BYU ENGINEERING
IRA A. FULTON COLLEGE OF ENGINEERING

18 April 2023
Final Submission

System Design Summary:
Final Design Report

Project Sponsor:
Sandia National Laboratories

Capstone Team 37: Herculift

Tyler Dickson, Joseph Edmund, Chris Payne,

Brinler Tanner, Isaac Sorensen, Joshua Vanderpool

Revision History

Revision	Date	Description
--	06 April 2023	Initial release
A	19 April 2023	Updated packet based on reviewer feedback from previous submission

Approval Signatures:

Tyler Dickson	19 April 2023 Date:
Christian Payne	19 April 2023 Date:
Isaac Sorensen	19 April 2023 Date:
Joshua Vanderpool	19 April 2023 Date:
Brinler Tanner	19 April 2023 Date:
Joseph Edmund	19 April 2023 Date:
Rob Cloward – Team Coach	19 April 2023 Date:

High-Level Contents

Detailed Contents

BYU ENGINEERING
IRA A. FULTON COLLEGE OF ENGINEERING

18 April 2023
Rev A

System Design Summary:
Assisted Lift Device

Project Sponsor:
Sandia National Laboratories

Capstone Team 37: Herculift

Tyler Dickson, Joseph Edmund, Chris Payne,

Brinler Tanner, Isaac Sorensen, Joshua Vanderpool

Revision History			
Revision	Revised by	Checked by	Date
--	Joshua Vanderpool	Joseph Edmund	06 April 2023
A	Joshua Vanderpool	Isaac Sorensen	18 April 2023

1. Introduction

For the past 8 months, we have been working with David Wood and Jason Wheeler of Sandia National Labs to address a high-impact area of worker health and safety for the Department of Energy. Department of Energy workers repetitively lift heavy lead blankets while working on nuclear cleanup sites. Repetitive lifting of these blankets on cleanup sites has led to high rates of bicep and shoulder tears which is an overall detriment to worker health and a financial liability to the DOE to cover workers compensations costs for injuries.

Given this background, we were tasked to begin development of an assisted lifting device intended to reduce fatigue in the biceps and shoulder during repetitive heavy lifting. Our goal was to produce and deliver a functional design for a one-armed prototype to Sandia by April 2023 who would then continue further testing, refinement, and preparation for market release. To accomplish this task, we were provided with a budget of $4500 and we allocated 1800 man-hours to the effort.

To guide our efforts, we were to focus on the following key success measures for our device: (1) System response time, (2) Percent of load redirected to the trunk, (3) User comfort, (4) Total system weight, and (5) Predicted battery life. Wholistically, the system was to be smooth and intuitive for the user while redirecting the load from the arm to the trunk of the user.

In all, our final design excelled in its ability to redirect more than half the load felt by the arm, to be lightweight, and have a long-lasting battery life. The system's comfortability and response time met sufficient baselines but can be significantly improved by future effort. This summary will provide a high-level summary of the design, its overall performance, and future recommendations that we have for Sandia National Labs.

2. Design Description

For a video of our system functioning click here.
[https://byu.box.com/s/jravn9cqzokav8k3jhzvot867zqrqb0s]

2.1 Overall System

This design consists of a back-mounted frame with a motor-cable system driven by a proportional control system. A cable runs from the motor, through a swivel joint at the shoulder, and connects to a handle at the hand to provide load assistance. Force sensors in the handle sense both the external load held by the handle and the cable tension assisting the user. The frame is worn like a backpack with both shoulder and hip straps to carry and redistribute the load across a high surface area of the user's body. We defined our system as the combination of 5 subsystems and they are defined as follows:

2.2 Frame – Housing for All Subsystems and Load Redistribution

The frame serves as the mounting place for the motor, "shoulder crane" swivel joint, control system, battery, motor, and cable spool. The frame also serves the function of transferring load from the cable to the trunk of the user via the hip straps. More details regarding this subsystem can be found in [013_DESIGN_Frame_Subsystem_Definition].

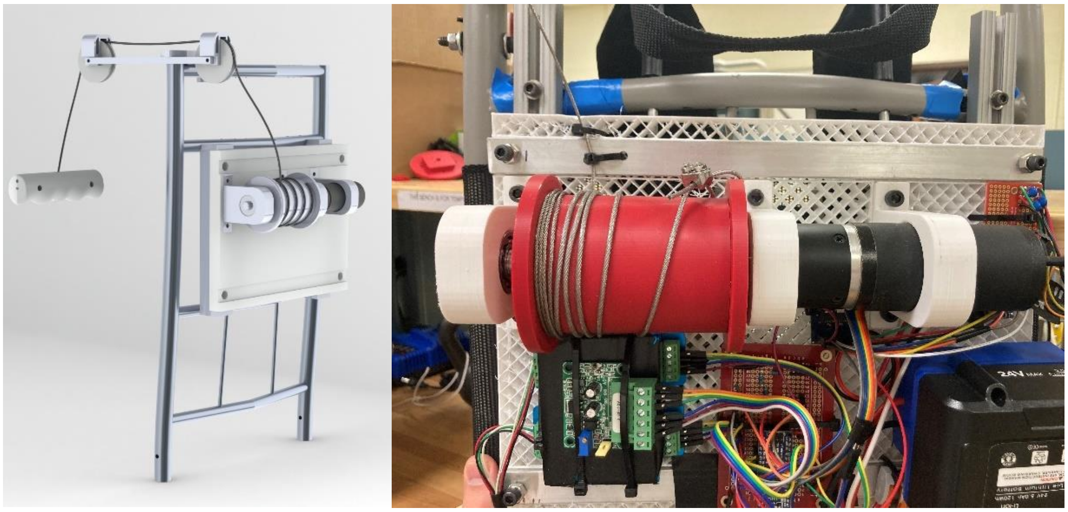


Figure 1. System frame (left) and motor/cable subsystem that provides actuation (right)

2.3 Handle – The Main Human-System Interface

Figure 2. System handle with integrated force sensors

The handle is designed for ergonomic use. In its current iteration, it consists of a 3D-printed handle and two uniaxial gauges. One strain gauge senses the load at the hook which carries lead blankets. The other gauge measures cable tension. The handle is in two halves, joined by screws to encapsulate the sensors. Currently, 4 ft long wires travel from the handle to other electronic components located on the back of the frame. More details regarding this subsystem can be found in [014_DESIGN_Handle_Subsystem_Definition].

2.4 Power – Energy Source for Standalone System

In order to be used in the work field, our system is battery powered. A drill battery is used to maximize the battery life to weight ratio. The selected battery is relatively light weight and has enough powers storage to run our one-armed device for an entire workday. Based on our predictions, we also anticipate that only a single battery will be required for the final two-armed device that Sandia will continue to develop. More details regarding this subsystem can be found in [015_DESIGN_Power_Subsystem_Definition].

2.5 Control System – The Brains of Our Smooth/Intuitive Device

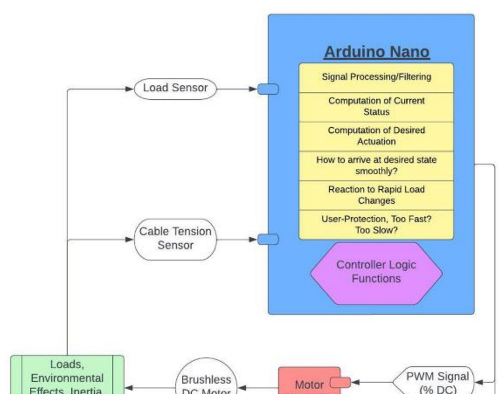


Figure 3. Overall control system logic

The control system is controlled using an Arduino Nano and consists of all the amplifiers, signal converters, and wiring for the system. The control system controls the motor based off the comparison between the readings of the two force sensors in the handle and then outputs and updates the signal to a motor that adjusts to the appropriate speed and torque. The logic is not described here, but an overview can be seen in Figure 3. It is a proportional controller with built-in flexibility to be used as a full PID controller pending a more extensive analysis. More details regarding this subsystem can be found in [016_DESIGN_Control_Subsystem_Definition].

2.5 Motor and Spool – Source of Offloading Actuation

The motor provides all the dynamic assistance to the user. It consists of a brushless DC motor with an integrated planetary gear to provide sufficient torques and speeds for our application. Overall, our motor is highly efficient, low-noise, and performs its proper function with no noticeable heating. More details regarding this subsystem can be found in [017_DESIGN_Motor_Gear_Subsystem_Definition].

3. Final Performance Summary

Table 1. Key success measure summary

Measure	Stretch Goal	Excellent	Good	Poor
System Response Time (Qualitative)	No perceptible delay	Very little delay	Functional despite delay & actuation discontinuities	Delay is an impediment to the task
Load Redirected to the Trunk (%)	50-70%	40-50%	20-40%	<20%
User Comfort (Qualitative 0-5)	Very Comfortable (4.2+)	Moderately Comfortable (3.6-4.2)	Neither Comfortable nor Uncomfortable (2.6-3.5)	Moderately Uncomfortable (1.5-2.5)
Total System Weight (lbs)	0-10	10-12	12-20	20+
Predicted Battery Life (hrs)	>5	4-5	2-4	<2

3.1 Tests and Measurements

Our total system performance was gauged using 5 key success measures. These measures are listed in **Table 1** along with a summary of our original goals regarding the system functionality. Overall, we excelled in our capabilities to provide a long battery life and a significant load-redirection from the hand to the trunk all while keeping the system very lightweight.

Although not the most important key success measures, we have defined several other performance measures regarding our total system performance. These are summarized in **Table 2.** These metrics have been chosen since they describe other desirable traits as defined by our sponsor, Sandia National Labs. They describe the overall range of motion for the device and the ability for the user to easily don the device.

For a more detailed summary of the test results, see the [003_TRES_System_Performance_Summary].

Table 2. Miscellaneous System Performance Measures

Measure	Excellent	Good	Poor	Measured Val/Notes
Time for user to don device (sec)	< 30	30-59	60	18
Time required for total shutoff and safe-fail of device (s)	.1-.15	.15-.5	0.5+	0.25
Max tension of cable with motor run at full power (lb)	60 +	45 -60	<22.5	*Only applied 25 lbs.*
Force required to trigger initial assistance (lb)	3	5	7	<< 3 lbs. (highly sensitive)
Max angle range of shoulder adduction/abduction (degree)	160-180+	90-159	45-89	No restriction
Shoulder range of motion in flexion (degree)	200-225+	60-199	30-59	90
Max angle range of lateral rotation of shoulder (degree)	150-180+	60-150	30-59	60

3.2 Market Response

Uniquely, our market is not directly the DOE workers, but rather the Sandia National Labs team that will continue the testing and refinement of our device. Our correspondence and demonstration of the final device's performance produced highly satisfactory results. They expressed a desire for our recommendations and testing documentation, all of which are provided in the overall packet.

4. Conclusion and Recommendations

Per our project success agreement [035_PSA] and discussion with the Sandia team, we have developed an effective design with sufficient justification and recommendations for improvement to send to Sandia to assist them in their long-term development of this project.

We were able to accomplish our assigned tasks under budget and using the allocated time provided by BYU's capstone program. The overall system does effectively redirect the load and reacts smoothly to the user input. The prototype has been sent to Sandia along with a complete design summary that is sufficient for the recreation and full understanding of our design.

With all that we learned from the design of our project prototype, we recommend that the following innovations be implemented. Here, we have organized by subsystem and provide a concluding summary and recommendations for each. A summary of how the device can be replicated along with more detailed recommendations for improvement can be found in [003_TRES_System_Performance_Summary].

4.1 Handle

The handle worked sufficiently well for our prototyping purposes, but it was not the focus of our scope.

- The handle should be redesigned for a more rigid hook like those already used by the DOE workers.

- Instead of single-axis force sensors, multi-axis load cells could be used in order to sense both the forces and moments applied at the hand.
- To avoid the interference of wires coming out the side of the handle, the steal cable could be replaced with a sufficiently strong and insulated bundle of wires.

4.2 Frame

As it was not in our primary scope, a custom and ergonomic design was not used to develop the frame. Rather a simple and somewhat uncomfortable hiking frame was used.

- We recommend that the future frame include solid hip straps and a breathable back.
- A biomechanical analysis of the strains generated in the back and trunk should be performed to optimize components placement and load redistribution.
- A torsional spring should be added to the swivel joint to stabilize the rotation of the device's arm.

4.3 Power

The chosen battery is very effective at providing sufficient battery life.

- We recommend that one 24V, 5.0 Amp-hour battery should be sufficient when developing the two-armed version of this device.
- The battery placement on the back of the frame should be optimized for user comfort.

4.4 Motor & Gearing

Although our current motor works extremely well, the spool could be greatly improved.

- When misaligned the cable runs off the spool and thus, we recommend the spool be placed immediately below the shoulder crane, neither medial nor lateral. This should prevent the need for a Boden tube.
- We also recommend optimizing the placement of the motor on the back of the frame for user comfort.

4.5 Control

Our current control system is effective at smoothly reacting to the user inputs and providing a quick-reacting output of the appropriate magnitude. Currently, only a simple proportional control is used. However, the code and system have the capability to utilize a full PID setup.

- We recommend doing a more thorough characterization of the system dynamics and then performing a PID tuning process.
- Additionally, we recommend adding a nested loop to control and monitor the speed of the motor, not simply the tension produced by the cable.

Artifact ID: 002	Artifact Title: Written and Visual Description of Design	
Revision: A	Revision Date: 18 April 2023	
Prepared by: Brinler Tanner		**Checked By:** Isaac Sorensen
Purpose: *To provide a high-level description of the final design of our system. This document briefly describes the design in words and with appropriate top-level pictures.*		

Revision History			
Revision	Revised by	Checked by	Date
--	Brinler Tanner	Isaac Sorensen	6 April 2023
A	Joshua Vanderpool	Isaac Sorensen	18 April 2023

1. Introduction

The purpose of this document is to provide a top-level description of our design. More detailed information can be found in the subsystem-specific artifacts listed for each subsystem.

In all, we have divided our total subsystem into to 5 subsystems. These include: (1) Frame, (2) Handle, (3) Power, (4) Control, and (5) Motor & Gearing. Figure 1 shows the relative location of each of these subsystems on the total finished design.

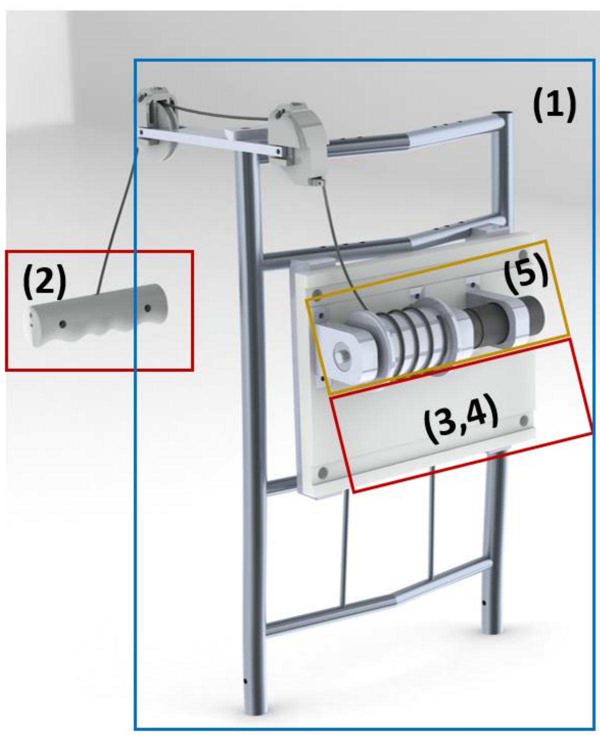


Figure 1. Location of subsystems [(1) Frame, (2) Handle, (3) Power, (4) Control, (5) Motor & Gearing. Note that the electronic components of the power and control subsystems are not explicitly shown

2. Written and Visual Design Descriptions

2.1 Total System

This design consists of a back-mounted frame with a motor-cable system driven by a proportional control system. A cable runs from the motor, through a swivel joint at the shoulder, and connects to a handle at the hand to provide load assistance. Force sensors in the handle sense both the external load held by the handle and the cable tension assisting the user. The frame is worn like a backpack with both shoulder and hip straps to carry and redistribute the load across a high surface area of the user's body.

Figure 2. Frame without shell and electronics (left), frame with protective shell (middle), mounted electronic components (right)

2.2 Frame

A more detailed summary of components, test, and design details can be found in [013_DESIGN_Frame_Subsystem_Definition].

The frame serves as the mounting place for the motor, "shoulder crane" swivel joint, control system, battery, motor, and cable spool. The frame also serves the function of transferring load from the cable to the trunk of the user via the hip straps.

The backpacking frame and swivel piece are made from aluminum. All other components (shell, baseboard, pulleys, and pulley guards) are made from PLA or polyurethane. This allows the overall design to be very lightweight. Components are connected by various sized bolts (see physical prototype for reference), none of which bear high or critical loads.

Figure 3. Total frame (right), swivel beam attachment (middle), and angle stop block (right)

2.3 Handle

A more detailed summary of components, test, and design details can be found in [043_DESIGN_Handle_Subsystem_Definition].

The handle is designed for ergonomic use. In its current iteration, it consists of a 3D-printed handle and two uniaxial gauges. One strain gauge senses the load at the hook which carries lead blankets. The other gauge measures cable tension. The handle is in two halves, joined by screws to encapsulate the sensors. Currently, 4 ft long wires travel from the handle to other electronic components located on the back of the frame.

Strain gauges were derived from HEETA fishing scales and soldered to stranded wire. Shrink wrap is used to reinforce hook. Steal cable with cable tie-down is used to secure to top of handle. Channels were printed for wire management, but some slight sanding and manipulation was required to ensure wires did not become pinched.

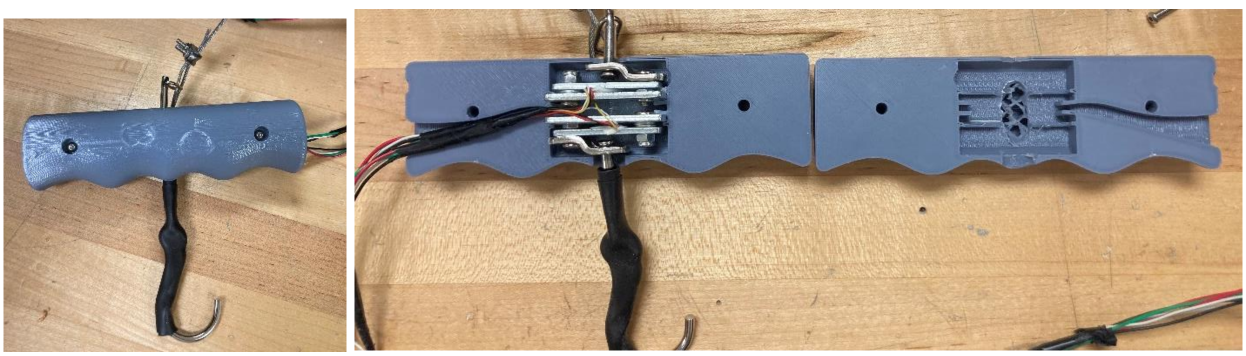


Figure 4. Assembled handle with hook and cable mount (left), strain gauges in handle halves before assembly (right)

2.4 Power

A more detailed summary of components, test, and design details can be found in [015_DESIGN_Power_Subsystem_Definition].

In order to be used in the work field, our system is battery powered. A drill battery is used to maximize the battery life to weight ratio. The selected battery is relatively light weight and has enough powers storage to run our one-armed device for an entire workday.

Our battery runs at 24 V. This was determined by our motor voltage, but conveniently also runs our strain gauge amplifiers and PWM to analog signal converter. To power the Arduino Nano, the voltage was stepped down to 5 V using a Buck Converter.

