	The cost of the actuation and additional hardware.
Robustness	The ability to not fail under various load conditions.
Torque Control	Ability to meet the torque requirements and precision of torque supplied.

TABLE 14: DESCRIPTION OF CRITERIA FOR THE LOCATION OF THE ACTUATION DEVICE.

Actuation Location	
Criterion	**Description**
Cost	The cost of additional hardware to place the actuation device.
Ease of Installation	Ease of placing the actuation device at desired location.
Ease of Manufacturing	Ease of building the hardware to hold the actuation device.
Weight Distribution	Rating of how minimal the impact is on the pendulum arm's weight.

TABLE 15: DESCRIPTION OF CRITERIA FOR THE VOLTAGE SOURCE.

DC/AC Voltage Selection	
Criterion	**Description**
Cost	Cost of hardware.
Power	Amount of power supplied.
Safety	Ease of handling and ease of enacting measures to minimize risk of shock

E CONCEPT SELECTION

After refining the list of concepts and creating criterion for the concepts to be evaluated the team came up with a scoring scheme to effectively measure the effectiveness of various ideas. The scoring system in weighted between 1 and 5. A benchmark concept was used for each group and all others evaluated against it.

TABLE 16: DESCRIPTION OF CRITERIA FOR THE ELECTRONIC CONTROLLER.

Electronics Control	
Criterion	**Description**
Connectivity	The ease of connecting the hardware with actuation devices and to a human machine interface.
Cost	The cost of the hardware.
GPIO	Having general purpose input and output slots.
Open Source	The capability of using only open source software.
Programmability	The ease of programming the hardware.

TABLE 17: CONCEPT SELECTION MATRIX FOR THE CART.

		Concepts					
Perturbation Unit Design (CART)		**A. Trackless (RC)**		**B. Tracked (Guided Rails**		**C. Floating (Boat**	
Selection Criteria	Weight	Rate	Wtd	Score	Wtd	Score	Wtd
Dynamic Predictability	30%	3	0.9	5	1.5	1	0.3
Total Weight	5%	3	0.15	2	0.1	1	0.05
Total Size	5%	3	0.15	2	0.1	1	0.05
Ease of Setup	10%	3	0.3	3	0.3	1	0.1
Ease of Usea	10%	3	0.3	3	0.3	2	0.2
Power Transmission	10%	3	0.3	4	0.4	1	0.1
Manufacturability	10%	3	0.3	3	0.3	3	0.3
Cost	20%	4	0.8	3	0.6	2	0.4
Total Weighted Score		**3.2**		**3.6**		**1.5**	
Rank		**2**		**1**		**3**	
Continue		**No**		**Develop**		**No**	

TABLE 18: CONCEPT SELECTION MATRIX FOR THE CART ACTUATION

		Concepts							
Perturbation Actuation Selection		**A. A. Motor**		**B. Pneumatic**		**C. Solenoid**		**D. Hydraulic**	
Selection Criteria	Weight	Score	Wtd	Score	Wtd	Score	Wtd	Score	Weight
Additional Hardware	30%	3	0.9	2	0.6	3	0.9	1	0.3
Accuracy	10%	3	0.3	2	0.2	2	0.2	4	0.4
Ease of Setup	20%	3	0.6	2	0.4	3	0.6	3	0.6
Power Transmission	10%	2	0.2	3	0.3	2	0.2	4	0.4
Manufacturability	10%	3	0.3	3	0.3	1	0.1	3	0.3
Cost	20%	3	0.6	2	0.4	1	0.2	2	0.4
Total Weighted Score		**2.9**		**2.2**		**2.2**		**2.4**	
Rank		**1**		**1**		**3**		**2**	
Continue		**Develop**		**No**		**No**		**No**	

TABLE 19: CONCEPT SELECTION MATRIX FOR CART ACTUATION TRANSMISSION.

		Concepts					
Rotary to Linear Transmission Selection		**A.Timing Belt**		**B. Ballscrew**		**C. Leadscrew**	
Selection Criteria	Weight	Score	Wtd	Score	Wtd	Score	Wtd
Accuracy	30%	3	0.9	4	1.2	3	0.9
Speed	10%	3	0.3	2	0.2	1	0.1
Weight	10%	3	0.3	2	0.2	2	0.2
Robustness	10%	2	0.2	4	0.4	3	0.3
Power Transmission	10%	3	0.3	3	0.3	1	0.1
Cost	30%	3	0.9	2	0.6	3	0.9
Total Weighted Score		**2.9**		**2.9**		**2.5**	
Rank		**2**		**1**		**3**	
Continue		**Develop**		**Develop**		**No**	

TABLE 20: CONCEPT SELECTION MATRIX FOR PENDULUM JOINTS ACTUATION.

		Concepts					
Pendulum Joint Actuation		**A. Motor**		**B. Pneumatic**		**C. Hydraulic**	
Selection Criteria	Weight	Score	wtd	score	wtd	score	wtd
Torque Control	20%	2	0.4	3	0.6	3	0.6
Additional Hardware	40%	3	1.2	1	0.4	1	0.4
Robustness	10%	3	0.3	3	0.3	3	0.3
Cost	30%	3	0.9	2	0.6	2	0.6
Total Weighted Score		**2.8**		**1.9**		**1.9**	
Rank		**1**		**2**		**3**	
Continue		**Develop**		**No**		**No**	

TABLE 21: CONCEPT SELECTION MATRIX FOR THE LOCATION OF THE ACTUATION.

		Concepts			
Actuation Location		**A. Base Mount**		**B. Direct Mount**	
Selection Criteria	Weight	Score	Wtd	Score	Wtd
Ease of Installation	20%	3	0.6	1	0.2
Weight Distribution	40%	3	1.2	1	0.4
Ease of Manufacturing	10%	3	0.3	3	0.3
Cost	30%	3	0.9	3	0.9
Total Weighted Score		**3**		**1.8**	
Rank		**1**		**2**	
Continue		**Develop**		**No**	

TABLE 22: CONCEPT SELECTION MATRIX FOR THE ARRANGEMENT OF THE MASS DISTRIBUTION.

		Concepts			
Mass Distribution Changer		**A. Threaded Rod**		**B. Holes**	
Selection Criteria	Weight	Score	wtd	score	wtd
Ease of Installation	20%	2	0.4	3	0.6
Distribution Variation	40%	4	1.6	3	1.2
Ease of Manufacturing	10%	3	0.3	3	0.3
Cost	30%	3	0.9	2	0.6
Total Weighted Score		**3.2**		**2.7**	
Rank		**1**		**2**	
Continue		**Develop**		**No**	

TABLE 23: CONCEPT SELECTION MATRIX FOR SIMPLE PENDULUM CONVERSION.

		Concepts					
Single Pendulum Simplification		**A. Detachable Arm**		**B. Holding Pin**		**B. Software**	
Selection Criteria	Weight	Score	Wtd	Score	Wtd	Score	Wtd
Ease of Conversion	50%	1	0.5	3	1.5	3	1.5
Manufacturing	20%	2	0.4	3	0.6	2	0.4
Cost	30%	3	0.9	5	1.5	5	1.5
Total Weighted Score		**1.8**		**3.6**		**3.4**	
Rank		**2**		**1**		**3**	
Continue		**No**		**Develop**		**No**	

TABLE 24: CONCEPT SELECTION MATRIX FOR THE VOLTAGE SUPPLY.