The battery's capacity is 5-amp hours and weighs approximately 1.5 lbs. It is quickly rechargeable using a standard battery port and has an indicator light to display the current battery level in the device.

Figure 5. Battery mount and wiring (left), Kobalt 24 V battery (middle), Buck Converter (right)

2.5 Control System

A more detailed summary of components, test, and design details can be found in [016_DESIGN_Control_Subsystem_Definition].

The control system is controlled using an Arduino Nano and consists of all the amplifiers, signal converters, and wiring for the system. The control system controls the motor based off the comparison between the readings of the two force sensors in the handle and then outputs and updates the signal to a motor that adjusts to the appropriate speed and torque. It is a proportional controller with built-in flexibility to be used as a full PID controller pending a more extensive analysis.

The external load is sampled with a strain gauge and converted to a usable form with an amplifier and ADC. An identical process also samples the cable tension force sensor. These signals are weighted and added to define our control “error.” This error than gets passed through the controller logic which (1) determines whether the user wants to lift or lower the weight based on the imbalance of forces, and (2) outputs the appropriate motor direction and output power. Our microcontroller outputs a PWM signal, which must be converted to an analog voltage to interface with the brushless motor controller board. The phase voltages are activated, causing the motor to spin with a torque/speed defined by the motor dynamics and acts on the environment. The loop then repeats at approximately 2,600 iterations per second.

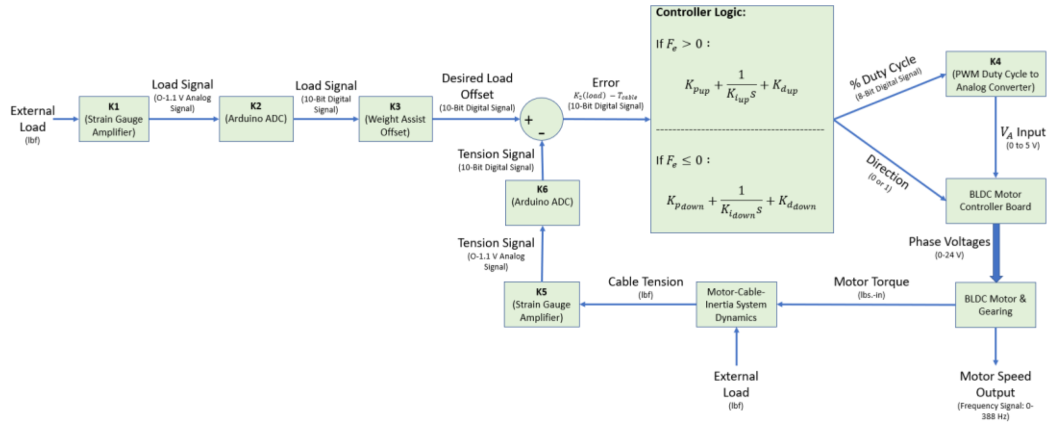


Figure 6. Simplified block diagram for controller logic

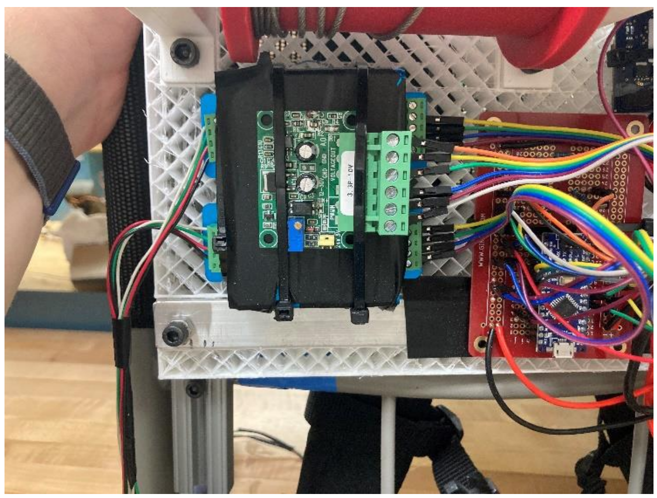


Figure 7. Mounted strain gauge amplifiers and PWM to analog signal converter with wiring to Arduino Nano microcontroller

2.5 Motor and Spool

A more detailed summary of components, test, and design details can be found in [017_DESIGN_Motor_Gear_Subsystem_Definition].

The motor provides all the dynamic assistance to the user. It consists of a 63 W brushless DC motor with an integrated planetary gear (ratio 15:1) to provide sufficient torques and speeds for our application. Overall, our motor is highly efficient, low-noise, and performs its proper function with no noticeable heating.

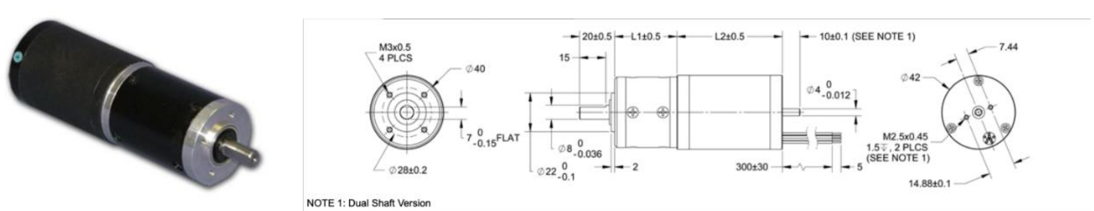


Figure 8. Brushless DC Motor (173S from Anaheim Automation) (left), motor dimensions (right)

To transfer torque to our cable system, we designed a custom spool to fit onto the keyed shaft of the motor and securely attach to the cable. It was built with an interchangeable end to be able to interface with various motor types.

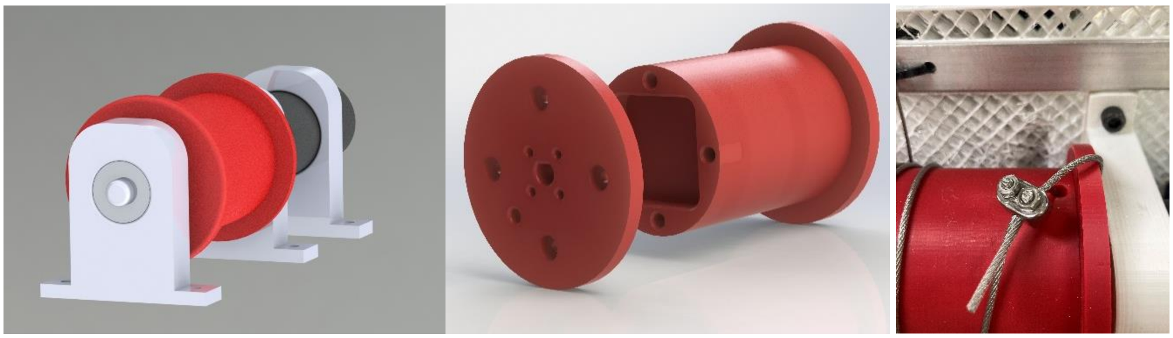


Figure 9. Motor and spool attached to frame mounts (left), interchangeable spool (middle), cable attachment to spool (right)

Artifact ID: 003	Artifact Title: System Performance Summary	
Revision: A	Revision Date: **14 April 2023**	
Prepared by: I. Sorensen		Checked by:
Purpose: *To compile a summary of the system performance*		

Revision History			
Revision	Revised by	Checked by	Date
A	Joshua Vanderpool	Brinler Tanner	14 April 2023

1. Introduction and Summary

In this document, we summarize the ways in which our total system's performance has been measured and validated. We provide links to the more detailed test procedures and some recommendations for future testing.

2. Total System Performance

Our total system performance was gauged using 5 key success measures. These measures are listed in **Table 1** along with a summary of the expected ranges and the empirically measured values.

Table 1. Key success measure summary

Measure	Stretch Goal	Excellent	Good	Poor
System Response Time (Qualitative)	No perceptible delay	Very little delay	Functional despite delay & actuation discontinuities	Delay is an impediment to the task
Load Redirected to the Trunk (%)	50-70%	40-50%	20-40%	<20%
User Comfort (Qualitative 0-5)	Very Comfortable (4.2+)	Moderately Comfortable (3.6-4.2)	Neither Comfortable nor Uncomfortable (2.6-3.5)	Moderately Uncomfortable (1.5-2.5)
Total System Weight (lbs)	0-10	10-12	12-20	20+
Predicted Battery Life (hrs)	>5	4-5	2-4	<2

3. Summary and Links to Key Tests

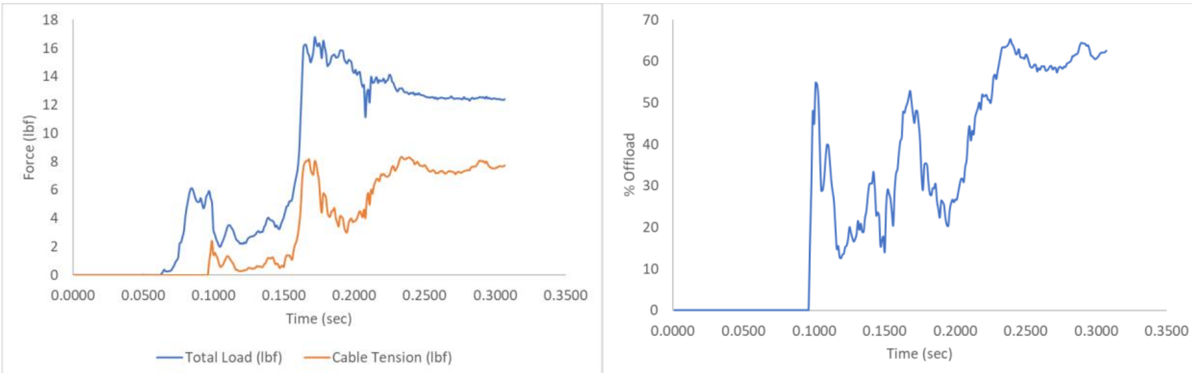
3.1 Load Redirected to Trunk (%)

Objective: To determine how much of the weight felt by the user’s hand is redirected to the trunk.

Procedure: See [024_TPRO_Load_Offloading]

Detailed Results: See [028_TRES_Load_Offloading]

Summary of Results: Overall, the system is currently calibrated to provide approximately 60% redirection of the arm load, particularly when the load is held stably or being lowered. Some nuance is present in the data for the load lifting as the system lags slightly. A representative figure of this test is shown here:



3.2 User Comfort

Objective: To determine how comfortable the overall device is to wear and use. Additionally, it tests how easy it is to don and doff the device.

Procedure: See [025_TPRO_User_Comfort]

Detailed Results: See [029_TRES_User_Comfort]

Summary of Results: Table 2 summarizes the results of the population polled.

Table 2. Results compiled from User Comfort Test

Performance Measure	Recorded Values	Ideal Value
Discomfort after 15 mins	4, 3, 3, 4, 3 **Avg: 3.4**	3
Time to don device (sec)	20, 30, 10, 12, 20 **Avg: 18.4**	30
Time to doff device (sec)	15, 15, 7, 6, 12 **Avg: 11**	30
Time required to learn the device. (mins)	3, 1.5, 15, 5, 5 **Avg: 5.9**	10
Perceived exertion with device on (qualitative percentage)	30%, 20%, 40%, 30%, 40% **Avg: 32%**	50%
Response Time	3, 4, 4, 3.5, 3 **Avg: 3.5**	3

3.3 Total System Weight

Objective: To determine the combined total weight of the entire system. This is a metric of how streamlined and desirable our device would be to wear.

Procedure: See [026_TPRO_System_Weight]

Detailed Results: See [030_TRES_System_Weight]

Summary of Results: The weight of the device was determined to be 10.9 lbs.

3.4 Predicted Battery Life

Objective: To determine the combined total weight of the entire system. This is a metric of how streamlined and desirable our device would be to wear.

Procedure: See [027_TPRO_Predicted Battery Life]

Detailed Results: See [031_TRES_Predicted Battery Life]

Summary of Results: We determined that the average current draw is **0.2 Amps** (if battery can recharge), or **.325 Amps** (if battery cannot recharge). At these current levels, this battery could last approximately **25 hours or 15 hours**, depending on the rechargeability of battery. This is for our one-arm device. Thus, for a two-armed device, we could reasonably assume that the battery could last up to **12.5 or 7.5 hours**. A more refined estimate would require a better understanding of the particular battery.

Figure 1. Test used to determine cycle of device use

4. Miscellaneous Performance Measures

Although not the most important key success measures, we have defined several other performance measures regarding our total system performance. These are summarized in **Table 2.** These metrics have been chosen since they describe other desirable traits as defined by our sponsor, Sandia National Labs. Most of these were so simple that they did not require a separate procedure and results artifact.

Table 3. Miscellaneous System Performance Measures

Measure	Excellent	Good	Poor	Measured Val/Notes
Time for user to don device (sec)	< 30	30-59	60	18
Sampling Rate of Control System (kHz)	1+	0.5-1	<0.5	2.6
Time required for total shutoff and safe-fail of device (s)	.1-.15	.15-.5	0.5+	0.25
Max tension of cable with motor run at full power (lb)	60 +	45 -60	<22.5	*Only applied 25 lbs. to prevent break*
Force required to trigger initial assistance (lb)	3	5	7	<< 3 lbs. (highly sensitive)
Max angle range of shoulder adduction/abduction (degree)	160-180+	90-159	45-89	No restriction
Shoulder range of motion in flexion (degree)	200-225+	60-199	30-59	90
Max angle range of lateral rotation of shoulder (degree)	150-180+	60-150	30-59	60

5. Recommendations for Future Testing

We recommend the following future tests:

- EMG testing of arm and back muscles to determine if overall muscle activation has decreased.
- Metabolic cost testing to determine actual usefulness of device in lowering energy expenditure.
- Our population size for the user comfort testing was small. We recommend repeating this test for a larger population.
- Determine the effects of the Back EMF on battery life. Does it increase the time before the battery drains, or does it damage the battery?

Artifact ID: 004	Artifact Title: Design Reproducibility Guide	
Revision: A	Revision Date: 19 April 2023	
Prepared by: Joseph Edmund		Checked by: Isaac Sorensen
Purpose: *To give a succinct guide and steps to reproduce this project efficiently.*		

Revision History			
Revision	Revised by	Checked by	Date
A	**I. Sorensen**	**J. Edmund**	19 April 2023

1. Introduction and Purpose

This document is intended to provide a high-level overview for how to reproduce our design and the necessary artifacts to do so. We describe which systems are critical and which ones can be adapted, as necessary. We also provide recommendations during each step of how the system could be more easily and effectively made.

2. Steps to Reproduce

1. The first step is to get or make a frame. The exact sizing and type of material used is not as important as ensuring the frame can transfer the load to the trunk of the user. For this reason, we chose to use a backpacking frame due to it already being designed to transfer load to the trunk of the user. See [013_DESIGN_Frame_Subsystem_Definition].

    a. We recommend using a custom-built frame using lighter materials to keep the overall weight down, but whatever is designed should include some form of hip strap as that was very useful and necessary to the design.

2. Next you will need to make the custom parts for the shoulder extension, pulleys, and spool to connect the motor to the cable and the motor mounts. See [013_DESIGN_Frame_Subsystem_Definition]. Like before, it is less important that you follow our design and more important that you get the cable over the shoulder and to the handle in a useful and low friction manner. Length of shoulder extension could be longer due to preference and pulleys on the shoulder extension could be much smaller to save on weight. The cable does however need to be enclosed on the pulleys via some enclosure or other pulley, otherwise it will come off the pulley easily. The spool of our motor could also be much smaller. The diameter of our spool is sufficient for our torque and speed needs; however, this too could be changed if done thoughtfully.

    a. We recommend making the shoulder extension longer to put the neutral handle position further from the body making it more comfortable and useful.

   b. We also recommend using smaller pulleys.

3. Next you will need to make a custom handle to house the strain gauges that will tell the load at the handle and the tension in the cable. To use our design, see [014_DESIGN_Handle_Subsystem_Definition]. This is a crucial subsystem that needs to be done correctly to ensure that the controller logic has correct values to work off of. If done incorrectly it may lead to overall issues in the system that become hard to debug.

   a. We recommend switching to multi-axial strain gauges to get rid of unwanted moments that can cause incorrect readings.
   b. We also recommend adjusting the outer shell of the handle to be more ergonomic.

4. Next you will need to order and connect all the electrical components according to the electrical schematic found [023_System_Wiring_Schematic]. To see full list of materials including the electrical components we used see [022_DESIGN_Full_Bill_Of_Materials]. Like before you may choose to use other components then the ones we used.

   a. We recommend putting the components on a custom PCB to get rid of wasted space weight, and to help with unwanted noise in the system.
   b. We also recommend that you use a dedicated controller for sampling the inputs from the strain gauges in the hand because the faster that sampling the smoother your control will be.

5. Finally, you will want to have a way to connect your components to the backpack. We used a 3D printed lattice type material rigidly attached to the back of the frame. See [013_DESIGN_Frame_Subsystem_Definition]. This was useful for prototyping and testing as it was easy to move components around. How you connect the components is not as important as ensuring that they are in good places and are secure to the frame.

   a. We recommend having the spool attached further out from the center to align the spool with the shoulder. This gets rid of a lot of unnecessary friction and focuses the force put on the cable from the motor in one direction rather than pulling the cable at an angle.
   b. The use of a Boden tube on the cable in between the shoulder extension and the motor spool could also be a useful change.

6. Once the entire system is connected and put on the frame the only thing left is to upload the code to the Arduino or other controller. See [Appendix B] for our code. Once code is uploaded the system is ready to be used/tested.

   a. We recommend keeping the code the same initially and leaving the derivative control at 0. However, we do recommend that you test other values for the PID coefficients to get a stable system as the coefficients will need to be changed if your overall system is different.

Arifact ID	Artifact Title
5	Total System Requirements Matrix
Revision: Rev D	Date: Rev Date 4/19/2023
Team: Herculift	
Prepared By: Isaac Sorensen	
Checked By: Joshua Vanderpool	

		Key Success Measures					Basic Measures						
Units		%	Qualitative	Comfort Scale	Lbf	Hours	Seconds	Seconds	Degrees	Degrees	Lbf		
Performance Measures		Percent of load at hand offloaded by actuated cable tension.	Response time of actuation system	User Comfort	Total Device Weight	Battery life under normal work conditions	Time for user to don device	Time required for total shutoff and safe-fail of device	Shoulder range of motion in flexion	Shoulder range of motion in abduction/adduction	Max tension of cable with motor run at full power	Market Ratings	
Market Requirements	Importance (optional)	1	2	3	4	5	6	8	9	10	12	Rating	Artifact ID
1 Reduce fatigue, specifically biceps and deltoid fatigue		*	*	*	*				*	*		3	028/029
2 Device assisted lifting is task-agnostic		*	*						*	*		2	/028
3 The device can be used continuously for half a work shift				*	*	*						2	029/031
4 The device can be used comfortably for multiple days of work				*	*		*					2	029/031
5 Device fails safely and protects against injury from cables and actuating parts.			*					*			*	3	/029
6 The device permits use of site equipment (Whites, PPE, Tools, Lifts, Etc)							*					2	/029
7 Device aids in repeatedly lifting 45 lbf tarps (with two hands) by redirecting a portion of the load to the trunk		*									*	2	/028
8 Device support adapts to tarp weight and dynamic stresses			*					*			*	3	/028
9 The device is intuitive to the user			*				*	*	*	*		1	/029
Importance (optional)													

Market Ratings: Rating 1-3. 3 is most relevant, 1 is least.

			1	2	3	4	5	6	8	9	10	12
Ideal Values		Lower Acceptable Limit	20%	Slight jumping	"Neither comfortable or uncomfortable" (2.6-3.5)	NA	3	NA	NA	90°	80°	22.5
		Ideal	50%	unpercievable	"Moderately comfortable" (3.6-4.2)	10	4	30	0.5	120°	100°	45
		Upper Acceptable Limit	NA	unpercievable	NA	20	NA	60	0.75	200°	150°	60
		Target	50%	slightly percievable	"Moderately Comfortable" (3.6-4.2)	12.5	4	30	0.5	120°	100°	
		Stretch	60%	unpercievable	"Very comfortable" (4.2+)	8	5	30	0.5	200°	150°	45
Real Values	Predicted	Artifact	/028	/029	/029	/026	/031	/029	—	—	—	—
		Value	50%	slightly percievable	"Very comfortable" (4.2+)	12.5	4.5	30	0.5	200°	150°	50
	Measured	Artifact	/028	/029	/029	/026	/031	/029	—	—	—	—
		Value	60%	slightly percievable	"Very comfortable" (4.2+)	10	15	25	0.65	200°	150°	55

Revision History

Rev.	Date.	By	Checked By	Description
--	9/16/2022	Team 37	Yes	Initial release
A	11/15/2022	I. Sorensen	I. Sorensen	Preparation for Architecture Review
B	12/1/2022	I. Sorensen	I. Sorensen	Revision from Sponsor/Pod Instructor Feedback
C	15-Feb	J. Vanderpool	I. Sorensen	Updated to new 5 subsystems. Clarified measurement
D	4/18/2023	C. Payne	I. Sorensen	Cleaning and refining for final submission

Requirements Matrix Templaterev 3.2 8 June 2018 CDS

Arifact ID	Artifact Title
006	Herculift frame Requirement Matrices

Revision: Rev D	Date: Rev Date 4/10/2023
Team: Herculift	
Prepared By: Isaac Sorensen	
Checked By: Brinler Tanner	

	Market Requirements	Importance (optional)	Key Success Measures					Basic Measures				
	Units		Inches	Lbs	Scalar	Lbf	Scalar	Scalar	Sec	Degrees	Degrees	Degrees
	Performance Measures		Max displacement/deflection of frame components while in use	Frame weight	Time before user-discomfort rating exceeds 4 on a scale from 0-10)	Maximum theoretical load at endpoint before failure (using FEA)	Max angle range of shoulder adduction/abduction	Shoulder range of motion in flexion	User Don and Doff time	Max angle range of lateral rotation of shoulder	Spinal flexion angle with frame on	Spinal rotation range while wearing frame
			1	2	3	4	8	9	10	11	12	13
1												
2	Frame can maintain rigidity during actuation		*			*						
3	Frame is lightweight											
4	Frame distributes applied load to the torso											
5	Frame minimizes restraints of natural movements			*	*				*			
6	Frame mounts to shoulders and torso in a secure manner				*		*	*				
7	Allows for freedom of movement in normal shoulder abduction/adduction and rotation						*	*		*	*	*
8	Don/Doff Method is intuitive to the user.								*			
9	Attaches securely and comfortably to the arm such that it can be used comfortably for multiple continous work days.				*		*				*	

			1	2	3	4	8	9	10	11	12	13
Ideal Values		Lower Acceptable Limit	NA	NA	1	100	40	+/- 30	NA	40	10	15
Ideal Values		Ideal	0.25	4	2	300	60	+/- 45	30	60	20	22.5
Ideal Values		Upper Acceptable Limit	0.5	8	4	NA	90	+/- 60	60	90	30	45
Real Values		Target	0.25	4	2	300	60	+/- 45	30	60	20	22.5
Real Values		Stretch	0.15	2	1	400	90	+/- 60	25	90	25	45
Real Values	Predicted	Value	0.1	2	1	400	90	+/- 60	25	100	25	45
Real Values	Measured	Value	0.1	2	1	400	90	+/- 60	25	100	25	45

Revision History

Rev.	Date.	By	Checked By	Description
--	9/16/2022	Team 37	Joseph Edmund	Initial release
A	11/16/2022	I. Sorensen	Tyler Dickson	Preparation for Architecture Review
B	12/6/2022	B.M.Tanner	Brinler Tanner	Clarification of ideal values
C	15-Feb	J. Vanderpool	C. A. Payne	Incorporated Shoulder cantilever into subsystem
D	4/10/2023	C. A. Payne	I. Sorensen	Cleaning and refining for final submission

Requirements Matrix Templaterev 3.2 8 June 2018 CDS

Arifact ID	Artifact Title
7	Handle Subsystem Requirements Matrix

Revision: Rev D	Rev Date 4/10/2023
Team: Herculift	
Prepared By: Isaac Sorensen	
Checked By: Brinler Tanner	

Key Success Measures

		Importance (optional)	1	2	3	4
	Performance Measures		Dimensions of wrist subcomponent	User Comfortability (0-5)	Time to pickup and release handle completely	Handle design allows for proper strain guage function
	Units		Inches	Qualitative	Seconds	Y/N
	Market Requirements					
1	Device is compatible with clean room suit.		*			
2	Protects against wrist injuries -- adding no additional stress to the wrist			*		
3	Handle can be used comfortably for 8-hour shifts for multiple repeated days			*		
4	Don/Doff Method Allows for Quick Pickup/Drop off of handle		*		*	
5	Handle contains emergency shut-off button					*
		Importance (optional)				
Ideal Values	Lower Acceptable Limit		NA	2	NA	NA
	Ideal		3x1x1	4	3	Yes
	Upper Acceptable Limit		4x2x2	NA	5	NA
Real Values	Target		3x1x1	3	3	Yes
	Stretch		3.5x1.5x.15	4	2	Yes
	Predicted	Value	5.5X1.5x1.5	3	<.02	Yes
	Measured	Value	5.5X1.5x1.5	2.5	<.02	Yes

Revision History

Rev.	Date.	By	Approval	Description
--	10/24/2022	Team 37		Initial release
A	11/16/2022	I. Sorensen	I.Sorensen	Preparation for architecture review
B	12/6/2022	B.M.Tanner	I.Sorensen	Clarification of ideal values and stretch goals
C	15-Feb	J. Vanderpool	I.Sorensen	Incorporated Cable into this subsystem
D	4/10/2023	C. A. Payne	I.Sorensen	Cleaning for final submission

Requirements Matrix Templaterev 3.2 8 June 2018 CDS

Arifact ID	Artifact Title
008	Power Requirements Matrix
Revision: Rev. C	Rev Date 4/10/2023
Team: Herculift	
Prepared By: Isaac Sorensen	
Checked By: Brinler Tanner	

Key Success Measures

	Subsystem Requirements	Importance (optional)	1	2	3	4	5	6	7
	Performance Measures		Average power draw of device during normal use case.	Number of steps to turn device on	Weight of Battery	Dimensions of Battery	Time required to change Battery	Max temperature of any component in electrical system after 1 hour of use	Someone unfamiliar with our project was able to activate the device
	Units		Amps	Scalar	Lbs	In x In x In	seconds	Temperature (deg F)	Y/N
1	Battery lasts for half of a work shift		*						
2	Activation/Deactivation is user friendly			*					*
3	Power systems are contained to prevent electrical shock or burns							*	
4	Battery is quickly changeable					*	*		
5	Activation/Deactivation possible while wearing the device								
6	Battery is light				*				
	Importance (optional)								

			1	2	3	4	5	6	7
Ideal Values	Lower Acceptable Limit		NA	1	NA	NA	NA	NA	NA
	Ideal		0.5	2	2	3x3x3	4	80	Yes
	Upper Acceptable Limit		0.75	4	4	6x6x3	8	106	NA
Real Values	Target		0.5	2	2	3x3x3	4	80	Yes
	Stretch		.35.	1	1.5	4x4x4	2	70	NA
	Predicted	Value	0.8	1	1.5	4x4x4	2	70	Yes
	Measured	Value	0.75	1	1.5	2X4.5X3	2	70	Yes

Revision History

Rev.	Date.	By	Approval	Description
--	9/16/2022	Team 37	Yes	Initial release
A	11/16/2022	I. Sorensen	I.Sorensen	Preparation for architecture review
B	12/6/2022	B.M.Tanner	I.Sorensen	Correction of target and ideal values
C	4/10/2023	C.A. Payne	I.Sorensen	Cleaning and revising for final submission

Requirements Matrix Templaterev 3.2 8 June 2018 CDS

Arifact ID	Artifact Title
9	Control Requirements Matrix
Revision: Rev. C	Date: 4/10/2023
Team: Herculift	
Prepared By: Isaac Sorensen	
Checked By: Chris Payne	

Key Success Measures

	Market Requirements	Importance (optional)	Acutation response time to change in load	Max cable pull speed	Robust code tests with various 'failure or edge case' inputs	Force required to trigger initial assistance
	Units		Seconds	in/sec	NA	Lbf
	Performance Measures – Importance (optional)		2	3	4	7
1	Control system fails safely. Breakpoints are intended and built into system. (Positive feedback, protect against unstable system, root locus--find the zeros in the TF of the control function)					
2	Control system supports task-agnostic nature of device					
3	The device is intuitive to the user		*			*
4	Device offloading adapts to tarp weight and dynamic stress.					*
5	Control system reacts smoothly and quickly			*	*	
6	Device has an emergency shut off button		*			
	Importance (optional)					
Ideal Values	Lower Acceptable Limit		0.1	0.1	NA	3
	Ideal		0.25	0.3	Pass	5
	Upper Acceptable Limit		0.5	0.5	Pass	7
Real Values	Target		0.25	0.3	Pass	5
	Stretch		0.15	0.4	Pass	4.5
	Predicted	Value	0.2	0.25	Pass	3.5
	Measured	Value	0.15	0.3	Pass	3.5

Revision History

Rev.	Date.	By	Approval	Description
A	9/16/2022	Team 37	Yes	Initial release
B	12/6/2022	B.M.Tanner	I.D. Sorensen	clarification of target values and stretch goals
C	2/15/2023	I.D. Sorensen	I.D. Sorensen	Clarification of performance measures with refined control system
D	4/10/2023	C.A. Payne	I.D. Sorensen	Final revisions and cleaning document

Requirements Matrix Templaterev 3.2 8 June 2018 CDS

Arifact ID	Artifact Title
10	Motor and Gearing Requirements Matrix

Revision:	Date:
Rev D.	19-Apr-23

Team:
Herculift

Prepared By:
Isaac Sorensen

Checked By:
Christian Payne

Performance Measures

			1	2	4	5
	Units		Seconds	Ft/sec	Hours	Lbf
	Performance Measures		Reaction time when new direction or load sensed	Max cable pull speed	Time Required for new user to learn and use device	Force required to trigger initial assistance
	Market Requirements	**Importance (optional)**				
1	Control system fails safely. Breakpoints are intended and built into system. (Positive feedback, protect against unstable system, root locus--find the zeros in the TF of the control function)					
2	Control system supports task-agnostic nature of device				*	
3	The device is intuitive to the user		*			*
4	Device offloading adapts to tarp weight and dynamic stress.					*
5	Control system reacts smoothly and quickly			*	*	
6	Device has an emergency shut off button		*			
		Importance (optional)				
Ideal Values		Lower Acceptable Limit	0.1	0.1	NA	3
		Ideal	0.25	0.3	4	5
		Upper Acceptable Limit	0.5	0.5	8	7
Real Values		Target	0.25	0.3	4	5
		Stretch	0.15	0.4	3	4.5
	Predicted	Value	0.2	0.4	1	3.5
	Measured	Value	0.005	0.4	1	3.5

Revision History

Rev.	Date.	By	Checked By	Description
A	9/16/2022	Team 37	Yes	Initial release
B	12/6/2022	B.M.Tanner	I.D. Sorensen	clarification of target values and stretch goals
C	2/15/2023	J. Vander	I.D. Sorensen	Update requirements
D	4/19/2023	C.A. Payne	I.D. Sorensen	Cleaning and refining for final submission

Requirements Matrix Templaterev 3.2 8 June 2018 CDS

Artifact ID: 011	Artifact Title: **Overall System Definitions**	
Revision: **D**	Revision Date: **13 April 2023**	
Prepared by: **Joshua Vanderpool**		Checked by: **Isaac Sorensen**
Purpose: This document defines the system and each subsystem, their interactions, and justifications for each decision made. Target values and the design criteria for all systems are found in the respective matrices. For subsystem interactions if subsystem B is not mentioned in the interaction for subsystem A, then subsystems A and B do not interact.		

Revision History				
Revision	Revised by	Checked by	Date	Changes
A	**B. M. Tanner**	**J. Vanderpool**	**Dec 08 2022**	
B	**B.M. Tanner**	**I. Sorensen**	**Jan 18 2023**	**Updated for new architecture (See DM 018)**
C	**B.M. Tanner**	**J. Vanderpool**	**Feb 24 2023**	**Modified subsystem definitions. Reduced to 5 subsystems. Updated all related information.**
D	**J. Vanderpool**	**B. M. Tanner**	**13 April 2023**	**Updated for Final design packet.**

1. Overall Summary

Our project goal is to design a lift assist device for Sandia National Laboratories to further develop and test. This lift assist device is intended to help Department of Energy workers who repetitively lift heavy lead blankets while working on nuclear waste sites. This repetitive lifting causes bicep and deltoid tears. We are to develop a test-ready, electronically-controlled, one-arm device to reduce fatigue in the bicep and shoulder during repetitive heavy lifting. Our design is to be delivered by April 06, 2023 using less than $3000, and within 1800-man hours.

Sandia National Labs has charged us with developing a prototype and control system to assist a single-arm. At the end of the semester, we will deliver the design to Sandia for further testing, refinement, and preparation for market release. Therefore, they have instructed us to not prioritize adjustability of the design. The priority is the selection of appropriate components, motor sizing, design concept, and control system documentation.

Our design consists of a frame with a motor and control system mounted on the back. A cable runs through a swivel joint at the shoulder and connects to a handle at the hand. Two sensors in the handle senses the load at the hand. Sensors at the motor sense both the current drawn by the motor and the displacement of the cable. These signals are combined at the microcontroller to determine the needed actuation. A clutching system is also integrated to allow a stable carry of the device in low power.

Figure 1: Physical design of architecture

2. Design Decisions & Justification

2.1 Design Q & A:

Q: Why is only one arm being designed for the end product of this project?

A: The device is symmetrical and designing one arm means that the other arm will also be designed. As the project does not require a consumer-ready product, one arm is sufficient. The only system this affects is the power, which will eventually need to have twice the capacity for two arms. The system will be designed for only one arm, including the battery, and the next team will expand the battery capacity once the design is delivered at the end of this project.

Q: How was the overall system design justified?

A: The overall system design was justified by comparison to market exoskeleton designs, physical prototyping, and observation of subsystem interactions through CAD models. The design decisions were based on mathematical models of force in relation to geometrical lengths of the actuation subsystem, simplicity and targeting of off-the-shelf parts, market comparison to current exoskeletons (ShoulderX, UC Berkeley HART Exoskeleton Lab), and initial prototyping and development of CAD models to observe biomechanics and interfaces.

Q: Why was a scoring matrix used for subsystem justification?

A: A scoring matrix was used to justify the design decisions for subsystems using characteristics such as user-safety, actuation and biomechanical compatibility, manufacturability, and complexity. The scoring matrix helped rank the above actuation subsystem as the highest ranking in terms of its characteristics. (See CR_003_Evaluation_Matrix_Shoulder)

Q: Why was a backpacking frame chosen for the exoskeleton?

A: The backpacking frame was chosen for the exoskeleton because it was extremely cheap, readily accessible, and easy to cannibalize. Additionally, the use of a waist strap allows for effective transfer of the load to the trunk, which has been refined by the industry for maximum comfort and load distribution.

Q: Why was the control system designed for simplicity?

A: The control system was designed for simplicity to make it easier to use. The main control uses input from the load at the hand, motor current, and cable displacement. The components were selected based on their accessibility, and the team was familiar with Arduino microcontrollers.

Q: How was the power system for the exoskeleton chosen?

A: The power system for the exoskeleton was chosen based on its optimized weight and battery life.

While the end-product will eventually include both arms the device is symmetrical and thus if one arm is designed, the other is as well. As we do not need a consumer-ready product at the end of this project one arm is sufficient. The only system this affects is the power, as eventually the power will need to have twice the capacity for two arms. But we will design the system for only one arm, including the battery. Once the design is delivered at the end of this project the next team will expand the battery capacity.

The overall system was justified by comparison to market exoskeleton designs, physical prototyping, and observation of subsystem interactions through CAD models. Much of the overall justification is grounded in the individual subsystem justification, described below. Furthermore, we have justified our architecture through the weight and cost estimates (see Table 1), which fall within Sandia's request for the overall component cost to be less than $1000 and the weight to be minimized. In all our justification is founded in:

- Mathematical models of force in relation to geometrical lengths of the actuation subsystem
- Simplicity and targeting of off-the shelf parts.
- Market comparison to current exoskeletons (ShoulderX, UC Berkely HART Exoskeleton Lab)
- Initial prototyping and development of CAD models to observe biomechanics and interfaces.

2.2 Subsystem Justification

We justified our design decisions, particularly for the subsystems, using market studies and scoring matrices. A scoring matrix was developed using characteristics such as user-safety, actuation and biomechanical compatibility, manufacturability, and complexity. The above actuation subsystem was the highest ranking of this matrix.

The backpacking frame was extremely cheap, readily accessible, and easy to cannibalize. The use of a waist strap allows for effective transfer of the load to the trunk—these backpacking frames and straps have been refined by the industry for maximum comfort and load distribution.

The control system is designed for simplicity. The main control will use input from the load at the hand, motor current, and cable displacement. The components were selected based on component accessibility and our familiar with Arduino microcontrollers. Similarly, the power system was chosen because of its optimized weight and battery life.

3. Subsystem Decomposition

The total architecture is divided into the following subsystems and key components:

Table 2: Description of subsystems

Subsystem	Description
Controls	The control system will be the brain connecting the sensor inputs (current to motor, force at hand, displacement of cable) to outputs (motor acutation, cable clutch). This system will be driven by an Arduino nano microcontroller, powered by our battery (see below), and connected to the drill motor and clutch mechanism.
Power	The power control subsystem will interface directly with the Controls subsystem to power our controls and motors. It will be an 24V 5.0ah Kobalt drill battery. This will be routed through a voltage regulating circuit.
Frame	The frame subsystem will be the glue that holds the rest of the subsystems together. It contains a swiveling joint at the shoulder that routes the cable to the handle.
Handle & Cable	The cable is 1/16'' steel cable spooled near the motor and connects at the handle. This handle is a simple hook connected perpendicular to a hand grip. It also houses a force sensor cantilever beam and has a connection for the cable. There will also be a “kill-switch” attached.
Motor & Gearing	The motor is an Anaheim Automation motor. This motor interfaces with gears of our own design attached to the cable spool.

4. Interactions

The subsystems interact with each other as shown below. All components involved in interactions are described in the respective subsystems.

	Motor/ Gearing	Cable/ Handle	Frame	Power	Control
Control	1	2		3	
Power	4		5		
Frame	6	7			
Cable/ Handle	8				
Motor/ Gearing					

Explanation of interactions: (See numbers above)

1. The control system interacts with the motor via the motor controller.
2. The handle has wires from the two embedded strain gauges that are read into the Arduino Nano through two signal amplifiers.
3. The battery powers the Arduino and motor, though a buck converter is used to provide 24 V for the motor and 5 V for the Arduino.
4. The battery powers the Arduino and motor, though a buck converter is used to provide 24 V for the motor and 5 V for the Arduino.
5. The battery is mounted to the back of the frame.
6. The motor and spool are mounted to the frame via motor mounts.
7. The cable is laid over two pulleys above the user's shoulder.
8. The cable is spooled onto the spool connected directly to the motor.