		Concepts			
DC/AC Voltage Selection		**A. DC**		**B. AC**	
Selection Criteria	Weight	Score	wtd	score	wtd
Safety	50%	3	1.5	1	0.5
Power	20%	1	0.2	3	0.6
Cost	30%	3	0.9	3	0.9
Total Weighted Score		**2.6**		**2**	
Rank		**1**		**2**	
Continue		**Use**		**No**	

TABLE 25: CONCEPT SELECTION MATRIX FOR THE ELECTRONIC CONTROLLER.

		Concepts							
Electronics Control		**A. Arduino**		**B. Raspberry Pi**		**C. PLC**		**D. BeagleBone**	
Selection Criteria	Weight	Score	Wtd	Score	Wtd	Score	Wtd	Score	Wtd
Connectivity	30%	3	0.9	4	1.2	3	0.9	5	1.5
GPIO	10%	3	0.3	3	0.3	3	0.3	3	0.3
Open Source	10%	3	0.3	2	0.2	1	0.1	3	0.3
Programability	20%	3	0.6	3	0.6	2	0.4	3	0.6
Cost	30%	3	0.9	3	0.9	1	0.3	2	0.6
Total Weighted Score		**3**		**3.2**		**2**		**3.3**	
Rank		**2**		**3**		**1**		**4**	
Continue		**No**		**No**		**No**		**Develop**	

F CAD IMAGES OF SYSTEM

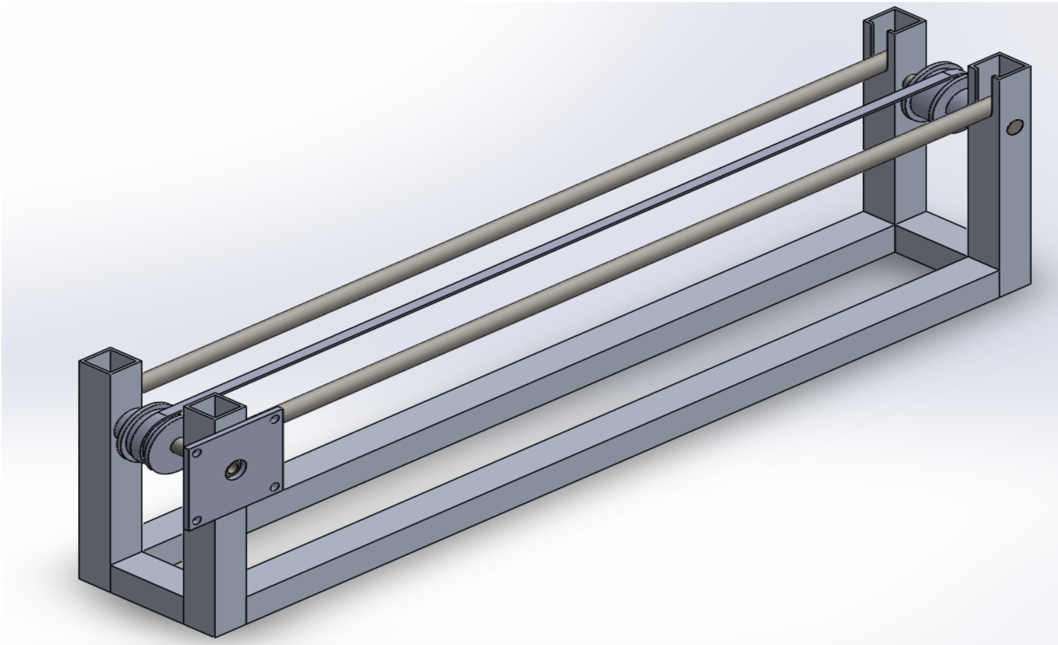


FIGURE 3: PENDULUM FRAME WITH MOUNTED MOTOR AND BELTS.