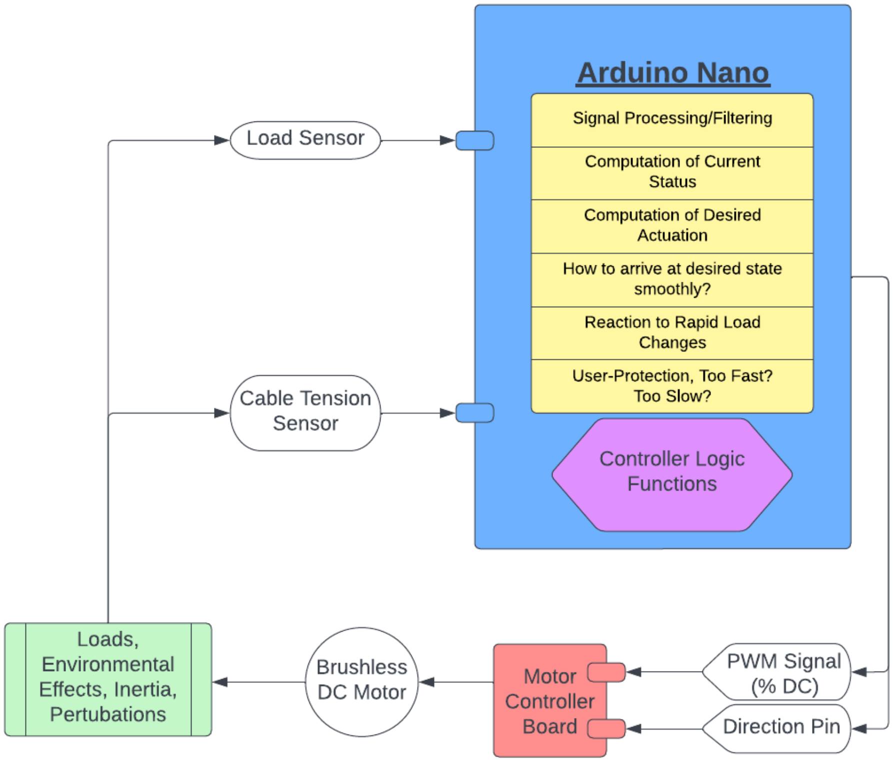


Figure 2: Power, Microcontroller, Sensing, and Actuation Interactions

5. Key Technologies

Subsystem	Technology	Off the Shelf or Custom Designed?
Frame	1. Shoulder swivel joint and pulleys **Key:** Keeps cable contained, determines high range of motion 2. Wearable frame **Key:** Determines user comfort and redistribution of load	1. Custom designed in EB Prototyping Lab 2. Off-the-shelf part
Power	1. Rechargeable System Battery & Charger **Key:** Determines duration of system use, system weight	1. Off-the-shelf part (24V 5.0ah Kobalt drill battery)
Control	1. Microcontroller (Arduino Nano) **Key:** Provides computation power, determines system reaction time 2. Voltage regulators **Key:** Keeps power consumption and voltage in check 3. Current and motor displacement sensors	1. Off-the-shelf-part 2. Off-the-shelf part 3. Off-the-shelf part

	Key: Provides essential inputs to sense current state of output	
Cable & Handle	1. Steel cable **Key:** Determines max load that can be supported 2. Ergonomic grip handle **Key:** Determines user comfort during long use of device 3. Hand load force sensor **Key:** Provides essential input for control system	1. Off-the-shelf part 2. Custom designed part 3. Off-the-shelf part
Motor & Gearing	1. Motor with Motor Driver **Key:** Determines max torque and lifting power of system, determines power consumption 2. Gearing and Spool **Key:** Transfer torque from motor to linear cable motion	1. Off-the-shelf part (Anaheim Automation) 2. Custom Deisgned Part

6. Cost, Weight, and Size Estimates

For clarity, we once again present this table for the overall estimates of the architecture. For a more complete breakdown of parts and materials, see 019_DESIGN_Bill_of_Materials.

Table 3: Estimates of cost, weight, dimensions, and feasibility

Total Estimates	Details
Cost ($ USD)	$875.28
Weight (lb.)	10.90 lb.
Size	24x8x40 inches (in anatomical position)

Artifact ID: 012	Artifact Title: **Subsystem Interactions**
Revision: C	Revision Date: **13 April 2023**
Prepared By: Chris Payne	Checked By: Joshua Vanderpool
Purpose: This document defines the system and each subsystem, their interactions, and justifications for each decision made. Target values and the design criteria for all systems are found in the respective matrices. For subsystem interactions if subsystem B is not mentioned in the interaction for subsystem A, then subsystems A and B do not interact.	

Revision History				
Revision	Revised by	Checked by	Date	Changes
A	**B. M. Tanner**	**J. Vanderpool**	**Dec 08 2022**	
B	**B.M. Tanner**	**I. Sorensen**	**Jan 18 2023**	**Updated for new architecture (See DM 018)**
C	**J. Vanderpool**	**C. Payne**	**13 April 2023**	**Updated for Final Design Packet**

Interactions

The subsystems interact with each other as shown below. All components involved in interactions are described in the respective subsystems.

	Motor/ Gearing	Cable/ Handle	Frame	Power	Control
Control	1	2		3	
Power	4		5		
Frame	6	7			
Cable/ Handle	8				
Motor/ Gearing					

Explanation of interactions: (See numbers above)

1. The control system interacts with the motor via the motor controller.
2. The handle has wires from the two embedded strain gauges that are read into the Arduino Nano through two signal amplifiers.
3. The battery powers the Arduino and motor, though a buck converter is used to provide 24 V for the motor and 5 V for the Arduino.
4. The battery powers the Arduino and motor, though a buck converter is used to provide 24 V for the motor and 5 V for the Arduino.
5. The battery is mounted to the back of the frame.
6. The motor and spool are mounted to the frame via motor mounts.
7. The cable is laid over two pulleys above the user's shoulder.
8. The cable is spooled onto the spool connected directly to the motor.

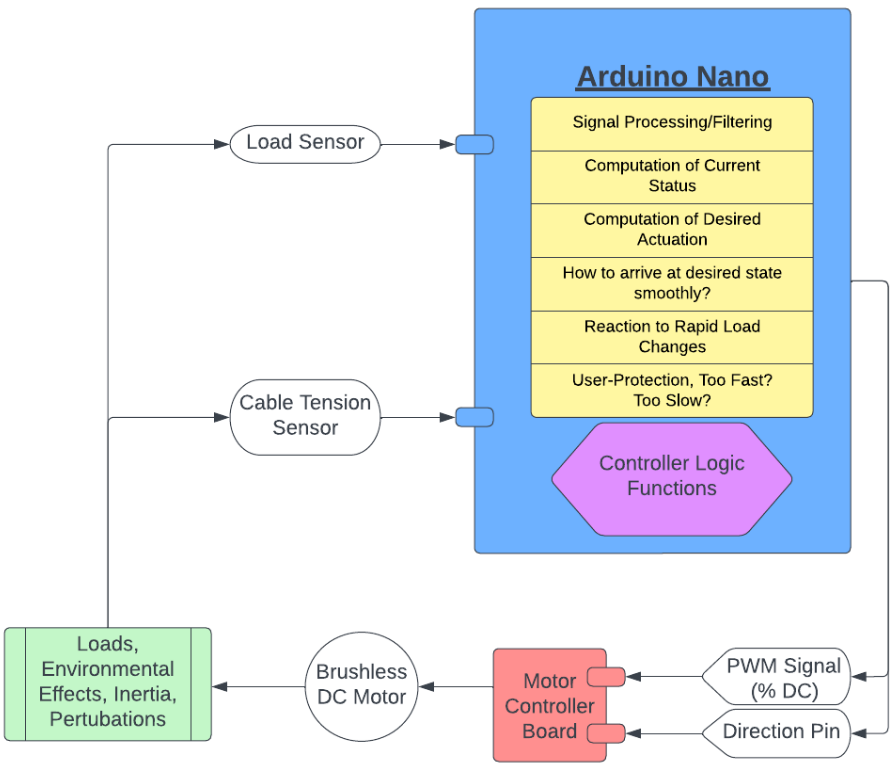


Figure 2: Power, Microcontroller, Sensing, and Actuation Interactions

Artifact ID: 013	Artifact Title: Frame Definition	
Revision: D	Revision Date: 18 April 2023	
Prepared by: Chris Payne		**Checked by:** Brinler Tanner
Purpose: *Provide definition for the Frame Subsystem*		

Revision History			
Revision	Revised by	Checked by	Date
--	Chris Payne	Brinler Tanner	06 January 2023
A	Brinler Tanner	Chris Payne	02 January 2023
B	Brinler Tanner	Isaac Sorensen	27 February 2023
C	Joshua Vanderpool	Chris Payne	11 April 2023
D	Isaac Sorensen	Brinler Tanner	18 April 2023

1. Design Summary

Figure 1: Solid Works model of our frame subsystem

The frame of the device attaches to the user's torso with over-the-shoulder straps typical of backpacks, as well as waist straps. The power, controls, and shoulder subsystems are connected to the frame, which also holds the motor, wiring, and spool. The cable runs from the spool over a cantilever beam, which extends six inches from the frame over the shoulder to the handle. The frame design was chosen because it fits like a backpack and is already established and developed. The mounting on the back of the frame was designed to fit this specific frame, but the exact mounting configuration is not crucial as it may change based on the frame used. Drawings of the cantilever beam (shoulder crane) and motor mounts are included in this final report.

1.1 Recommendations for Improvement:

- Find a more ergonomic base-frame.
- Design placement of components to not add strain or moments to user's back when motor is actuated.
- Create a more rigid connection for motor and spool.
- Add torsional spring to swivel at shoulder to create an equilibrium point for the system.

2. Design Details

2.1 General

All components used in this subsystem can be found in the Control Subsystem Section of the [022_DESIGN_Full_Bill_Of_Materials]

The 3D CAD files for the pulley guards, angle stop, and motor/spool housing can be found here.

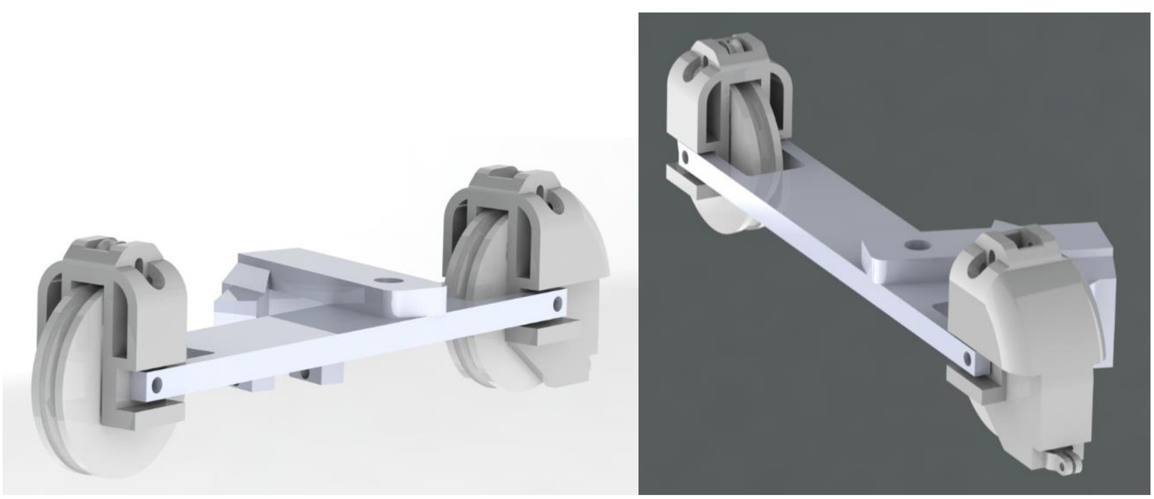
The drawing for the aluminum cantilever can be found here:

2.2 Added Parts and Features

We developed the following components:

1. Pulley guards
2. An angle-stop device
3. Mounting brackets for the motor and spool.

Although it displayed a high range of motion, this caused the cable to easily slip out of the pulley track. Additionally, we needed to protect the user from over-rotation of the rigid aluminum bar that swiveled at the shoulder of the frame.



Figures 2 and 3: Two views of the shoulder cantilever with pulley guards and angle stop.

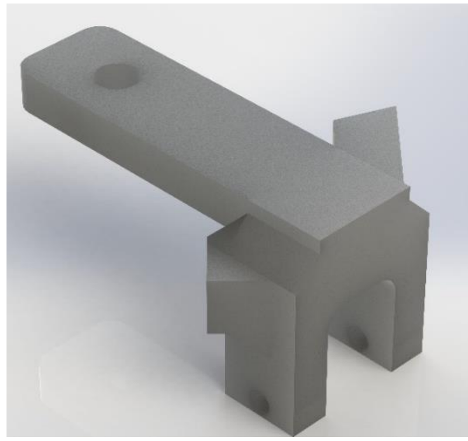


Figure 4: Angle stop device

The housing that attaches the motor and spool is essential for maintaining alignment and also is what transfers the load from the cable to the frame and hopefully the hips of the user.

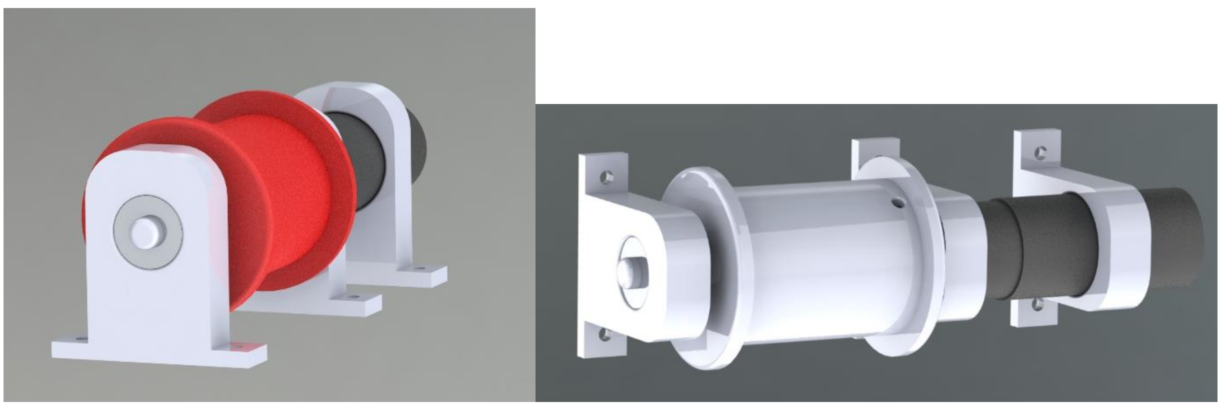


Figure 5: Motor and Spool mounts to attach to the frame

3. Design Decisions

Q: What tests were run on to confirm the function of this subsystem?

[033_TRES_Motor_Characterization]

[028_TRES_Load_Offloading]

Q: How did we arrive at this design?

A: The frame was purchased early on in our prototyping process, and we never encountered a need to change to a different frame. We wanted to have some modularity in our design so we used aluminum t-slot so that the mounting system could be shifted up or down.

Q: How was this subsystem validated?

A: It has been an effective system throughout prototyping while also being comfortable and providing protection. At this step in the project the frame needed to provide mounting for all other systems which this does effectively. The design of the frame also provides protection for the user from the electrical and physical components.

Q: What is the frame design for the device, and why was it chosen?

A: The frame of the device attaches snugly to the user's torso and has over-the-shoulder straps typical of backpacks, as well as waist straps to improve the re-direction of load from the biceps and shoulders to the torso and hips. The frame design was chosen because it fits like a backpack and is already established and developed.

Q: What components are connected to the frame?

A: The power, controls, and shoulder subsystems are all connected to the frame. Additionally, the motor, wiring, and spool are also connected to the frame.

Q: How does the cable run from the spool to the handle?

A: The cable runs from its spool over the cantilever with two pulleys to the handle.

Q: How does the frame design reduce stress in the back?

A: Placing weight lower on the back will reduce stress in the back and improve the user's experience.

Our decision is in line with our observations of the design of a product already on the market: [GA_004_Shoulder_X_Lessons | Powered by Box]

A link to the model, code, and explanation of such that generated the graphs below is documented here: [MO_003_Arm_Patella_Model | Powered by Box]

4. Interfaces

As the attachment point for all other subsystems the frame has interactions with almost all other subsystems.

Subsystem:	Interaction with Frame:
Power	**The battery of the device is mounted at the base of the frame.**
Controls	**The electronics, motors, and force sensors are all located on the middle and base of the frame.**
Motor and Gearing	**The frame provides the mounting for the gearing and alignment for their central axis. It must be rigid enough to not flex under the loads provided.**

Artifact ID: 014	Artifact Title: Wrist subsystem definition	
Revision: B	Revision Date: 19 April 2023	
Prepared by: Brinler Tanner		**Checked by:** Tyler Dickson
Purpose: *Definition of Wrist subsystem*		

Revision History			
Revision	Revised by	Checked by	Date
A	Brinler Tanner	J. Vanderpool	13 April 2023
B	Isaac Sorensen	Joseph Edmund	19 April 2023

1. Design Summary

The handle consists of a plastic housing with two strain gauges in opposite directions of each other. These strain gauges serve as the input to the control system. The handle secures the cable and allows for force transfer between the motor and the load. A second load cell measures the external load being carried. Supportive scaffolding is present inside the handle to support the forces experienced by the strain gauges. A channel for wires is also present.

Although a more ergonomic is recommended for future use, we were tasked with reducing elbow and bicep injuries–injuries typically do not occur in the wrist.

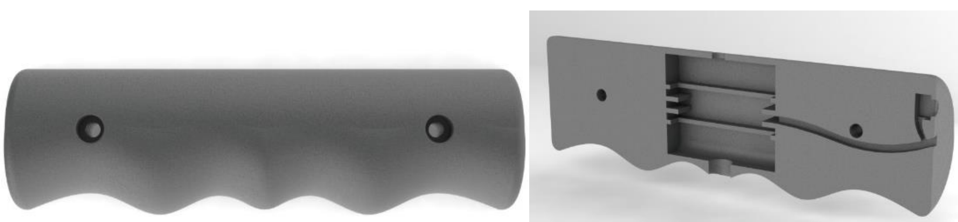


Figure 1. Custom 3D printed handle

Figure 2. Printed version of handle with wiring and hook

1.1 Recommendations for Improvement:

- The outside shape of the handle could be optimized for an ergonomic feel.
- Instead of running wires through the side of the handle, find a wire cable that can both hold the load and house the wire connections.
- Create a more rigid connection for the hook.
- Replace single-axis strain gauges with multi-axis gauges.

2. Design Details

2.1 General

All components used in this subsystem can be found in the Control Subsystem Section of the Bill of Materials [022_DESIGN_Full_Bill_Of_Materials]

For CAD Files see CAD Directory

2.2 Strain Gauges

The strain gauges were pulled from 2 HEETA Fishing Scales with a 110 lbs capacity. These were chosen because of their sufficient accuracy, attached hook, and compact design.

Figure 3. HEETA scale from which strain gauges were made

The following steps were taken to create the strain gauges as a “made from part”:

1. The outer housing of the scales was removed, including the screen output.
2. The cantilever-style strain gauge was then removed, and the 4 connecting wires were identified.
3. Use a multi-meter to guarantee which wire serves which function (each strain gauge may be wired differently i.e. a full bridge, quarter bridge, etc.).
4. In general, we found that the wires were as follows: Red (Positive Excitation E+), Black (Negative Excitation E-), Yellow (Positive Signal S+), and White (Negative Signal S-).

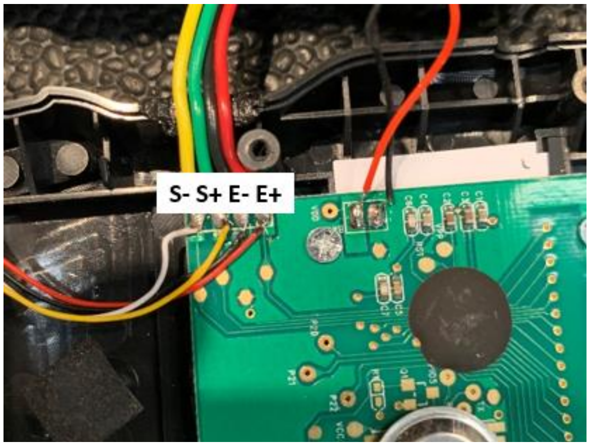


Figure 4. Wiring of strain gauge connections

5. Remove the wires from the original PCB and solder them to long stranded wire for connection to the strain gauge amplifiers. [016_DESIGN_Control_Subsystem_Definition]
6. Repeat both strain gauges. When plugged in, ensure that a positive tension (pulling on the hook) results in a positive change of voltage. *We found that a 25 lbs load only produced a change of approximately 2 mV.*

These strain gauges were tested to ensure linearity with respect to the applied load.

See [032_TRES_Strain_Gauge_Characterization]

2.3 Handle Assembly

With the strain gauges soldered with long wires, we then placed them in our 3D printed handle as shown here:

Figure 5. Inside of handle--note the grooves for strain gauges and wire management

We recommend ensuring that the wires are not pinched against the back of the housing: they should be loose in the middle, as shown here. The two halves were then connected using long bolts and nuts.

WARNING: ***Be sure that while putting the two halves of the handle together that the strain gauge wires do not become pinched or get cut by sharp edges. Hot glue and the wire redirection channel can both be used to avoid this issue.***

To add rigidity, shrink wrap was then added to the hook, as shown here:

Figure 6. Hook and cable connections of handle

The hook from the top strain gauge was then removed using pliers and the cable was attached as shown.

3. Design Decisions

Q: What tests were run on to confirm the function of this subsystem?

[032_TRES_Strain_Gauge_Characterization]

Q: How did we arrive at this design?

A: The first strain gauge was included because we needed a way to measure the amount of weight the user was carrying, and a strain gauge was a simple choice that we had familiarity with. When we needed a way to analyze the amount of weight the machine was assisting in carrying a strain gauge along the cable was suggested by Capstone leadership, as we tested the idea it worked, so we continued with it.

Q: What issues were overcome in this design?

A: Previous iterations of our handle design produced the following issues. Their solutions are also presented:

1. The strain gauges would change in value when the handle was squeezed.
    a. It was determined that there was not sufficient room in a previous design for the cantilever pieces and so squeezing the handle would deflect the cantilever beams.
2. The zero point of the strain gauges drifted considerably.
    a. It was determined that some of the strain gauge screws became loose, thus not rigidly holding and maintaining the cantilever.

Q: How was this subsystem validated?

A: This subsystem was validated through several iterations of quick testing. We wanted to make sure that the housing would not interfere with the strain gauges. The strain gauges themselves worked for our purposes in that when we got the correct electronics hardware, we were reading data fast enough and accurate enough to get the response we wanted. This concept has been validated in a weekly meeting on Nov 16, 2022, with the sponsor contact, David Wood.

Q: Why is a rigid body not needed to support the wrist?

A: Injuries typically occur at elbows and biceps, not the wrist or forearm.

Q: What is the purpose of the load cells?

A: One load cell will read the weight of the load that is being lifted, the other one will provide a measure of the assistance being provided by the motor.

4. Interfaces

Subsystem:	Interaction with Wrist:
Controls	**The wire for the kill switch will be hard wired to the controls system.**
Motor	**The cable will connect from the motor run over the frame and be secure into the handle.**

Artifact ID: 015	Artifact Title: Power subsystem definition
Revision: A	Revision Date: 11 April 2023
Prepared by: Brinler Tanner	**Checked by:** Joshua Edmund
Purpose: *To document the design of the power subsystem.*	

Revision History			
Revision	Revised by	Checked by	Date
--	Brinler Tanner	Joshua Edmund	--
A	Joshua Vanderpool	Isaac Sorensen	11 April 2023

1. Design Summary

Figure 1. Kobalt 5.0 Amp Hour 24 Volt Battery (left), Buck Converter (right)

The project will be using a Kobalt drill battery, which has a voltage of 24V and a capacity of 5Ah. The decision to use this battery was made after conducting calculations to determine the required battery capacity for lifting a 15lbs weight a distance of 1.5 m at a rate of 2 lifts per minute. The calculations showed that a battery with a capacity of 16.625Wh would be required to last for 5 hours of normal use, assuming no losses. However, due to estimated losses and the fact that a voltage of 24V was selected (typical to many power tool batteries), the required capacity was determined to be 0.8 Ah, which is significantly less than the 5 Ah battery selected. The 5 Ah battery weight is only 1.25 lbs, so it seems that adding extra battery power comes at a very low weight cost.

Our motor, strain gauge amplifiers, and PWM to analog signal converter are all powered by the 24V source, but we use a buck converter to step down and regulate the voltage for the Arduino Nano.

1.1 Recommendations for Improvement:

- This battery has plenty of life. Per our battery life testing, just one should be able to power a 2-armed service for several hours.
- Create a more robust connection to the frame for the battery port.
- Evaluate the effect of the back EMF from the motor on the battery recharging.

2. Design Details

2.1 General

All components used in this subsystem can be found in the Control Subsystem Section of the Bill of Materials. [022_DESIGN_Full_Bill_Of_Materials]

A 24V battery was chosen specifically for our motor specs. Conveniently, it was also an appropriate voltage for the PWM to Analog signal converter. The housing was simple and had a built in 5A fuse to prevent the system from drawing too much current.

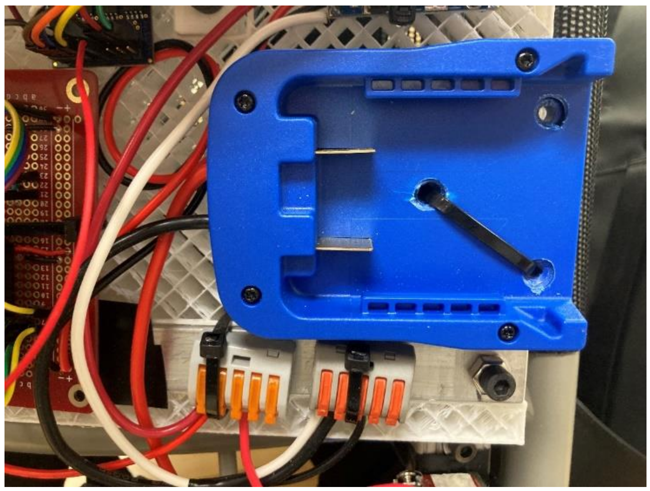


Figure 2. Battery adapter & mounting

The buck converter serves to step down and smooth the voltage. We note that a high level of back EMF is present when the weight is lowered and the motor is spun by external inertia. We highly recommend future studies to investigate the effects of this back EMF on the long-term power considerations.

3. Design Decisions

Q: What tests were run on to confirm the function of this subsystem?

[031_TRES_Predicted Battery Life]

Q: What battery will be used for the project?

A: The project will be using a Kobalt 24V drill battery with a voltage of 24V and a capacity of 5 Ah.

Q: Why was this particular battery selected?

A: The battery was selected after conducting calculations to determine the required battery capacity for lifting a 15lbs weight a distance of 1.5 m at a rate of 2 lifts per minute. While the calculations showed that a battery with a capacity of 0.8 Ah would be sufficient, the selected battery was chosen due to estimated losses and the fact that a voltage of 24V was chosen. Additionally, the weight of a 2Ah and 5Ah battery are very comparable, which means that the system can last longer without much of a penalty in added weight.

Q: What factors were considered when selecting the battery?

A: The main factor that was considered when selecting the battery was the required battery capacity for the project. Other factors, such as the voltage of the battery and its weight, were also taken into account.

Q: How long is the battery expected to last?

A: The battery is expected to last for approximately 12 hours. See TRES_Predicted_Battery_Life

Q: Was any testing done to validate the battery selection?

A: Further validation of the power calculation was conducted and can be found in the 002 MODEL_Power_Calculation.docx | Powered by Box document.

4. Interfaces

Subsystem:	Interaction with Frame:
Controls	**The battery is wired to the buck converter (for Arduino) and the Motor controller. All other components are powered through the Arduino.**
Frame	**The battery will be mounted to the frame. It will be located and encased such that catastrophic failure of the battery will not reach the user.**

Artifact ID: 016	Artifact Title: Control Subsystem Architecture Definition	
Revision: B	Revision Date: 18 April 2023	
Prepared by: Isaac Sorensen		**Checked by:** Joshua Vanderpool
Purpose: *To document the detailed design of the control subsystem.*		

Revision History			
Revision	Revised by	Checked by	Date
--	Isaac Sorensen	Joshua Vanderpool	--
A	Isaac Sorensen	Joseph Edmund	28 February 2023
B	Isaac Sorensen	Joshua Vanderpool	18 April 2023

1. Design Summary

The goal of our control system is to sense the load being lifted and provide the appropriate tension in the cable-motor system to offload ½ of the load to the frame. It must also smoothly mesh with the user's desire to raise or lower the load.

Our control system is described by this diagram. A larger version of this is found in [Appendix A]

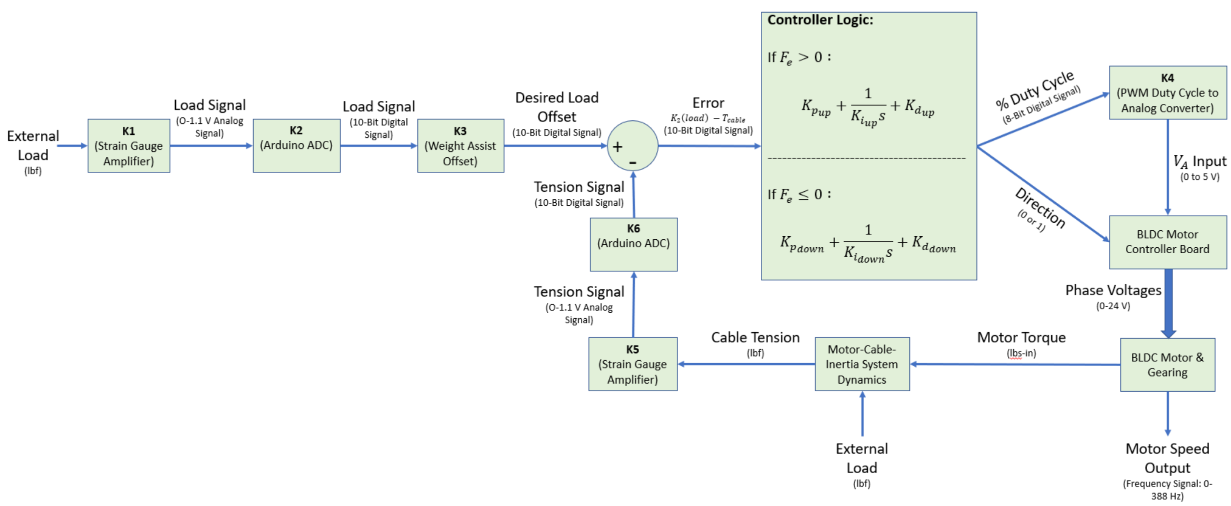


Figure 1. Total Control System

This describes how the system:

1. Senses and processes the external load.
2. Determines whether the motor should lift or lower the handle and load.
3. Uses two separate PID controllers to output an appropriate percent duty cycle to control the power to the motor.
4. This motor plant actuates the load, interacts with the external environment, and generates cable tension.

5. The system controller continuously samples the external load and cable tension to update the motor output to react to environmental changes and perturbations.

Overall, the gains set for the PID controllers allowed the system to operate smoothly and quickly.

1.1 Recommendations for Improvement:

- A more vigorous PID parameter tuning. Our efforts consisted mostly of guess and check.
- Offload the ADC computational time to an external ADC (not on the microcontroller).
- Create a Simulink model that can characterize the motor dynamics and its interaction with the environment.
- Reducing friction in the overall system will also mitigate inconsistencies due to static friction.
- Implement safety logic to prevent uncontrolled loops.
- Create a safety net if the current limiter on the motor controller board kicks in and shuts down this system (this would simply require toggling the Enable pin off/on if the READY pin goes to 0).

2. Design Details

2.1 General

All components used in this subsystem can be found in the Control Subsystem Section of the Bill of Materials. [022_DESIGN_Full_Bill_Of_Materials]

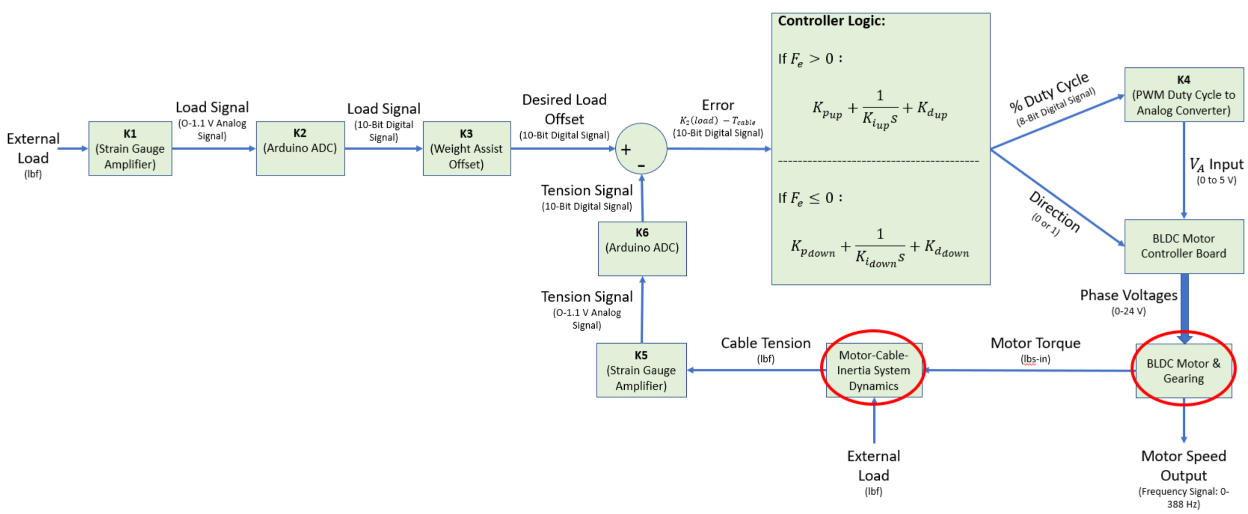


Figure 2. Control system with incomplete transfer functions highlighted

Due to their higher complexity, we intentionally left off the specific transfer functions for the BLDC motor and gearing along with the total system dynamics. We recommend using the following concepts to generate transfer functions for future simulation needs:

2.1.1 BLDC Motor & Gearing

The torque -speed-current curves provided by Anaheim Automation should be sufficient to map the applied power (in the form of the V_A input voltage) to the generated torque and speed of the motor. The green 24 V line corresponds with our motor type. **The speeds and torques should be adjusted by a factor of 15 due to the added planetary gearbox on our motor.**

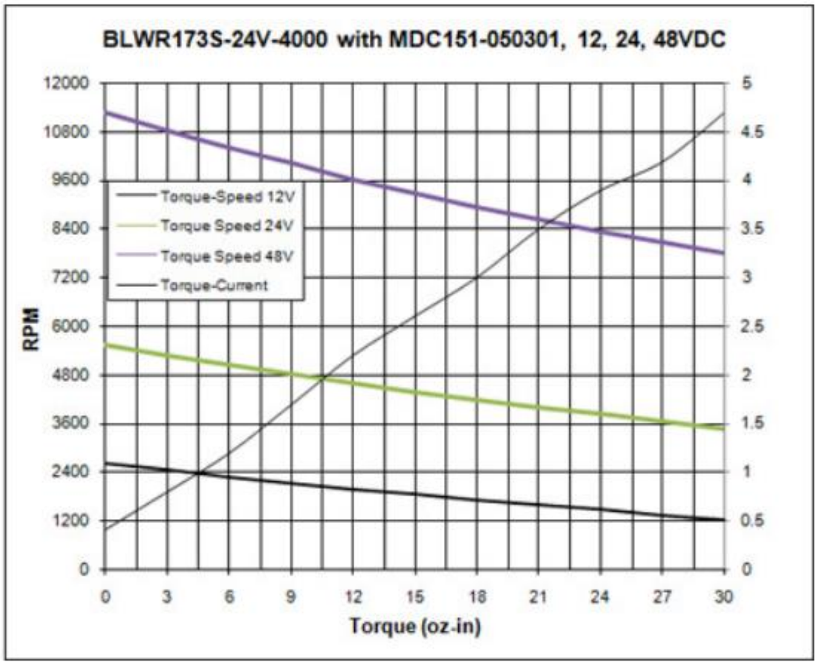
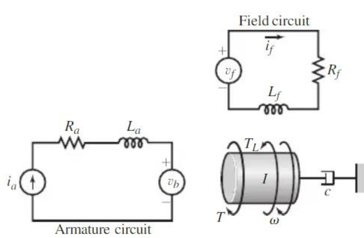


Figure 3. Torque speed curve of motor without gearing

2.1.2 Motor-Inertia-Torque Dynamics

The motor-inertia-external torque dynamics could most likely be modeled similar to a simply Brushed DC motor. In the 3rd edition of *System Dynamics* Palm et al., the following transfer functions are given:



$$\frac{I_a(s)}{V_a(s)} = \frac{Is + c}{L_a I s^2 + (R_a I + cL_a)s + cR_a + K_b K_T} \tag{6.6.1}$$

$$\frac{I_a(s)}{T_L(s)} = \frac{K_b}{L_a I s^2 + (R_a I + cL_a)s + cR_a + K_b K_T} \tag{6.6.2}$$

$$\frac{\Omega(s)}{V_a(s)} = \frac{K_T}{L_a I s^2 + (R_a I + cL_a)s + cR_a + K_b K_T} \tag{6.6.3}$$

$$\frac{\Omega(s)}{T_L(s)} = -\frac{L_a s + R_a}{L_a I s^2 + (R_a I + cL_a)s + cR_a + K_b K_T} \tag{6.6.4}$$

Figure 4. Transfer functions for DC motor with applied torque

2.2 Code and Execution

***NOTE: The execution of this code requires the Arduino IDE along with the PID library* by Brett Beauregard version 1.2.0**

This control system is implemented by using the code found in **Appendix B** of this artifact.

Using the code attached in **Appendix C** of this artifact, the execution speed of the code was measured. We found that the code could sample both force sensors and update the output duty cycle 1000 times in 0.375 seconds. Thus, our system can run at approximately **2.67 kHz.** This is a conservative estimate as its speed would be faster without output to the serial monitor.

2.3 Components

2.3.1 Input: Load Cells, Strain Gauges, Amplifiers, and ADC's

The force of the external load and the cable tension are measured by strain gauges in the handle. More detail on this subsystem can be found in [014_DESIGN_Handle_Subsystem_Definition].

These strain gauges are rated for loads up to 110 lbs. However, the change of resistance is only about 2 mV when 50 pounds are applied. Thus, we required significant applications. Op-Amps were NOT well suited for such low differential changes; thus, we found a strain-gauge specific amplifier (ATO Load Cell Weight Transmitter). The calibration for these amplifiers is listed below. Their datasheet is also included in [Appendix D].

The Arduino Nano built-in ADCs were used. Their 10-bit resolution and 4.5 kHz sampling rate were sufficient for our needs.

2.3.2 Controller: PID Controllers

After various controller logic iterations, we determined that two PID controllers were necessary. Proportional control should dominate. Internal friction provides sufficient damping to the system. **We recommend future tuning of these PID parameters.** Our final design consisted of using values of 0.5 for both the up and down controller proportional gains (Kp_up and Kp_down).