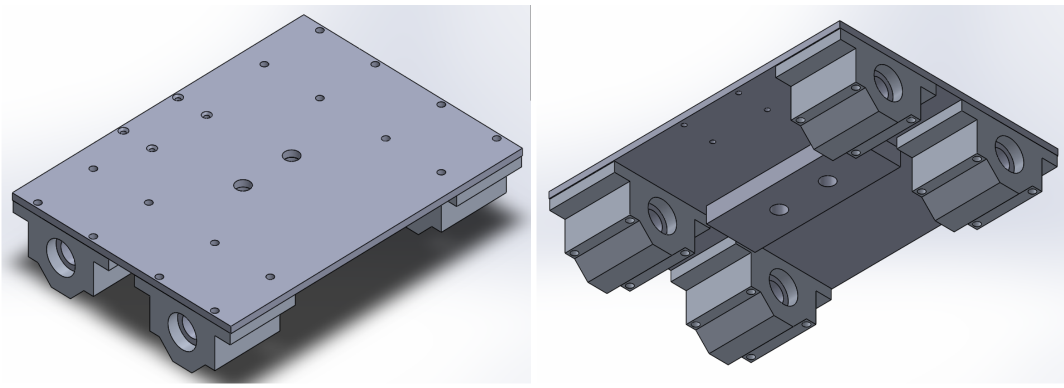


FIGURE 4: ISOMETRIC VIEWS OF TOP AND BOTTOM OF THE CART

FIGURE 5: ISOMETRIC VIEW OF PENDULUM ARM PULLEY SYSTEM

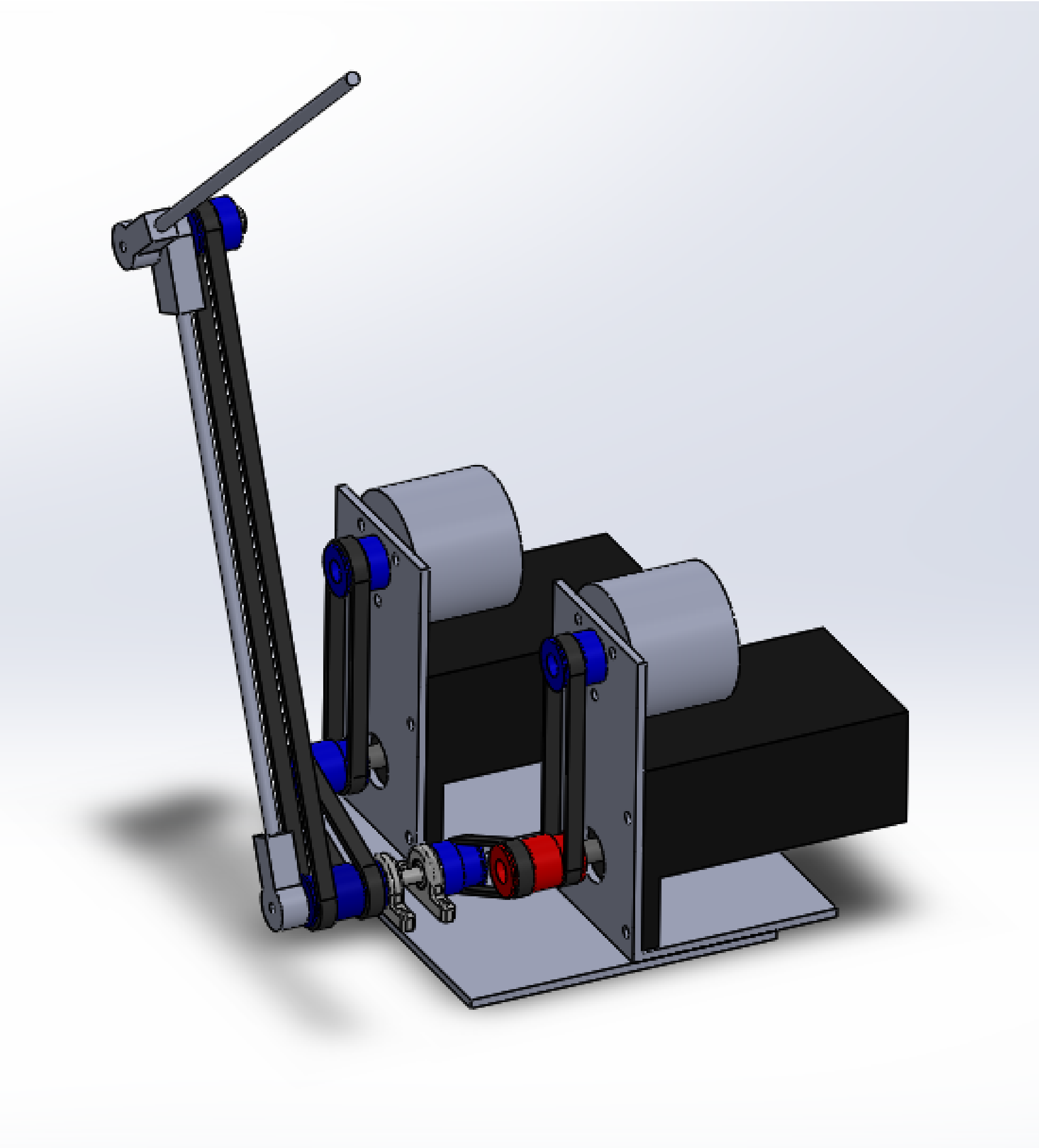
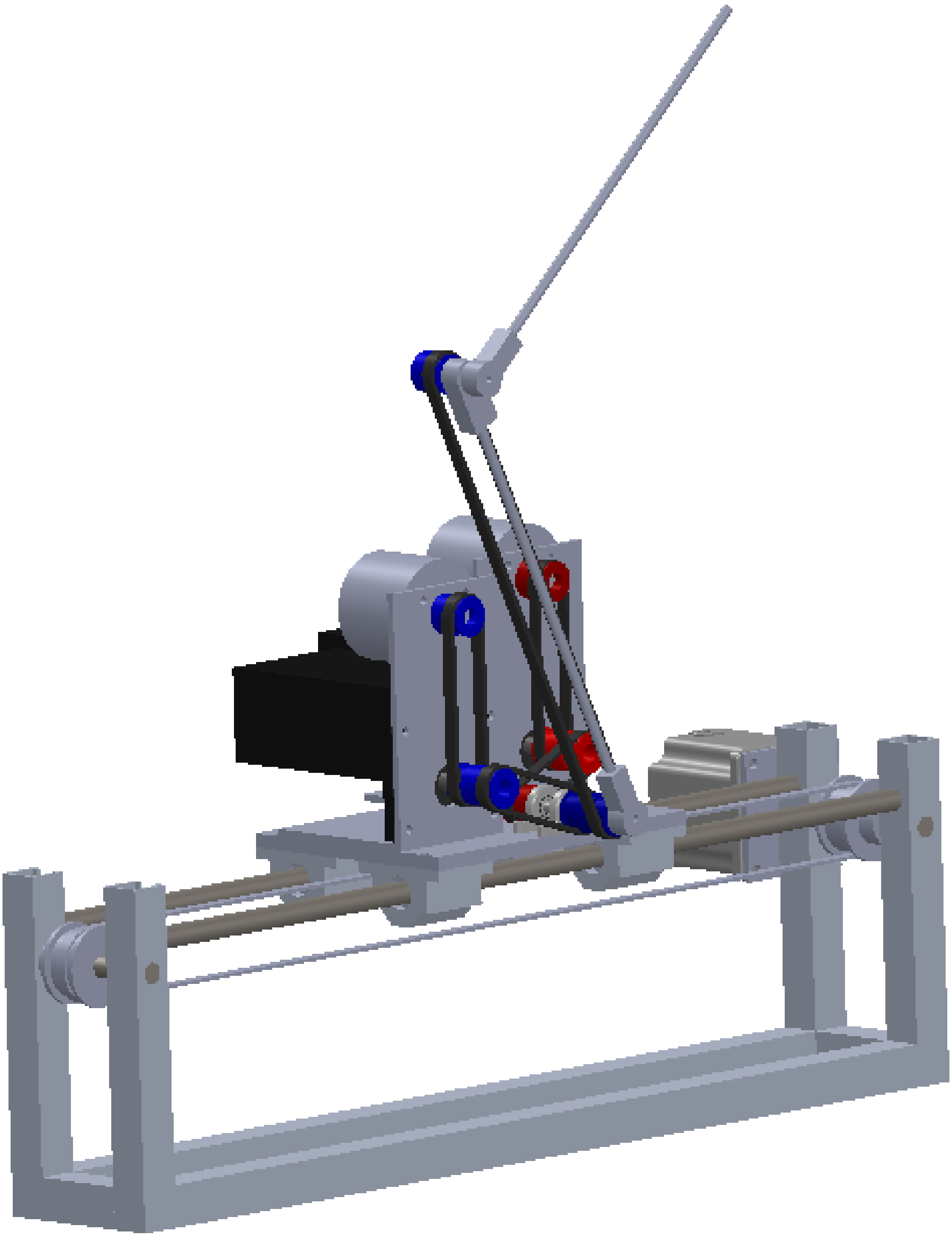


FIGURE 6: VIEW OF ENTIRE ROBOT



G STATIC ANALYSIS

The aim of the static analysis done below is to demonstrate that our design has enough factor of safety in all critical parts, and will not fail in static situations. In order to do that, firstly,we calculate factor of safety of the lower shaft. Then, we estimate the weight of the total cart, which includes the weight of two arm, two actuators, and the cart itself. Next, we calculate factor of safety and deflection of the rails. Finally, we calculate the stress concentration on the frame.

Lower Shaft For stainless steel,S_y=215 MPa

Free body diagram is shown below

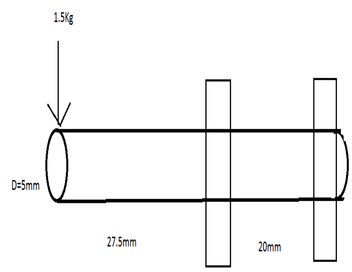


FIGURE 7: APPLIED FORCE OF LOWER SHAFT

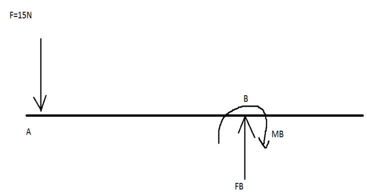


FIGURE 8: FREE BODY DIAGRAM OF LOWER SHAFT

$$g = 10m/s^2$$

$$\sum F = 0, F_A = F_B = 15N$$

$$\sum M = 0, M_B = F_B \times AB = 0.4125Nm$$

case 1:

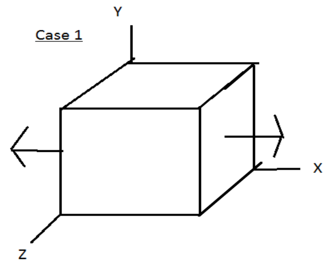


FIGURE 9: CASE 1

$$\sigma_x = My/I = 32M_B/\pi d^3 = 33.6MPa$$
$$\tau_{xy} = VQ/Ib, Q = 0, \tau_{xy} = 0$$
$$so$$
$$n = S_y/\sigma_x = 215/33.6 = 6.4$$

case 2:

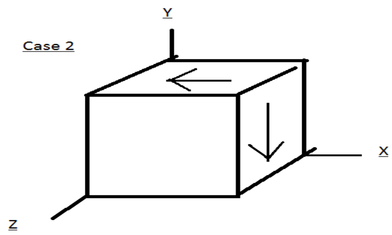


FIGURE 10: CASE 2

$$\sigma_x = My/I, y = 0, \sigma_x = 0$$
$$\tau_{xy} = VQ/Ib = 4V/3A = 4/3 \times F_A/\pi(d/2)^2 = 1MPa$$
$$so$$
$$\sigma_{max} = \sqrt{\tau_{xy}}^2 = 1MPa$$
$$n = S_y/\sigma_{max} = 215/1 = 215$$

Weight of the Robot

The weight of the robot is listed below:

For the actuators, we use motors. Each motor weights 0.6 Kg.