- The input was assigned to be the $Cable\ Tension.$
- The setpoint was assigned to be: $Weight\ Assist\ Factor * External\ Load$
- The output was assigned to be an 8-bit value (0-255) that corresponded to the PWM duty cycle.

2.3.3 Output: PWM to Analog, Motor Controller Board

Analog Pin 5 of the Arduino nano was used as the PWM output. By default, **the PWM frequency of this pin is 980 Hz.**

The BLDC motor controller board required a 0.75 – 5 V signal on its V_speed pin. Thus, we used a PWM to analog signal converter (Zerone 1-3 kHz PWM to Analog Signal Converter) to transform the PWM signal of our Arduino. Its datasheet and calibration method can be found in [Appendix E]. Note that although this was rated for a PWM signal of 1-3 kHz, it performed without issue with a 980 Hz signal. The board was put on the **12 V** setting. To reduce this to the needed range (maximum 5V signal), we fed this voltage signal to a resistor ladder to approximately halve the voltage output to the motor controller board. See the Wiring Diagram section in this artifact for more details.

Anaheim Automation's MDC020-050101 - 50V, 10A Brushless Controller was used to control the actual motor. The current limiting resister was set at **24 k-Ohms** to limit the current to 5 A. We connected the phases and hall sensors as shown in the datasheet, then used the V_speed, Direction, and Enable pins to control the motor. Some of the settings are listed here, but more are listed in [Appendix F] along with the datasheet and user guide.

Note: **If max current is exceeded, then the enable pin must be toggled or powering down and back up the driver.** See 'Fault Protection' in [Appendix F] for more information. **This is not included in the current version of the code.**

Power Requirements:	6 - 50VDC
Output Current Range:	0.5 - 10.0 Amps (Peak) 0.25 - 5 Amps (Continuous)
Ready: (P2, Pin 19)	Logic "1" - Ready Logic "0" - Fault
Enable: (P2, Pin 22)	Logic "1" - Motor phases on (enabled) Logic "0" (open) - Motor phases off (disabled)
Direction: (P2, Pin 23)	Logic "1" - Motor moves clockwise Logic "0" (open) - Motor imves counter clockwise
Current Limit Set: (P2, Pin 25)	Logic "1" (open) - 10A current limit Resitor to GND - Sets current limit (Refer to User's guide for values)
V Speed: (P2, Pin 26)	0.75V - 5V
Operation Temperature:	0°C to 70°C

Figure 5. Motor Controller Board specifications

2.4 System Calibration

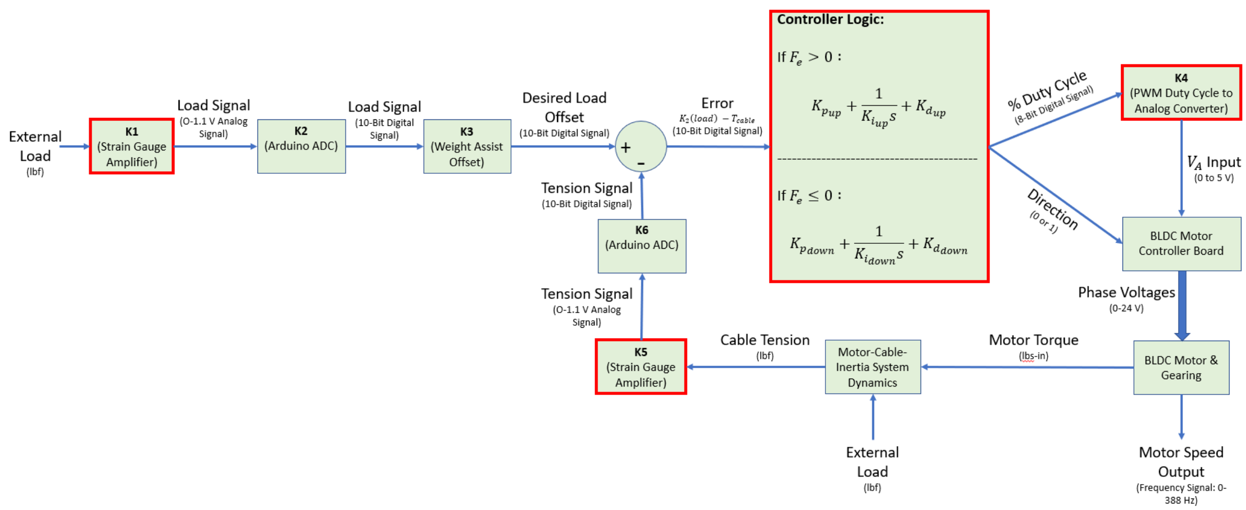


Figure 6. Control diagram with systems to be calibrated highlighted

All the above boxes highlighted in red required some form of initial calibration.

- The strain gauge amplifiers require that the 'Zero' and 'Span' for its output be tuned.
- The PWM to Analog Converter requires adjustment to a potentiometer.
- The controller logic requires some tuning of the proportional, derivative, and integral gains based on the friction inherent in the system and some personal preferences.
- *Note: Theoretically, the K3 weight assist factor can also be changed per user preference. We found that by setting this to 0.75 See [Appendix A] code, the cable tension offloaded between 40-60% of the weight during various phases of the movement.*

The observations made during the controller gain tuning is found in the 'Design Decisions' section. For the strain gauge amplifiers, we suggest the following procedure.

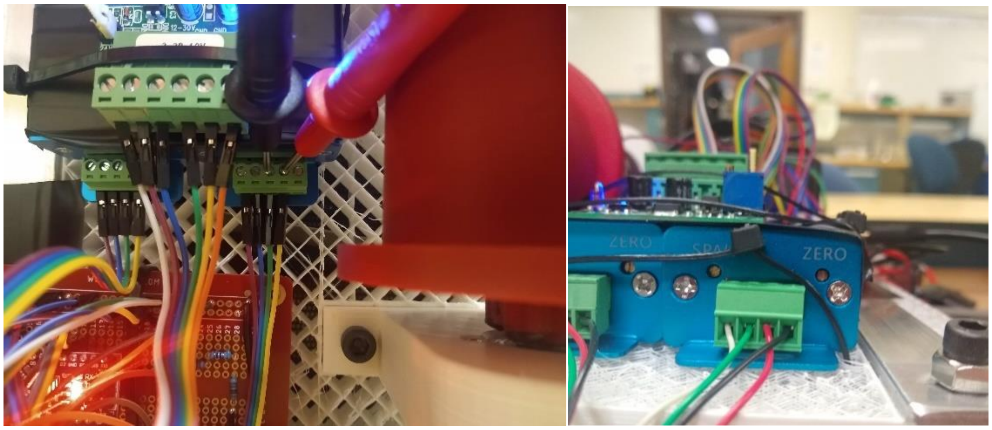


Figure 7. Strain Gauge Amplifiers with output probing (left) and zero/span screws (right)

WARNING: BOTH AMPLIFIERS SHOULD BE CALIBRATED AT THE SAME TIME AND WITH IDENTICAL PARAMETERS OR YOU MAY CAUSE NONLINEAR BEHAVIOR IN THE STRAIN GAUGE OUTPUT.

1. Remove the plate on the side of the box to access a jumper pin. This allows you to uncouple the ‘Zero’ and ‘Span’ screws. Failure to do so will cause an adjustment of the span to change the zero point you have set.
2. While adjusting the zero and span, be sure to measure the voltage at the output continuously for fine adjustment.
3. Without any load on the handle or strain gauges, set the zero point such that the output voltage is 0.
4. Then place a 25 lbs weight on the strain gauges (one at a time) and tune the span until the voltage reads approximately 0.9 V. *Note: The Arduino Code is set to accept an analog signal of 0-1.1 V. Tuning the span in this way helps avoid saturating the signal but maximizes the resolution of the signal differences that can be read by the Arduino. This is set with the following line of code:*

```
analogReference(INTERNAL); // Set the internal reference voltage to 1.1V
to increase resolution on force sensors
```

5. Remove the weight, ensure that the zero point has not moved, and ensure that an identical signal is obtained at various other weights between 0 and 25 lbs.

Test documentation to ensure the linearity of the strain gauge signal is found here. [032_TRES_Strain_Gauge_Characterization]

3. Design Decisions

Q: What tests were run to confirm the function of this subsystem?

[028_TRES_Load_Offloading]

Q: Why was an Arduino Nano chosen as the microcontroller?

A: We have experience with this microcontroller. They are small, relatively inexpensive, and they have enough computing power for our needs (4.5 kHz 10-bit ADCs and plenty of I/O Pins). Additionally, they are readily available. Its datasheet can be found in [Appendix G].

Figure 3- Arduino Nano

Q: How were the parameters of the PID controllers tuned.

A: Overall, the process was not entirely thorough, but we noted the following observations while tuning:

- Due to static friction, any added damping gain to the system would cause jumpiness.
- Too high or too low of proportional gains also led to jumpiness. After trial and error, it was determined that sufficient value for both the up and down PID gains was 0.5. Less jumpiness was observed here.
- With our limited time, the influence of the integral gains was not explored.

Q: Why did we choose to control the motor using only the force sensor values? Why not use speed feedback from the motor?

A: Using only the force sensor values was the simpler approach and we found appropriate parameters that allowed the system to run smoothly. Further exploration certainly could focus on using the speed feedback (the PG_out pin) which provides the speed of the motor encoded in a frequency signal between 0 and 380 Hz, with 380 Hz representing the max speed at the rated current of the motor.

Q: What other controllers logic methods were attempted?

A: All previous iterations did not use a built in PID library, but generally followed the concepts of developing a more complicated proportional controller. We attempted the following strategies:

- Using fixed proportional gains for the forwards and backwards directions.
  - This caused significant oscillations in the system.
- Using an error band to avoid constant switching on and off the motor. If the difference between desired and actual cable tension was below a certain threshold, no action would be taken.
  - This led to our system being a little too insensitive.
- Using a complicated ramping system to try to adjust the output change more slowly.
  - We simply mapped the value of the error to a given PWM duty cycle (see figure below). This still causes significant jumpiness of the system.

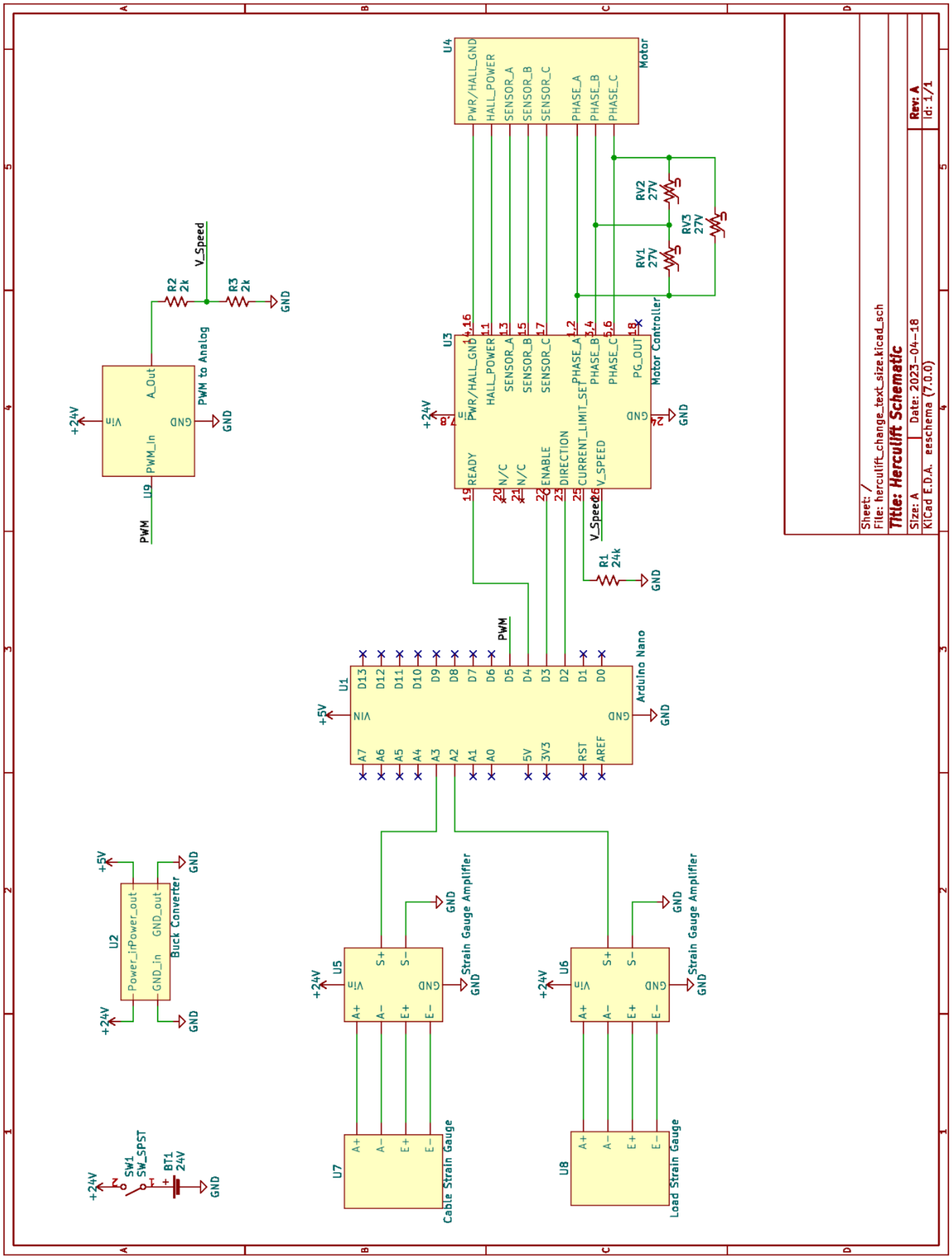
```
                             PWM
                             ||
________________             ||             ________________<- MAX DUTY CYCLE
               |\            ||            /|
               | \           ||           / |
               |  \          ||          /  |
               |   \         ||         /   |
               |    \        ||        /    |
               |     \       ||       /     |
               |      \______||______/<-----|----------------- MIN DUTY CYCLE (0)
===============|======|======||======|======|=============== Error
               |      |      ||      |      |
            -MOVE  -ERROR          ERROR   MOVE
             ZONE   ZONE           ZONE    ZONE
             VAL    VAL            VAL     VAL
```

4. Interfaces

Subsystem:	Interface Description:
Power	The battery is wired to the buck converter (for Arduino) and the Motor controller. All other components are powered through the Arduino.
Frame	Every component except the sensors, are fixtured to the frame (the force sensors are mounted to the frame).
Motor Gear	One motor of the control system will be attached to a transmission to pull on the cable attached to the shoulder.
Wrist	The Handle will include two load cells that will provide input to the control system.

5. Circuit Diagram

The following circuit diagram can be used to recreated all wired connections between components described in this document.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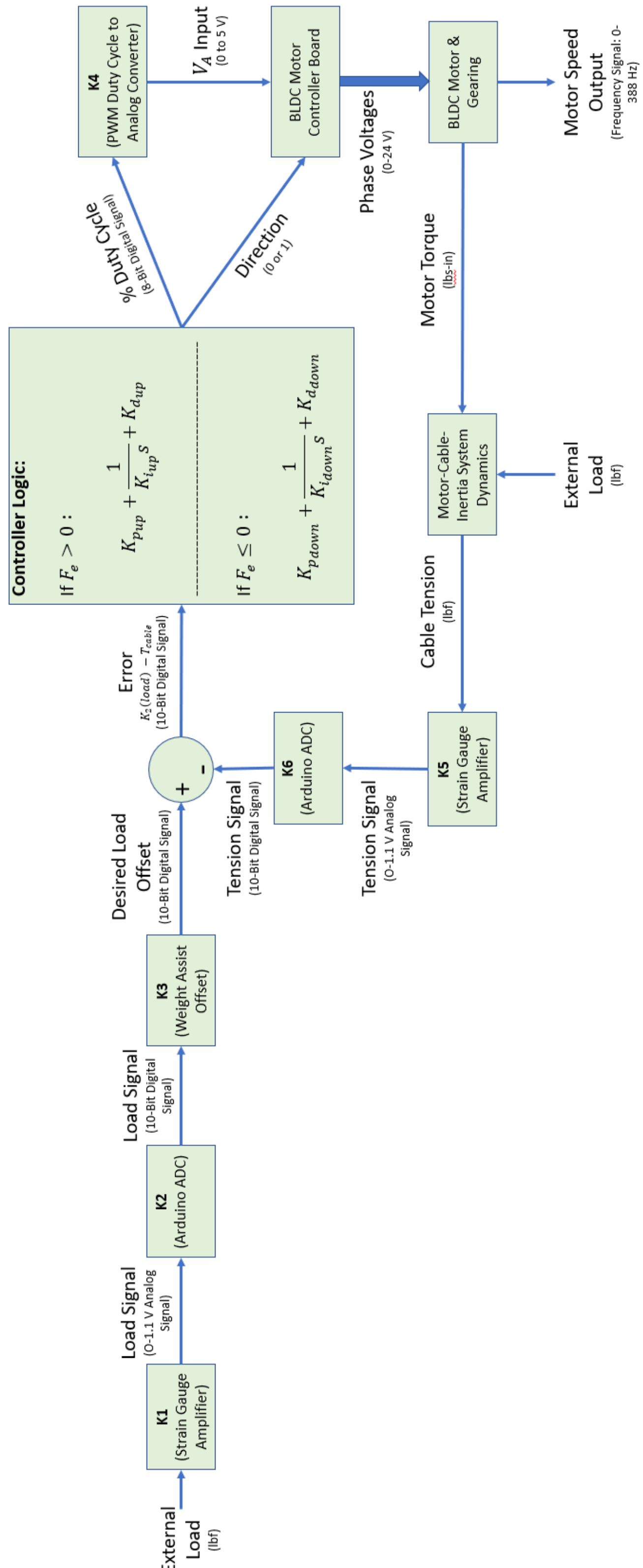
File: herculift_change_text_size.kicad_sch
Title: Herculift Schematic
Size: A
Date: 2023-04-18
Rev: A
KiCad E.D.A. eeschema (7.0.0)
Id: 1/1
U4
Motor
PWR/HALL_GND
HALL_POWER
SENSOR_A
SENSOR_B
SENSOR_C
PHASE_A
PHASE_B
PHASE_C
RV1
27V
RV2
27V
RV3
27V
U3
Motor Controller
READY
N/C
ENABLE
DIRECTION
CURRENT_LIMIT_SET
V_SPEED
PG_OUT
GND
+24V
V_Speed
R1
24k
GND
U9
PWM to Analog
Vin
PWM_in
A_Out
PWM
R2
2k
R3
2k
U1
Arduino Nano
VIN
+5V
D13
D12
D11
D10
D9
D8
D7
D6
D5
D4
D3
D2
D1
D0
A7
A6
A5
A4
A3
A2
A1
A0
5V
3V3
RST
AREF
U2
Buck Converter
Power_in
Power_out
GND_in
GND_out
U5
U6
Strain Gauge Amplifier
Vin
A+
A−
E+
E−
S+
S−
U7
Cable Strain Gauge
U8
Load Strain Gauge
SW1
SW_SPST
BT1
24V