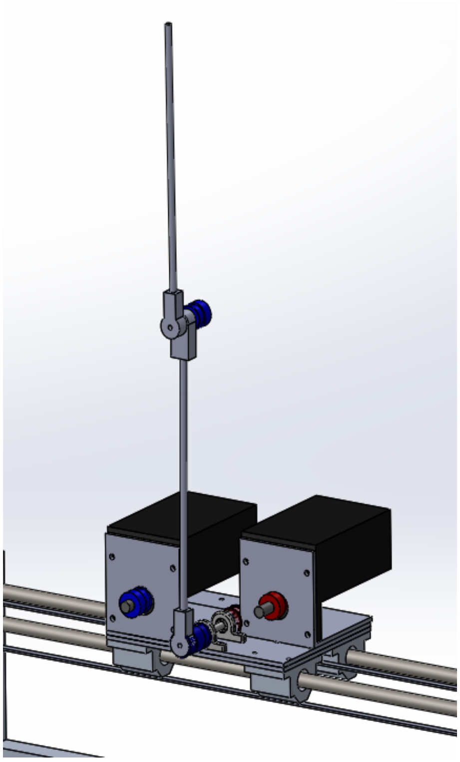


FIGURE 11: ROBOT ARM

TABLE 26: WEIGHT OF THE ARMS

Items	Weight Kg	Quantity	Total Weight Kg
Pendulums	1.5	1	1.5
Motor	0.6	2	1.2
Perturbation Unit(Cart)	0.74	1	1.3
			4

so the total weight of the robot is 4Kg

Static analysis of the rails.

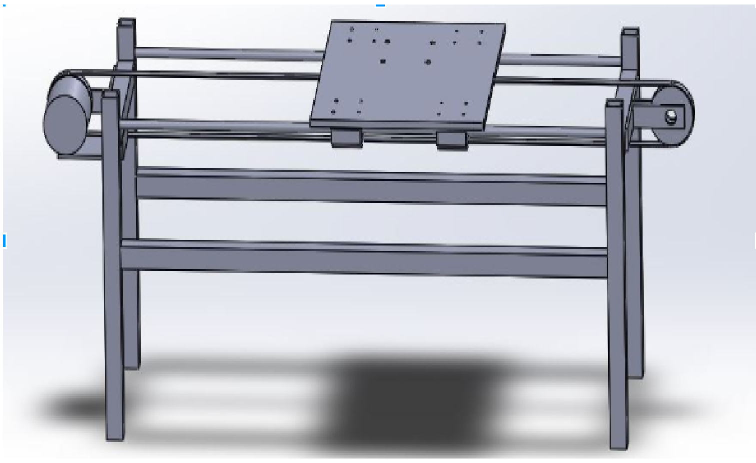


FIGURE 12: CART ON RAILS

There are two supporters on each slider, on each supporter the force is 4/4=1 Kg
Free body diagram is shown below:(The cart is in the middle of the slider)

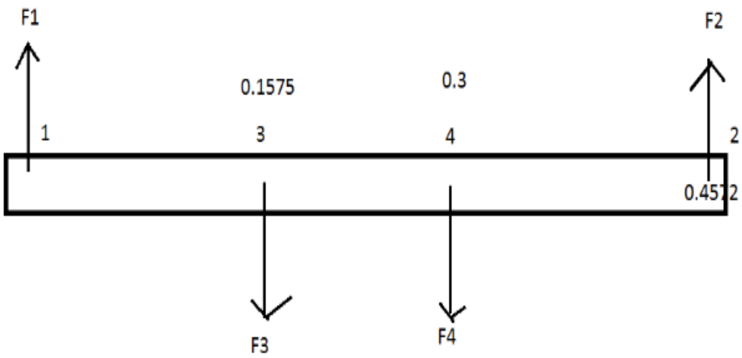


FIGURE 13: FREE BODY DIAGRAM OF RAILS

$F_3 = F_4 = 9.8N$

$So, F_1 = F_2 = 9.8N$

$Maximumbendingis@point3or4$

$Bending:$

$\sigma = Mc/I = 32M/\pi D^3$

$PluginM = F_1 l = 9.8N \times 0.15875m = 1.556Nm, D = 10mm$

$So \qquad \sigma = 15.85MPa$

For steel, the yield strength is 517 MPa
So we can get factor of safety for the rail:

n=$S_y/\sigma = 517/15.85 = 32.6$

$Inadditiontosingularityfunction, anacceptabledeflectionisalsorequired.$

$Themaximumdeflectionhappens@point3or4$

$Solvethisproblembyapplyingsingularityfunctions:$

$q = F_1 < x >^{-1} - F_3 < x - 0.15875 >^{-1} - F_4 < x - 0.3 >^{-1} + F_2 < x - 0.4572 >^{-1}$

$V = 9.8 < x >^0 - 9.8 < x - 0.15875 >^0 - 9.8 < x - 0.3 >^0 + 9.8 < x - 0.4572 >^0$

$M = 9.8 < x >^1 - 9.8 < x - 0.15875 >^1 - 9.8 < x - 0.3 >^1 + 9.8 < x - 0.4572 >^1$

$EIdy/dx = 4.9 < x >^2 - 4.9 < x - 0.15875 >^2 - 4.9 < x - 0.3 >^2 + 4.9 < x - 0.4572 >^2 + C_1 .... < 1 >$

$EIy = 1.63 < x >^3 - 1.63 < x - 0.15875 >^3 - 1.63 < x - 0.3 >^3 + 1.63 < x - 0.4572 >^3 + C_1 x + C_2 .... < 2 >$

Note the first singularity term in both equation <1> and <2> always exists, the last singularity term does not exist until x=0.4572 m, where it is zero. Thus:

EIdy/dx=4.9<x>$^2 - 4.9 < x - 0.15875 >^2 - 4.9 < x - 0.3 >^2 + C_1$

$EIy = 1.63 < x >^3 - 1.63 < x - 0.15875 >^3 - 1.63 < x - 0.3 >^3 + C_1 x + C_2$

$Pluginboundaryconditions$

:

$$y = 0@x = 0, wegetC_2 = 0$$
$$y = 0@x = 0.4572, wegetC_1 = -0.3526$$

So

$EIdy/dx = 4.9 < x >^2 - 4.9 < x - 0.15875 >^2 - 4.9 < x - 0.3 >^2 - 0.3526$

$EIy = 1.63 < x >^3 - 1.63 < x - 0.15875 >^3 - 1.63 < x - 0.3 >^3 - 0.3526x$

$Pluginthelocationofpoint3(x = 0.15875), Young'sModulusforsteel : E = 6.89 \times 10^{-10} m^4$

$I = \pi D^4/64 = 4.91 \times 10^-1^0 m^4$

$Weget$

$dy/dx = 1/EI[4.9 < x >^2 - 4.9 < x - 0.15875 >^2 - 4.9 < x - 0.3 >^2 - 0.3526]$

$y = 1/EI[1.63 < x >^3 - 1.63 < x - 0.15875 >^3 - 1.63 < x - 0.3 >^3 - 0.3526x]$

$dy/dx = -0.116degree$

$y = -0.00159m$

Analysis of the frame.

The thickness of our frame is only 1.59mm, so we need to calculate the stress concentration at each joint.

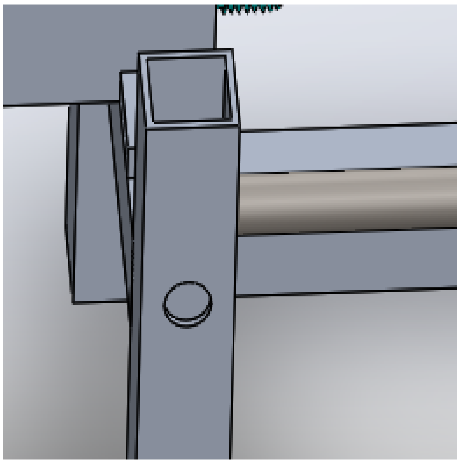


FIGURE 14: RAIL JOINT

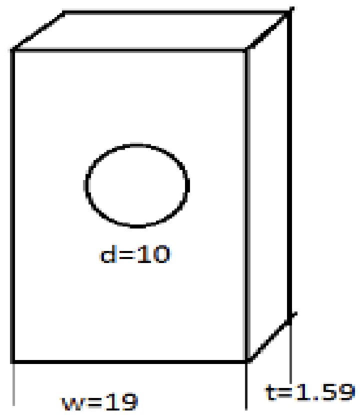


FIGURE 15: STRESS CONCENTRATION JOINT

The diameter of the rod (d) is 10mm. The thickness of the square tubing (t)is 1.59mm.The width of the tubing (w)is 19mm.

$$d/w = 0.52$$
$$A = (w - d)t = 14.31mm^2$$

Refer to Shigley's Mechanical Design Table A-15-1, Kt=2.2

$$F = 9.8N$$
$$\sigma_0 = F/A = 9.8/1.43110^{-5} = 0.685Mpa$$

For Aluminum 6061-T6, yield strength is 276 MPa
So factor of safety is n=y/$\sigma = 276/0.685 = 402.9$