Appendix A: Control Diagram



Appendix B (Also found on GitHub Repository)

```
////////////////////////////////////////////////////////////////////////////
//////////////
//
//  Title: Herculift Device Control System
//  Capstone Team: 37
//  Authors: Tyler Dickson, Joseph Edmund, Isaac Sorensen
//
//  Description: This is a body of code implementing the controls system of
the wearable lift
//    assist device (Herculift Device) by using a 2D mockup of the system.
//
////////////////////////////////////////////////////////////////////////////
//////////////

/****************************************Libraries**************************
*************/

#include <PID_v1.h>

/****************************************Debug******************************
*********/

#define PRINT_DEBUG

/****************************************Macros*****************************
**********/

//Per the Arduino Nano documentation, pins 3, 5, 6, 9, 10, and 11 support
pulse width modulation (PWM).
//The PWM pins 5 and 6 are connected to a 16-bit timer and run at a default
frequency of 976.56Hz.

//Pins connected to the motor controller.
#define MOTOR_DIRECTION_PIN 2
#define ENABLE_PIN 3
#define READY_PIN 4
#define MOTOR_PWM_INPUT_PIN 5         //Default frequency of 980 Hz

//Pin for strain gauge amplifier for the cable. Pin 16 corresponds to pin A2.
#define INPUT_PIN_CABLE 16

//Pin for strain gauge amplifier for the load. Pin 17 corresponds to pin A3.
#define INPUT_PIN_LOAD 17

//Define a number to use as the scaled value of the load tension.
#define WEIGHT_ASSIST_FACTOR 0.75

/****************************************Variables**************************
*************/

//Define variables for load cell readings.
double loadScaleReading; // load cell value
double cableScaleReading; // load cell value
```

```
double tensionError; // our defined error value

//Enum to simplify motor movement.
enum MotorMotion{UP, DOWN, NONE};

//Define the variables we'll be connecting to
double setpoint, input, outputUp, outputDown;

//Specify the links and initial tuning parameters
double kpUp=.5, kdUp=0.0, kiUp=0.0;
double kpDown=.5, kdDown=0.0, kiDown=0.0;
PID myPID_UP(&input, &outputUp, &setpoint, kpUp, kiUp, kdUp, DIRECT);
PID myPID_DOWN(&input, &outputDown, &setpoint, kpDown, kiDown, kdDown,
REVERSE);

/****************************************Function
Declarations****************************************/

//This function simply calculates the difference between the tension measured
by the load and the tension measured by the cable.
//In other words, the error is the difference between the desired tension
(cable value) and the actual tension (scaled load value).
//Parameters:
//  scaledTensionHandle- A double to hold the scaled value read in by the
force sensor attatched to the load.
//  tensionCable- A double to hold the value read in by the force sensor
attatched to the cable.
double calculateError(double scaledTensionHandle, double tensionCable);

//This function wraps the logic of motor control into a simple command.
//Parameters:
//  direction- uses the MotorMotion enum to specify UP, DOWN, or NONE.
//  dutyCycle- specify the duty cycle to run the motors at.
void moveMotor(MotorMotion direction, int dutyCycle);

//A function which defines the direction of the motor based upon the value of
the error in the strain gauges.
//Parameters:
//  tensionError- the error value when comparing the strain gauge values.
MotorMotion setMotorDirection(double tensionError);

//This function tells the respective PID controller to compute its value
based upon the updated information
//the motor is then moved in the appropriate direction at the calculated
speed.
//Parameters:
//  direction- Specifies whether we are using either the 'up' PID controller
or 'down' as well as the motor's direction
void computeAndMoveMotor(MotorMotion direction);

//A function that encapsulates the values we'd like to keep track of on the
serial monitor.
//Parameters:
//  loadRead- the load side strain gauge value
//  cableRead- the cable side strain gauge value
//  tensionError- the output of calculateError()
//  outputUp- the output of myPID_up()
```

```
//  outputDown- the output of myPID_down()
//  direction- the output of setMotorDirection() used to specify whether
outputUp or outputDown should be printed
void serialPrintDebug(double loadRead,   double cableRead,
                      double tensionError, double outputUp,
                      double outputDown, MotorMotion direction);

/****************************************Main********************************
********/

void setup() {
  //Set the pins as output.
  //These pins will control the motors by interfacing with the motor
controller.
  pinMode(MOTOR_PWM_INPUT_PIN, OUTPUT);
  pinMode(MOTOR_DIRECTION_PIN, OUTPUT);
  pinMode(ENABLE_PIN, OUTPUT);
  pinMode(READY_PIN, INPUT);

  //Set the enable pin high.
  digitalWrite(ENABLE_PIN, HIGH);

  //Set the direction pin high.
  digitalWrite(MOTOR_DIRECTION_PIN, HIGH);

  Serial.begin(9600);
  while (!Serial) {
   ; //Wait for serial port to connect. Needed for native USB port only.
  }
  analogReference(INTERNAL); // Set the internal reference voltage to 1.1V to
increase resolution on force sensors

  //Read and normalize the values from the strain gauges.
  loadScaleReading = analogRead(INPUT_PIN_LOAD);
  cableScaleReading = analogRead(INPUT_PIN_CABLE);
  tensionError = calculateError(loadScaleReading, cableScaleReading);

  //Initialize the variables we're linked to
  input = tensionError;
  setpoint = loadScaleReading * WEIGHT_ASSIST_FACTOR;

  //Turn the PID on
  myPID_UP.SetMode(AUTOMATIC);
  myPID_DOWN.SetMode(AUTOMATIC);
}

void loop() {
  //Read and normalize the values from the strain gauges.
  loadScaleReading = analogRead(INPUT_PIN_LOAD);
  cableScaleReading = analogRead(INPUT_PIN_CABLE);
  tensionError = calculateError(loadScaleReading, cableScaleReading);

  //Reinitialize the values for PID controllers
  input = cableScaleReading;
  setpoint = loadScaleReading * WEIGHT_ASSIST_FACTOR;

  //define which way the motor should move
```

```
  MotorMotion currentMotorDirection = setMotorDirection(tensionError);

  //Perform the PID computation and move the motor accordingly
  computeAndMoveMotor(currentMotorDirection);

#ifdef PRINT_DEBUG
  //Serial Output
  serialPrintDebug(loadScaleReading,
                   cableScaleReading,
                   tensionError,
                   outputUp,
                   outputDown,
                   currentMotorDirection);
#endif

  delayMicroseconds(100); // Insert a delay to set the sample rate
}

/****************************************Function
Definitions****************************************/

double calculateError(double scaledTensionHandle, double tensionCable) {
  return WEIGHT_ASSIST_FACTOR * scaledTensionHandle - tensionCable;
}

void moveMotor(MotorMotion direction, int dutyCycle) {
  switch (direction) {
    case UP:
      //When going UP put the direction pin of the motor control driver LOW.
      analogWrite(MOTOR_PWM_INPUT_PIN, dutyCycle);
      digitalWrite(MOTOR_DIRECTION_PIN, LOW);
      break;
    case DOWN:
      //When going UP put the direction pin of the motor control driver HIGH.
      analogWrite(MOTOR_PWM_INPUT_PIN, dutyCycle);
      digitalWrite(MOTOR_DIRECTION_PIN, HIGH);
      break;
    case NONE:
      //The driver naturally pulls the pin high so put the direction pin
HIGH.
      analogWrite(MOTOR_PWM_INPUT_PIN, 0);
      digitalWrite(MOTOR_DIRECTION_PIN, HIGH);
      break;
    default:
      break;
  }
}

MotorMotion setMotorDirection(double tensionError) {
  MotorMotion direction = (tensionError > 0) ? (UP) : (DOWN);
  return direction;
}

void computeAndMoveMotor(MotorMotion direction) {
  switch (direction) {
    case UP:
      myPID_UP.Compute();
```

```
      moveMotor(UP, outputUp);
      break;
    case DOWN:
      myPID_DOWN.Compute();
      moveMotor(DOWN, outputDown);
      break;
    default:
      break;
  }
}

void serialPrintDebug(double loadRead,   double cableRead,
                      double tensionError, double outputUp,
                      double outputDown, MotorMotion direction) {
  //Note that there is no space after ':' in any of these statements
  //This is for allowing the Arduino Serial Plotter to use these strings as a
labels
  Serial.print("Load:");
  Serial.print(loadRead, 3);
  Serial.print(", "); //Comma delimeter
  Serial.print("Cable:");
  Serial.print(cableRead, 3);
  Serial.print(", ");
  Serial.print("Error:");
  Serial.print(tensionError);
  Serial.print(", ");
  Serial.print("Output:");

  //Print the output of the currently used PID controller
  switch (direction) {
  case UP:
    Serial.print(outputUp);
    break;
  case DOWN:
    Serial.print(outputDown);
  default:
    break;
  }

  Serial.println();
}
```

Appendix C (System Speed Code)

```
/////////////////////////////////////////////////////////////////////////////
//////////////
//
//  Title: Herculift Device Control System
//  Capstone Team: 37
//  Authors: Tyler Dickson, Joseph Edmund, Isaac Sorensen
//
//  Description: This is a body of code implementing the controls system of
the wearable lift
//    assist device (Herculift Device) by using a 2D mockup of the system.
```

```
//
/////////////////////////////////////////////////////////////////////////////
//////////////

/****************************************Libraries***************************
*************/

#include <PID_v1.h>

/****************************************Debug*******************************
*********/
// #define PRINT_DEBUG
/****************************************Macros******************************
**********/
//Per the Arduino Nano documentation, pins 3, 5, 6, 9, 10, and 11 support
pulse width modulation (PWM).
//The PWM pins 5 and 6 are connected to a 16-bit timer and run at a default
frequency of 976.56Hz.

//Pins connected to the motor controller.
#define MOTOR_DIRECTION_PIN 2
#define ENABLE_PIN 3
#define READY_PIN 4
#define MOTOR_PWM_INPUT_PIN 5

//Pin for strain gauge amplifier for the cable. Pin 16 corresponds to pin A2.
#define INPUT_PIN_CABLE 16

//Pin for strain gauge amplifier for the load. Pin 17 corresponds to pin A3.
#define INPUT_PIN_LOAD 17

//Define a number to use as the scaled value of the load tension.
#define WEIGHT_ASSIST_FACTOR 0.75

/****************************************Variables***************************
*************/

//Define variables for load cell readings.
double loadScaleReading; // load cell value
double cableScaleReading; // load cell value
double tensionError; // our defined error value

//Enum to simplify motor movement.
enum MotorMotion{UP, DOWN, NONE};

//Define the variables we'll be connecting to
double setpoint, input, outputUp, outputDown;

//Specify the links and initial tuning parameters
double kpUp=.5, kdUp=0.0, kiUp=0.0;
double kpDown=.5, kdDown=0.0, kiDown=0.0;
PID myPID_UP(&input, &outputUp, &setpoint, kpUp, kiUp, kdUp, DIRECT);
PID myPID_DOWN(&input, &outputDown, &setpoint, kpDown, kiDown, kdDown,
REVERSE);

// Set the time duration for counting in seconds
const int countDuration = 10;
```

```
// Initialize the counter and timer variables
unsigned long startTime = 0;
unsigned long lastTime = 0;
unsigned long elapsedTime = 0;
unsigned long counter = 0;

/****************************************Function
Declarations****************************************/

//This function simply calculates the difference between the tension measured
by the load and the tension measured by the cable.
//In other words, the error is the difference between the desired tension
(cable value) and the actual tension (scaled load value).
//Parameters:
//  scaledTensionHandle- A double to hold the scaled value read in by the
force sensor attatched to the load.
//  tensionCable- A double to hold the value read in by the force sensor
attatched to the cable.
double calculateError(double scaledTensionHandle, double tensionCable);

//This function wraps the logic of motor control into a simple command.
//Parameters:
//  direction- uses the MotorMotion enum to specify UP, DOWN, or NONE.
//  dutyCycle- specify the duty cycle to run the motors at.
void moveMotor(MotorMotion direction, int dutyCycle);

//A function which defines the direction of the motor based upon the value of
the error in the strain gauges.
//Parameters:
//  tensionError- the error value when comparing the strain gauge values.
MotorMotion setMotorDirection(double tensionError);

//This function tells the respective PID controller to compute its value
based upon the updated information
//the motor is then moved in the appropriate direction at the calculated
speed.
//Parameters:
//  direction- Specifies whether we are using either the 'up' PID controller
or 'down' as well as the motor's direction
void computeAndMoveMotor(MotorMotion direction);

//A function that encapsulates the values we'd like to keep track of on the
serial monitor.
//Parameters:
//  loadRead- the load side strain gauge value
//  cableRead- the cable side strain gauge value
//  tensionError- the output of calculateError()
//  outputUp- the output of myPID_up()
//  outputDown- the output of myPID_down()
//  direction- the output of setMotorDirection() used to specify whether
outputUp or outputDown should be printed
void serialPrintDebug(double loadRead,   double cableRead,
                      double tensionError, double outputUp,
                      double outputDown, MotorMotion direction);
```

```
/**************************************Main********************************
********/

void setup() {
  //Set the pins as output.
  //These pins will control the motors by interfacing with the motor
controller.
  pinMode(MOTOR_PWM_INPUT_PIN, OUTPUT);
  pinMode(MOTOR_DIRECTION_PIN, OUTPUT);
  pinMode(ENABLE_PIN, OUTPUT);
  pinMode(READY_PIN, INPUT);

  //Set the enable pin high.
  digitalWrite(ENABLE_PIN, HIGH);

  //Set the direction pin high.
  digitalWrite(MOTOR_DIRECTION_PIN, HIGH);

  Serial.begin(9600);
  while (!Serial) {
   ; //Wait for serial port to connect. Needed for native USB port only.
  }
  analogReference(INTERNAL); // Set the internal reference voltage to 1.1V to
increase resolution on force sensors

  //Read and normalize the values from the strain gauges.
  loadScaleReading = analogRead(INPUT_PIN_LOAD);
  cableScaleReading = analogRead(INPUT_PIN_CABLE);
  tensionError = calculateError(loadScaleReading, cableScaleReading);

  //Initialize the variables we're linked to
  input = tensionError;
  setpoint = loadScaleReading * WEIGHT_ASSIST_FACTOR;

  //Turn the PID on
  myPID_UP.SetMode(AUTOMATIC);
  myPID_DOWN.SetMode(AUTOMATIC);
}

void loop() {
  //Read and normalize the values from the strain gauges.
  loadScaleReading = analogRead(INPUT_PIN_LOAD);
  cableScaleReading = analogRead(INPUT_PIN_CABLE);
  tensionError = calculateError(loadScaleReading, cableScaleReading);

  //Reinitialize the values for PID controllers
  input = cableScaleReading;
  setpoint = loadScaleReading * WEIGHT_ASSIST_FACTOR;

  //define which way the motor should move
  MotorMotion currentMotorDirection = setMotorDirection(tensionError);

  //Perform the PID computation and move the motor accordingly
  computeAndMoveMotor(currentMotorDirection);

#ifdef PRINT_DEBUG
  //Serial Output
```

```
  serialPrintDebug(loadScaleReading,
                   cableScaleReading,
                   tensionError,
                   outputUp,
                   outputDown,
                   currentMotorDirection);
#endif

  delayMicroseconds(50); // Insert a delay to set the sample rate

  // Increment the counter
  counter++;

  if (counter >= 1000){
    // Record the current time
    unsigned long currentTime = millis();

    // Calculate the elapsed time
    elapsedTime = currentTime - startTime;

    // Print the counter and elapsed time
    Serial.print("Counter: ");
    Serial.print(counter);
    Serial.print(", Elapsed Time: ");
    Serial.print(elapsedTime);
    Serial.println(" ms");

    // Record the start time when the loop begins
    startTime = millis();

    // Reset the counter
    counter = 0;
  }
}
/****************************************Function
Definitions****************************************/
double calculateError(double scaledTensionHandle, double tensionCable) {
  return WEIGHT_ASSIST_FACTOR * scaledTensionHandle - tensionCable;
}

void moveMotor(MotorMotion direction, int dutyCycle) {
  switch (direction) {
    case UP:
      //When going UP put the direction pin of the motor control driver LOW.
      analogWrite(MOTOR_PWM_INPUT_PIN, dutyCycle);
      digitalWrite(MOTOR_DIRECTION_PIN, LOW);
      break;
    case DOWN:
      //When going UP put the direction pin of the motor control driver HIGH.
      analogWrite(MOTOR_PWM_INPUT_PIN, dutyCycle);
      digitalWrite(MOTOR_DIRECTION_PIN, HIGH);
      break;
    case NONE:
      //The driver naturally pulls the pin high so put the direction pin
HIGH.
      analogWrite(MOTOR_PWM_INPUT_PIN, 0);
      digitalWrite(MOTOR_DIRECTION_PIN, HIGH);
```

```
      break;
    default:
      break;
  }
}

MotorMotion setMotorDirection(double tensionError) {
  MotorMotion direction = (tensionError > 0) ? (UP) : (DOWN);
  return direction;
}

void computeAndMoveMotor(MotorMotion direction) {
  switch (direction) {
    case UP:
      myPID_UP.Compute();
      moveMotor(UP, outputUp);
      break;
    case DOWN:
      myPID_DOWN.Compute();
      moveMotor(DOWN, outputDown);
      break;
    default:
      break;
  }
}

void serialPrintDebug(double loadRead,   double cableRead,
                      double tensionError, double outputUp,
                      double outputDown, MotorMotion direction) {
  //Note that there is no space after ':' in any of these statements
  //This is for allowing the Arduino Serial Plotter to use these strings as a
labels
  Serial.print("Load:");
  Serial.print(loadRead, 3);
  Serial.print(", "); //Comma delimeter
  Serial.print("Cable:");
  Serial.print(cableRead, 3);
  Serial.print(", ");
  Serial.print("Error:");
  Serial.print(tensionError);
  Serial.print(", ");
  Serial.print("Output:");

  //Print the output of the currently used PID controller
  switch (direction) {
  case UP:
    Serial.print(outputUp);
    break;
  case DOWN:
    Serial.print(outputDown);
  default:
    break;
  }

  Serial.println();
}
```

Appendix D: Datasheet ATO Strain Gauge Amplifier

510 Weigh the transmitter

- Product profile

DY510 The transmitter adopts the aluminum profile shell, internally using the original imported high-performance device to accurately amplify the sensor output signal, internal pressure stabilization, constant current supply bridge, voltage and current conversion, impedance adaptation, linear compensation, humidity compensation, etc. Turning mechanics and quantity into standard current and voltage signal output can switch 0 ± 5V/0 ± 10V/4-20mA/0-20mA. It can be directly connected with the automatic control device PLC single chip computer terminal or computer networking. It has the characteristics of standard signal zero adjustment and gain adjustment, input protection and output short circuit protection.