H SIMULATION TEST RESULTS

FIGURE 16: HUMAN BALANCE MODEL BUILD BY RESEARCH GROUP

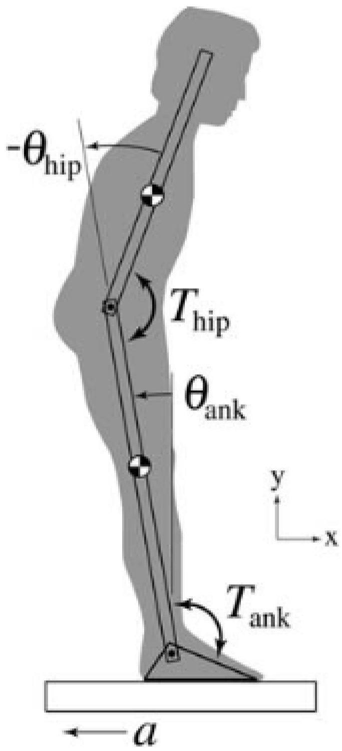


FIGURE 17: SKATEBOARD EXPERIMENT FOR HUMAN PERTURBATION INPUT

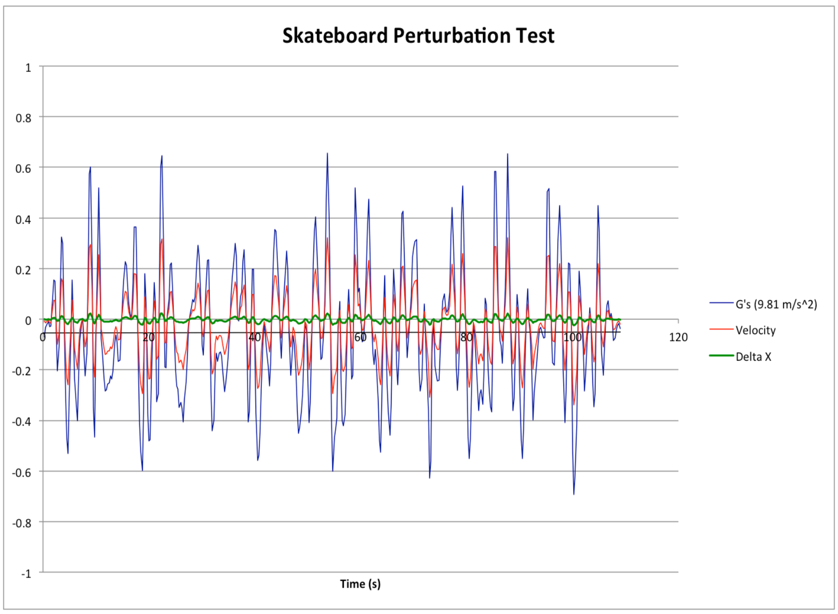


FIGURE 18: COMPARISON OF ANGLE OF ANKLE

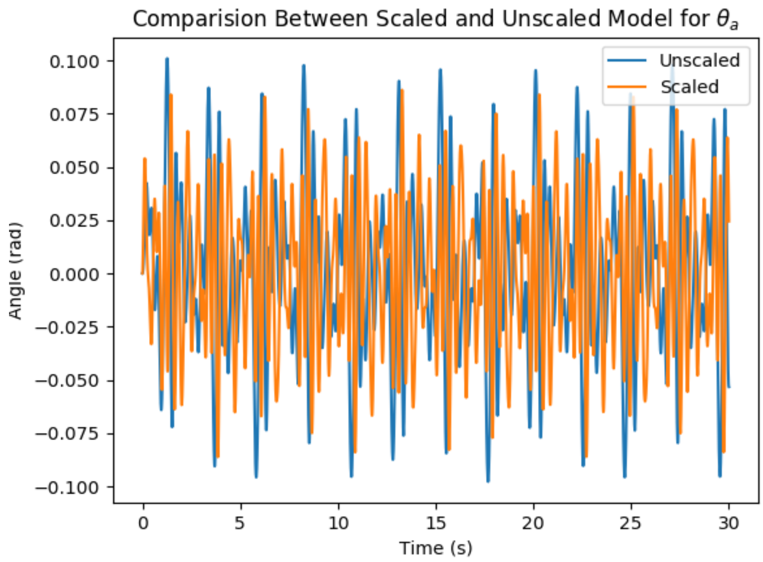


FIGURE 19: COMPARISON OF ANGULAR VELOCITY OF ANKLE

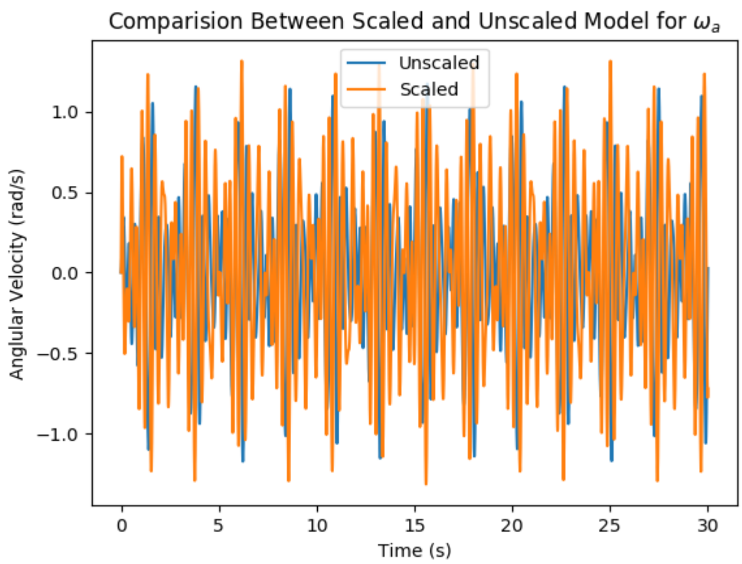


FIGURE 20: COMPARISON OF ANGLE OF HIP

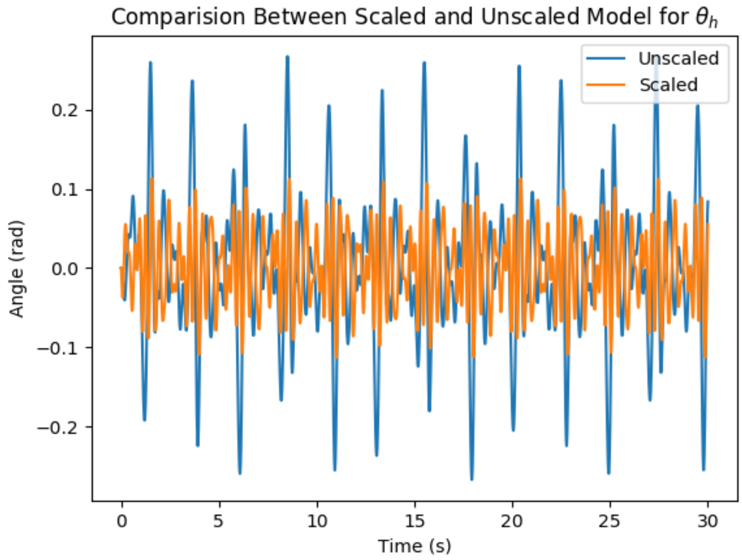


FIGURE 21: COMPARISON OF ANGULAR VELOCITY OF HIP

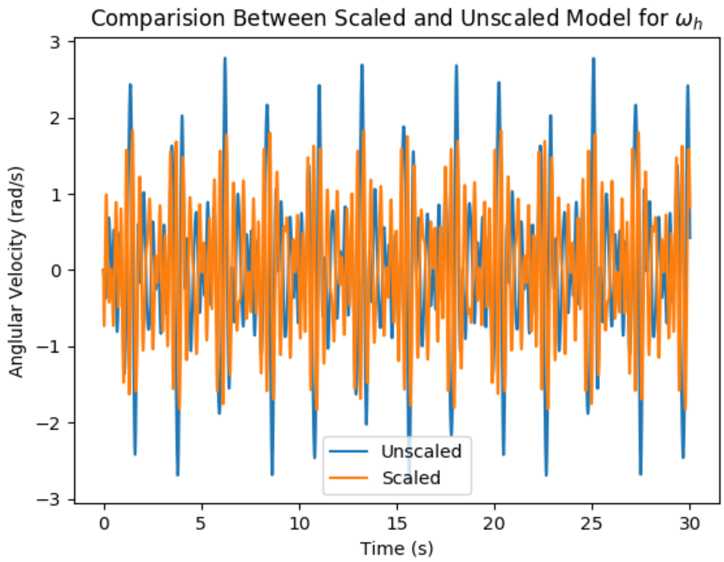


FIGURE 22: MOTION OF SCALED MODEL

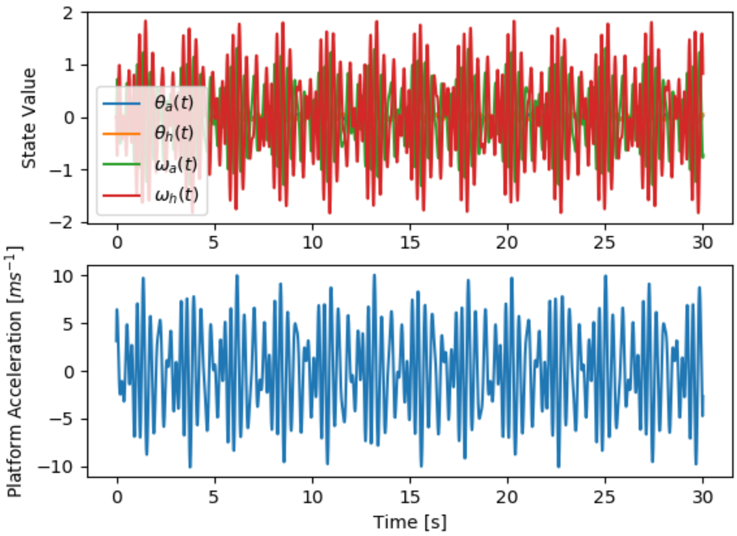


FIGURE 23: TORQUES OF SCALED MODEL

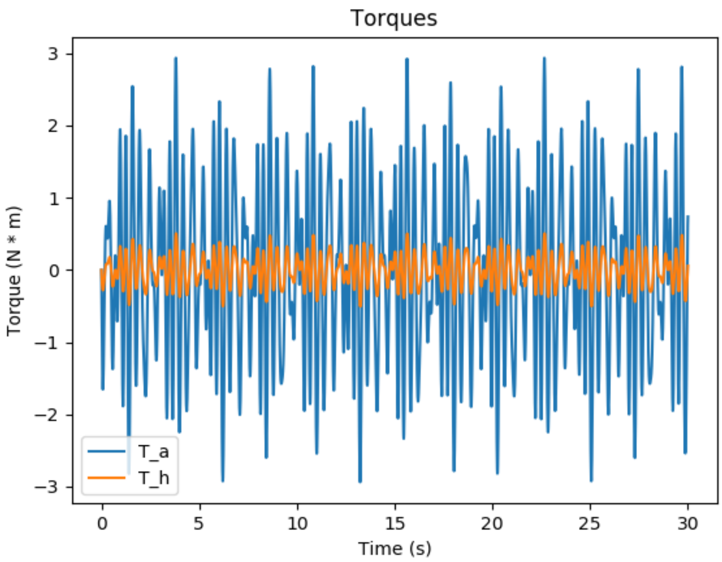


FIGURE 24: POWER OF SCALED MODEL

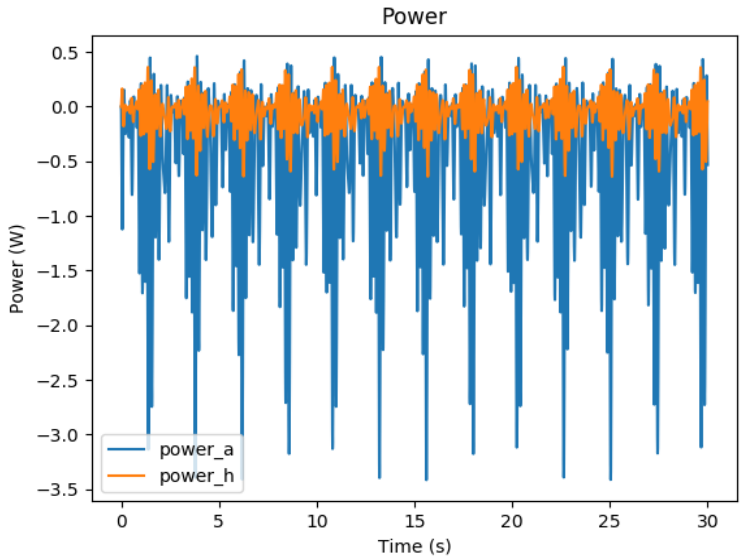
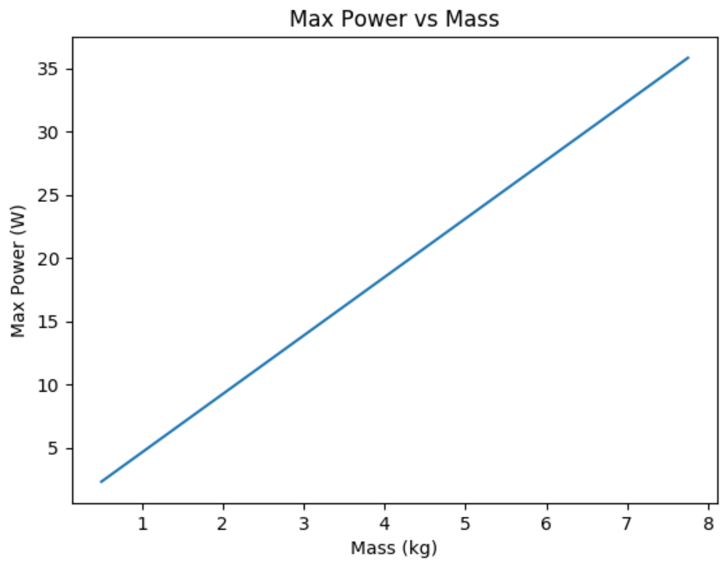


FIGURE 25: MAX POWER VS MASS FOR THE WHOLE SYSTEM



Ankle Torque	5 N*m
Hip Torque	2 N*m
Power for Whole System	15 W

TABLE 27: MAXIMUM TORQUES AND POWERS FROM SIMULATION.

I TORQUE SCALING OF BIOMECHANICAL DATA

Basic mass-inertia properties dimensional scaling based on scale factor, $s_f \geq 1$.

All lengths scale by s_f

$$l^* = \frac{l}{s_f} \qquad w^* = \frac{w}{s_f} \qquad t^* = \frac{t}{s_f}$$

Volumetric scaling:

$$V = l \times w \times t$$
$$V^* = l^* \times w^* \times t^* = \frac{l}{s_f}\frac{w}{s_f}\frac{t}{s_f} = \frac{V}{s_f^3}$$

Mass Scaling:

$$m = \rho V$$
$$m^* = \rho V^* = \frac{\rho V}{s_f^3} = \frac{m}{s_f^3} \tag{1}$$

Moment of Inertia Scaling:

$$I = mr^2$$
$$I^* = m^* r^{*2} = \frac{m}{s_f^3}\frac{r^2}{s_f^2} = \frac{mr^2}{s_f^5} = \frac{I}{s_f^5}$$
$$I^* = \frac{I}{s_f^5} \tag{2}$$

Summary:

$$l^* = \frac{l}{s_f} \qquad w^* = \frac{w}{s_f} \qquad t^* = \frac{t}{s_f} \qquad V^* = \frac{V}{s_f^3} \qquad m^* = \frac{m}{s_f^3} \qquad I^* = \frac{I}{s_f^5}$$

Deriving Force and Torque Scaling for a single simple pendulum.
Basic equation for total torque separated into static and dynamic torques.

$$T_{total} = I\alpha + mglsin\theta$$
$$T_{total} = T_{dynamic} + T_{static}$$

$$T^*_{total} = I^*\alpha + m^*g^*lsin\theta$$
$$T^*_{total} = T^*_{dynamic} + T^*_{static}$$

$$T_{dynamic} = I\alpha$$
$$T^*_{dynamic} = I^*\alpha = \frac{I\alpha}{s_f^5} = \frac{T_{dynamic}}{s_f^5}$$

$$T_{static} = mglsin\theta$$
$$T^*_{static} = m^*gl^*sin\theta = \frac{m}{s_f^3}g\frac{l}{s_f}sin\theta = \frac{mglsin\theta}{s_f^4} = \frac{T_{static}}{s_f^4}$$

$$\begin{aligned} T^*_{total} &= T^*_{dynamic} + T^*_{static} \\ &= \frac{T_{dynamic}}{s_f^5} + \frac{T_{static}}{s_f^4} \end{aligned}$$

The motors for the pendulum joints must be overestimates of the human strength torques recovered from biometric data. Assuming $s_f \geq 1$ we can use the following principle.

Where s $\geq$ 1.

$$\begin{aligned} \frac{x_1}{s^4} + \frac{x_2}{s^5} &\leq \frac{x_1 + x_2}{s^4} \\ \frac{x_1}{s^4} + \frac{x_2}{s^5} &\leq \frac{x_1}{s^4} + \frac{x_2}{s^4} \end{aligned} \tag{3}$$

$$\begin{aligned} \frac{x_2}{s^5} &\leq \frac{x_2}{s^4} \\ \frac{s^4}{s^5} &\leq \frac{x_2}{x_2} \\ \frac{1}{s} &\leq 1 \end{aligned} \tag{4}$$

Using the above result we find that we can make an overestimate by assuming the measured torque values from biomechanical data are all over estimates:

$$\begin{aligned} T^*_{total} &= \frac{T_{dynamic}}{s_f^5} + \frac{T_{static}}{s_f^4} \\ T^*_{total} &\leq \frac{T_{dynamic}}{s_f^4} + \frac{T_{static}}{s_f^4} \\ &\leq \frac{T_{dynamic} + T_{static}}{s_f^4} \\ T^*_{total} &\leq \frac{T_{total}}{s_f^4} \end{aligned} \tag{5}$$

J SCALED DIMENSION VALUES FOR SCALED HUMAN MODELS

These are the calculated values for a 1:3 and 1:4 scale 182 cm tall human model.

Basic measurements and weights

TABLE 28: SCALED GEOMETRIC PROPERTIES

	1:1	**1:3**	**1:4**
Height (cm)	180	60	45
Width (cm)	46	15.33333333	11.5
Thickness (cm)	25	8.333333333	6.25
Mass (kg)	80	2.962962963	1.25

Joint torques derived from biomechanical data (Anderson 2007) using results from Appendix I.

TABLE 29: OVERESTIMATED TORQUE AND POWER VALUES FOR SCALED HUMANS

	1:1	**1:3**	**1:4**
Max Hip Torque (Nm)	500	6.172839506	1.953125
Max Ankle Torque (Nm)	300	3.703703704	1.171875
Max Hip Power (W)	1744	21.5308642	6.8125
Max Ankle Power (W)	1046	12.91358025	4.0859375

K GANTT CHART

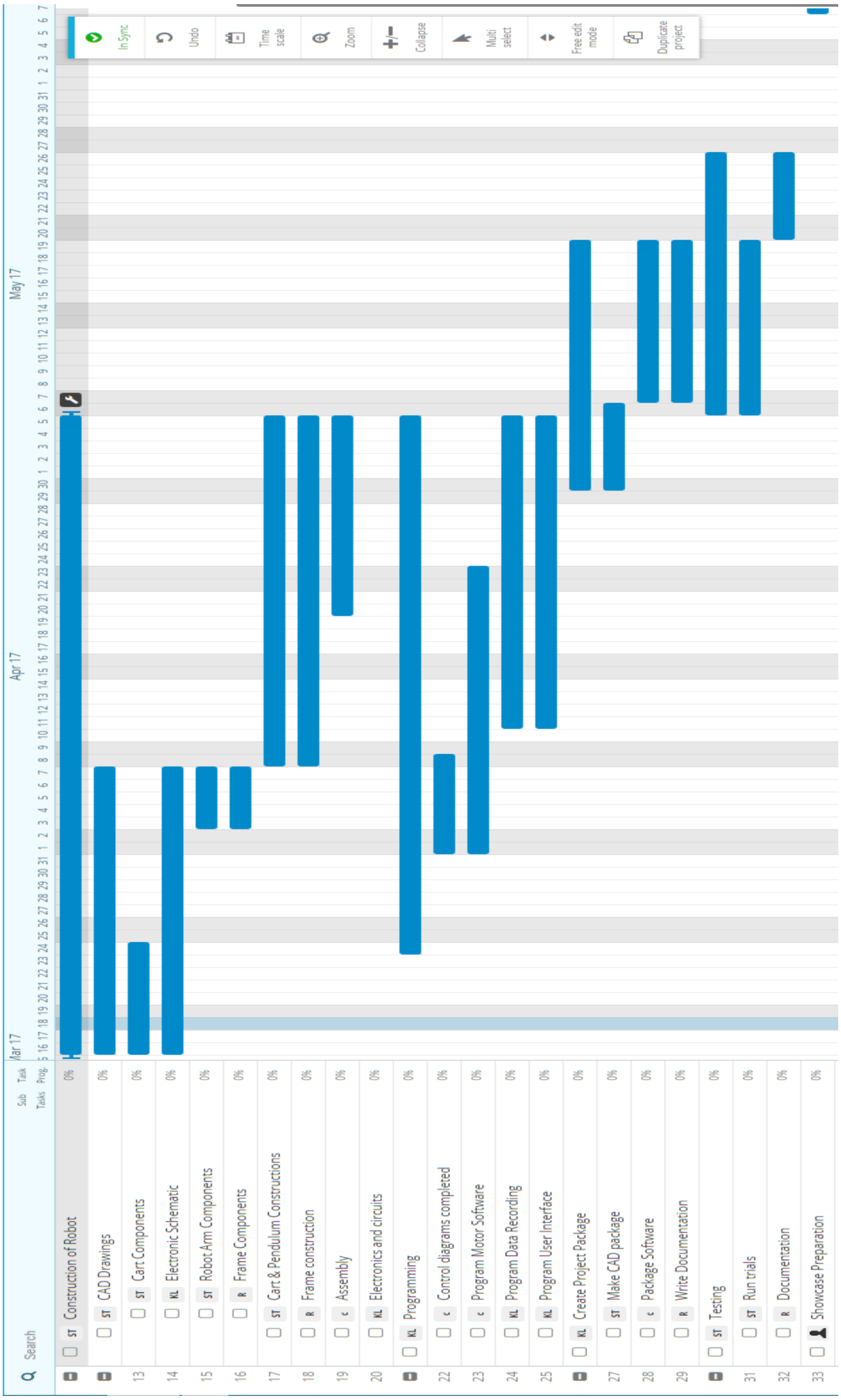


FIGURE 26: SPRING QUARTER GANTT CHART

L BILL OF MATERIALS

A Preliminary bill of materials to build 1 double pendulum testing unit. Does not currently account for shipping due to the unknown costs from McMaster-Carr and various other vendors.

TABLE 30: PERTURBATION UNIT BOM

			Perturbation Unit			
Part #	**Description**	**QTY**	**Unit**	**Total**	**Fabrication**	**Supplier**
6546k52	Standing Rod - 6 inches - holed - Aluminum	4	1.64	6.56	Purchase	McMaster-Carr
6546k52	Base Rod - 18 inches - Aluminum	2	4.56	9.12	Purchase	McMaster-Carr
6546k52	Supporting Rod - 1.75 inches - Aluminum	2	1.87	3.74	Purchase	McMaster-Carr
6112K470	Hardened precision metric drive shaft	2	15.07	30.14	Purchase	McMaster-Carr
1346K110	Shaft	2	3.63	7.26	Purchase	McMaster-Carr
1375K54	Drive Pulley	1	12.53	12.53	Purchase	McMaster-Carr
1375K54	Idler Pulley	1	12.53	12.53	Purchase	McMaster-Carr
1184	Timing Belt	1	9.95	9.95	Purchase	Adafruit
89015K239	Cart Platform Plate	1	14.28	14.28	Fabricated	McMaster-Carr
986832	Linear Ball Bearing - SC10UU	4	3.38	13.52	Purchase	Banggood
8741K33	Delrin Block	1	2.05	2.05	Purchase	McMaster-Carr
	Right Angle Brackets	20	0.34	6.89	Purchase	Amazon
91294A192	M4 x 0.7 screw	40	0.12	4.68	Purchase	McMaster-Carr
			Subtotal:	133.25		

TABLE 31: DOUBLE PENDULUM ARM BOM

Double Pendulum Robot Arm (Mechanical Assembly)

Part #	Description	QTY	Unit	Total	Fabrication	Supplier
6658K66	Oil- Embedded Sleeve Bearing	3	1.31	3.93	Purchase	McMaster-Carr
89015K235	Angle Motor Bracket	2	4.57	9.14	Purchase	McMaster-Carr
8600N11	Mounted Ball Bearing with Aluminum Housing	2	15.34	21.90	Purchase	McMaster-Carr
GT2-20T-8B-6-TW	8mm Double Headed Pulley	1	2.10	2.10	Purchase	RobotDigg
GT2-20T-8B-6	8mm Bore Pulley	5	1.50	7.50	Purchase	RobotDigg
GT2-20T-5B-6	5mm Bore Pulley	1	1.50	1.50	Purchase	RobotDigg
90278A508	Tight-tolerance Socket Drive Shoulder Screw	1	10.95	10.95	Purchase	McMaster-Carr
8974K21	Leg Beam	2	1.24	2.47	Purchase	McMaster-Carr
9146T66	Top Coupling	2	1.76	3.52	Fabricated	McMaster-Carr
9146T66	Shaft Holder	1	1.76	1.76	Fabricated	McMaster-Carr
90265A135	Stainless Steel Shoulder Screw	1	5.58	5.58	Purchase	McMaster-Carr
1184	Timing Belt	4	9.95	39.8	Purchase	Adafruit
			Subtotal:	110.15		

TABLE 32: ELECTRONICS AND ACTUATORS BOM

Electronics and Actuators						
Part #	**Description**	**QTY**	**Unit**	**Total**	**Fabrication**	**Supplier**
603-1640-ND	PMC AC/DC CONVERTER 24V 12V 300W	1	90.04	90.04	Purchase	DigiKey
811-2622-ND	DC-DC CONVRT 0.7525-5.5V 5A 5SIP	1	6.2	6.2	Purchase	DigiKey
COM-11102	Rotary Encoder	3	39.95	119.85	Purchase	Sparkfun
RB-Cyt-153	10A 5-25V Dual Channel DC Motor Driver	1	23.49	23.49	Purchase	RobotShop
102010027	SeeedStudio BeagleBone Green	1	39	39	Purchase	seeedstudio
CW230	24V∼36VDC 0.9A∼3.0A Stepper Motor Driver	1	39.5	39.5	Purchase	circuitspecialists
6627T53	Position-Control DC Motor	1	73.71	73.71	Purchase	McMaster-Carr
80803008-ND	GEARMOTOR 161 RPM 24VDC	2	83.3	166.6	Purchase	Digikey
			Subtotal:	558.39		

TABLE 33: TOTALS OF ALL COMPONENTS WITH TAX

Totals	
Taxes	68.15215
Subtotal:	801.79
Grand total:	869.94215

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Park, Sukyung, Fay B. Horak, and Arthur D. Kuo. ”Postural Feedback Responses Scale with Biomechanical Constraints in Human Standing.” Experimental Brain Research 154.4 (2004): 417-27. Web.

Anderson, Dennis E., Michael L. Madigan, and Maury A. Nussbaum. ”Maximum Voluntary Joint Torque as a Function of Joint Angle and Angular Velocity: Model Development and Application to the Lower Limb.” Journal of Biomechanics 40.14 (2007): 3105-113. Web.