- outline dimension

可选导轨安装
可选卡扣可安装标准宽35mm导轨

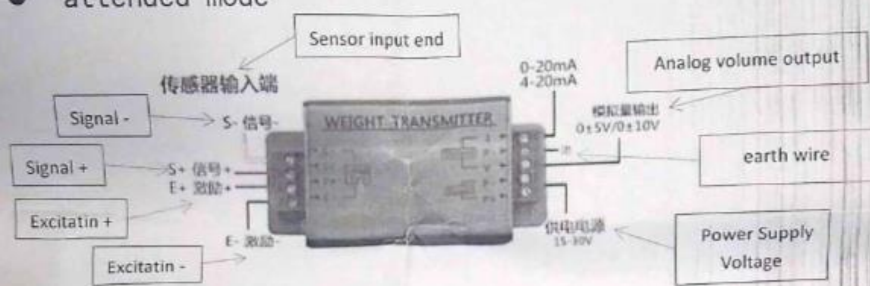
Optional guide rail installation
Optional card buckle for standard width 35mm rail

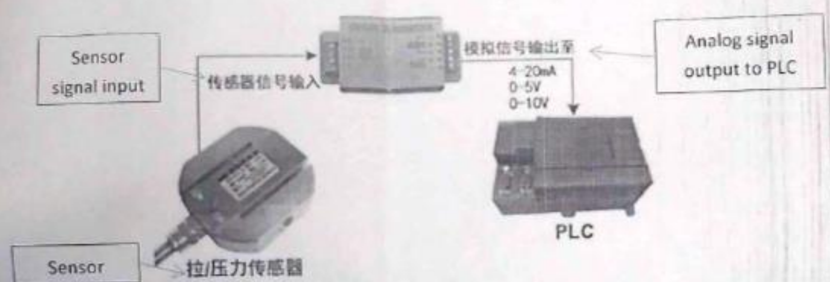
- qualification

Service voltage	15-30VDC	Comprehensive accuracy	0.05%
frequency of sampling	≥100KHz	working temperature	-30°C-80°C
incoming signal	0.5-4mV/V	output signal	0±5V/0±10V 0-20mA/4-20mA

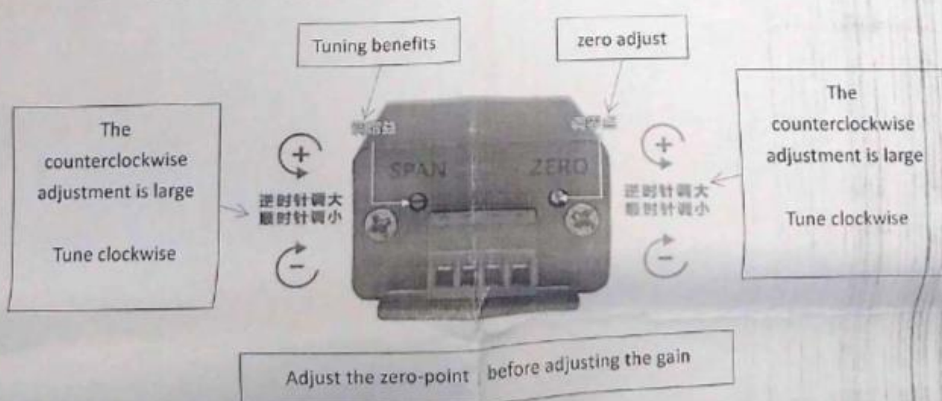
510 Weigh the transmitter

- attended mode





- calibration method



零点（Zero）：If the sensor has no load (except tooling), the initial voltage or current is called transmission zero。

增益（Span）：In the weighing state, the transmitter output changes in the range of 0-10V or

4-20-mA is called gain; adjusting the gain size depends on the comparative relationship between the weighing object and the sensor total range, see the example description。

- Example of the current calibration: The weight object is known to be 100KG, sensor total range of 1000KG, current output of 4-20mA;

operating steps : Empty tuning zero =4.00mA → load tuning gain is 5.60mA
(100kg/1000kg*16mA+4.0mA) →Zero point is after unloading 4.00mA;

1. After the sensor is installed with no load, call Zero to 4.00mA → to measure the multimeter current range (DC) and adjust the Zero potentiometer to 4.00mA;
2. Load 100KG weight object stable, adjust Span to 5.60mA → with the multimeter current and adjust the Span potentiometer to 5.60mA;
3. The measured I and P-current shall be 4.00mA;
4. After 100KG weight load is stabilized, I and P-currents are 5.60mA;

Note: If the first commissioning current output is not 5.60mA, ;

computational formula :

4-20mA	Gain output current = known weight object / Sensor total range * Net output + zero
net output 16mA	5.6mA = 100kg / 1000kg * 16ma + 4mA
0-20mA	Gain output current = known weight object / Sensor total range * Net output + zero
net output 20mA	2.0mA = 100kg / 1000kg * 20ma + 0mA
4--12-20mA	Gain output current = known weight object / Sensor total range * Net output + zero
net output 8mA	12.8mA = 100kg / 1000kg * 8ma + 12mA

Note: The transmitter has no negative current output, when the sensor pull is used (positive-negative torque), calibrate as 4-12-20mA (net output 8mA)。

method: 1.Zero zero to 4mA → to ates the adjustable current as: (100/1000kg*8mA+4mA=4.8mA)
→The overload weight remains stable after the adjusted SPAN gain is 4.8mA;

2. ZERO zero current I and P-shall be 4mA → adjusted zero ZERO of 12mA;
3. The I and P-currents are 12.8mA after reload weight;

- Voltage calibration example: Weight object is known to be 200KG, sensor total range of 1000KG, voltage output 0 ± 10V;

operating steps : Empty tuning zero 0V → load tuning gain;

510 Weigh the transmitter

1. Peel the dead load of the sensor after no load, measure the V and P-voltage with the multimeter voltage gear (DC) and adjust the Zero potentiometer to 0V;
2. After loading the 160KG weight object remains stable, adjust 2.0V, with the multimeter voltage gear (DC) and adjust the Span potentiometer to 2.0V;

computational formula:

0±10V	Gain output voltage = known weight object / sensor total range * 10V				
	2.0V	=	200kg	/	1000kg	*10V
0±5V	Gain output voltage = known weight object / sensor total range * 5V				
	1.0V	=	200kg	/	1000kg	*5V

Appendix E: Datasheet Zerone 1-3 kHz PWM to Analog Signal Converter

Impedance Matching

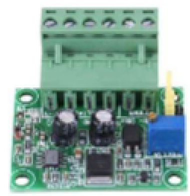
One more thing to consider is the impedance of your analog source (the output of your filter) and the load that you have on it. Impedance matching will maximize power transfer, but even in situations where power transfer is not important it may still be important. Depending on the circumstance, unmatched impedance can cause reflections or standing waves which increase attenuation and signal distortion. Choose the filter you use based on the impedance needed to match the load. Consider the Zerone 1-3kHz PWM to Analog Signal Converter board or similar board if needed. Otherwise, use a transformer to adjust the filter output impedance to match the load.

Zerone 1-3 kHz PWM to Analog Signal Converter

A PWM to Analog signal converter board can also be used if desired to convert a PWM signal into an analog voltage. This is more expensive and takes up more space, however it is easy to use and reliable.

Specs

PWM Input Voltage: 4.3-24V VPP
PWM Input Frequency: 1-3 kHz
Power Supply Voltage: 15-30V
Output Voltage: 0-10V



Basic Operation

This board generates a voltage between 0 and 10 volts proportional to the duty cycle of a PWM signal. This will create a true analog signal from a PWM. The voltage generated is related linearly to the PWM duty cycle between 5% and 95% duty cycle, but they are not proportional. If high accuracy is needed, see charts included below.

5V and 24V Jumper

A yellow jumper selects the VPP PWM input voltage. If the PWM voltage is between 0 and 10 volts, place the jumper vertically on the 5V option, as it is shown in the image under “Wiring Diagram”. If voltage is between 12 and 24 volts, place the jumper vertically on the 24V option.

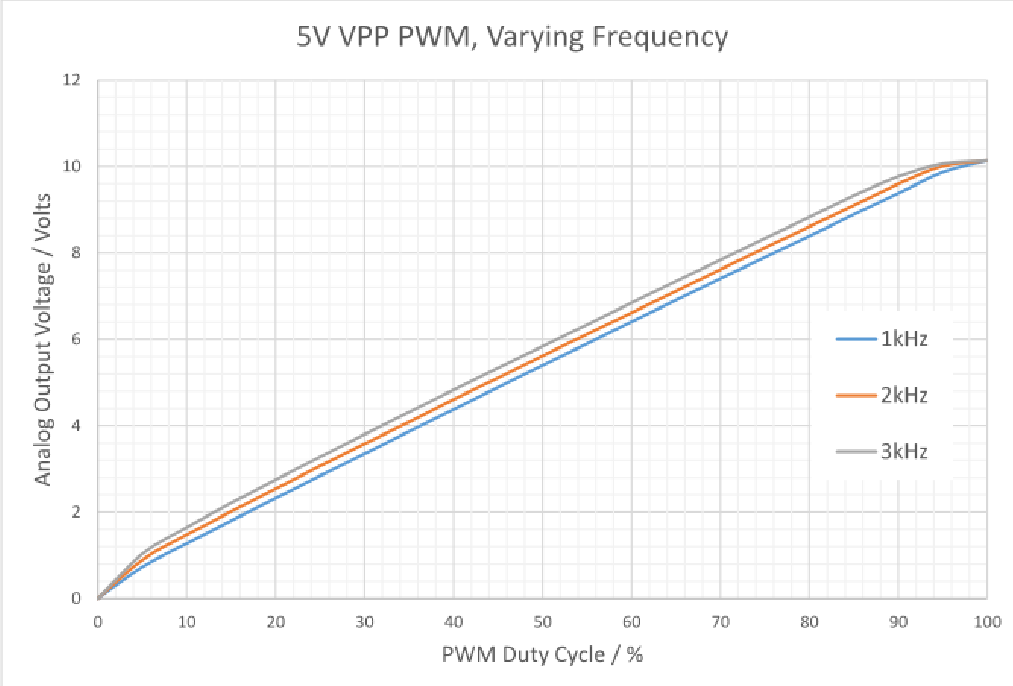
Calibration

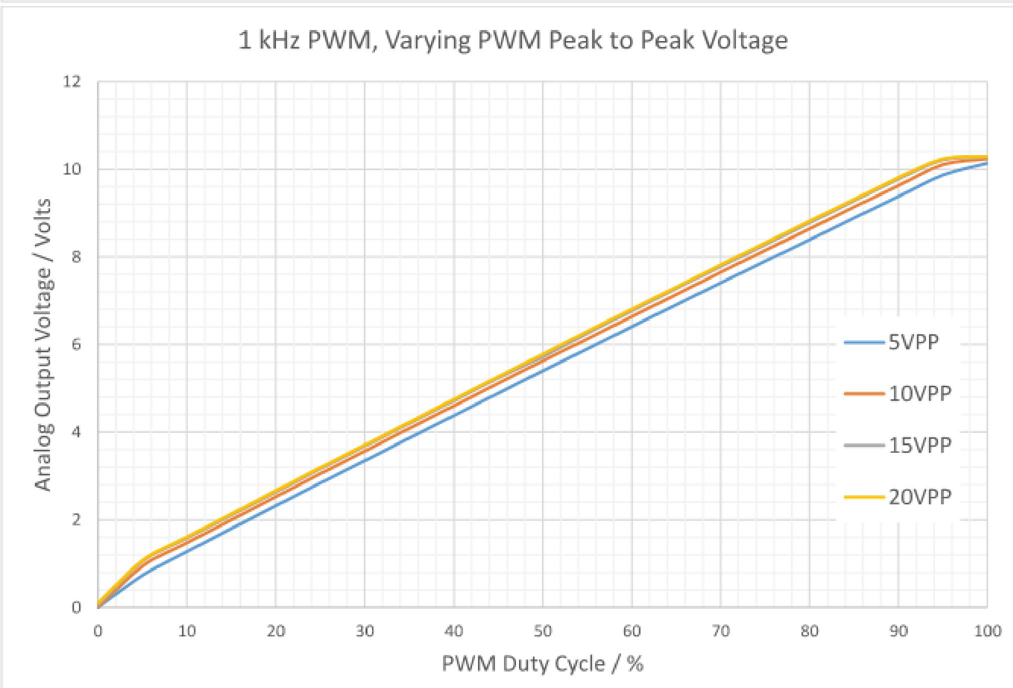
Before using, calibrate the board by using a small flat head screwdriver to adjust the gold potentiometer on the blue tower, labeled “voltage output adjust potentiometer” in the image under “Wiring Diagram”. Connect the output to a voltmeter and wire board to a 15V power supply, then use a function generator to input a 1kHz, 5VPP, 50% duty cycle. Adjust the gold potentiometer until the voltmeter reads 5.40 V DC.

Wiring Diagram

For more information, come to the Project Support Center.

Duty Cycle to Analog Output Relationship





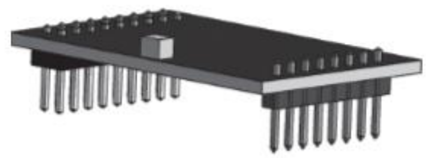
Appendix F: MCD020-050101 Motor Driver Datasheet & User Guide

MDC020-050101 - 50V, 10A Brushless Controller

ANAHEIM AUTOMATION

FEATURES

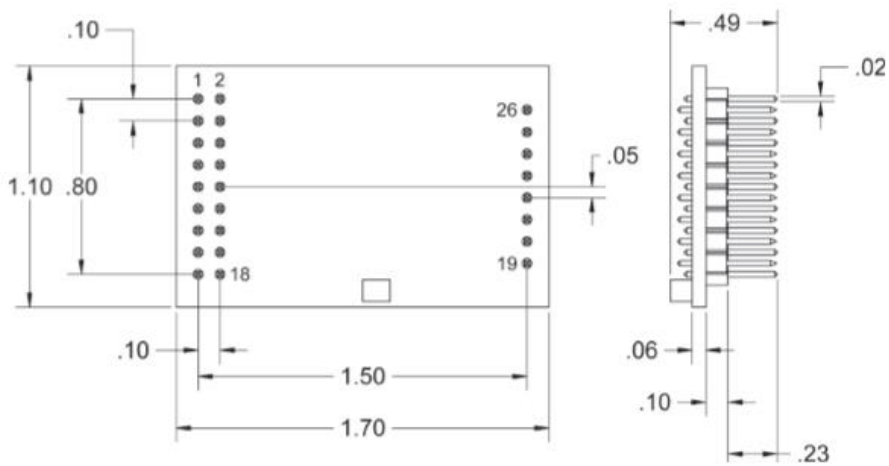
- *Open Loop Operation*
- *6 - 50VDC Voltage Range*
- *0.75V to 5V External Voltage Speed Control*
- *2-Quadrant Operation*
- *Hall Sensor Feedback*
- *Short Circuit Protection*
- *Maximum Current Limit at 10.0 Amps (peak)*
- *Enable and Direction Input*
- *TTL-CMOS Compatible Inputs*
- *Compact Size*
- *Easy Connectivity/Integration into Motherboard*



DESCRIPTION

The MDC020-050101 driver is designed to drive DC Brushless motors at currents of up to 10A (peak) and 50V. The driver operates in the basic open loop configuration with 120° DC Brushless motors. The driver is protected against over current, hall sensor error and under voltage. When an error occurs, a fault output is turned low logic '0' to notify the user. An external voltage (0.75-5VDC) is used to control the speed of the motor. The direction of the motor can be preset by the direction control input. The freewheel input overrides all other inputs into the driver. With two connector arrays arranged in a 2.54 mm pattern, it allows easy integration and connectivity to the MDC020-EVALBOARD or the OEM-side mother board.

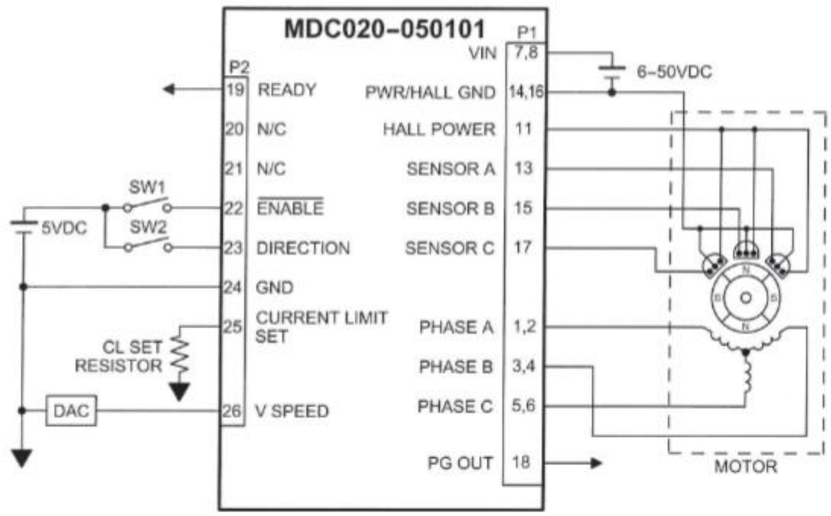
DIMENSIONS



L011803

4985 E. Landon Drive Anaheim, CA 92807 **Tel. (714) 992-6990** Fax. (714) 992-0471 **www.anaheimautomation.com**

WIRING DIAGRAM



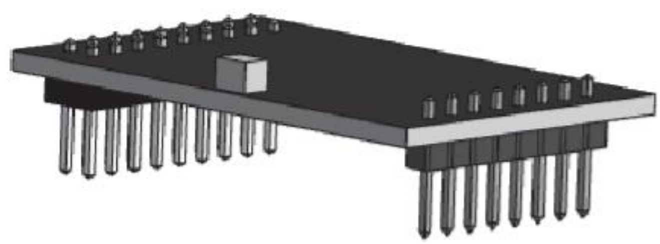
ADDITIONAL INFORMATION

Part #	Description
MDC020-050101	Featured BLDC driver 10A, 50V
PSEPM-0200-1-24V-8.4A	DC Power Supply 24VDC at 8.4mps
PSEPM-0200-1-48V-4.2A	DC Power Supply 48VDC at 4.2Amps
MDC020-EVALBOARD	Evaluation Board for Board Level OEM BLDC and DC Speed Controllers MDC020-024031, MDC020-050101, MBDC020-24031, and MBDC020-050101

Power Requirements:	6 - 50VDC
Output Current Range:	0.5 - 10.0 Amps (Peak) 0.25 - 5 Amps (Continuous)
Ready: (P2, Pin 19)	Logic "1" - Ready Logic "0" - Fault
Enable: (P2, Pin 22)	Logic "1" - Motor phases on (enabled) Logic "0" (open) - Motor phases off (disabled)
Direction: (P2, Pin 23)	Logic "1" - Motor moves clockwise Logic "0" (open) - Motor imves counter clockwise
Current Limit Set: (P2, Pin 25)	Logic "1" (open) - 10A current limit Resitor to GND - Sets current limit (Refer to User's guide for values)
V Speed: (P2, Pin 26)	0.75V - 5V
Operation Temperature:	0°C to 70°C

MDC020-050101 Series
50V, 10A Brushless Controller

User's Guide



ANAHEIM AUTOMATION
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website: www.anaheimautomation.com

MDC020-050101 Driver Features

- Open Loop Operation
- 6 - 50VDC Voltage Range
- 0.75V to 5V External Voltage Speed Control
- 2-Quadrant Operation
- Hall Sensor Feedback
- Short Circuit Protection
- Maximum Current Limit at 10.0 Amps (peak)
- Enable and Direction Input
- TTL-CMOS Compatible Inputs
- Compact Size
- Easy Connectivity/Integration into Motherboard

General Description

The MDC020-050101 driver is designed to drive DC Brushless motors at currents of up to 10A (peak) and 50V. The driver operates in the basic open loop configuration with 120° DC Brushless motors. The driver is protected against over current, hall sensor error and under voltage. When an error occurs, a fault output is turned low logic '0' to notify the user. An external voltage (0.75-5VDC) is used to control the speed of the motor. The direction of the motor can be preset by the direction control input. The freewheel input overrides all other inputs into the driver. With two connector arrays arranged in a 2.54 mm pattern, it allows easy integration and connectivity to the MDC020-EVALBOARD or the OEM-side mother board.

Fault Protection

A shut down over current protection is provided when the motor current level exceeding the set peak current limit is produced, 10A max. When the over current protection is activated, the controller shuts off the outputs to the motor. The motor can be turned back on by releasing the load and toggling the Enable line (P2 - pin 22) or powering down and up the driver.

Ordering Information

Part #	Description
MDC020-050101	Featured BLDC driver 10A, 24V
PSEPM-0200-1-24V-8.4A	DC Power Supply 24VDC at 8.4 Amps
PSEPM-0200-1-48V-4.2A	DC Power Supply 48VDC at 4.2 Amps
MDC020-EVALBOARD	Evaluation Board for Board Level OEM BLDC and DC Speed Controllers MDC020-024031, MDC020-050101, MBDC020-24031, and MBDC020-050101

MDC020-050101 Terminals

P1:

Pin #	Description	Pin #	Description
1	Phase A	10	0VDC
2	Phase A	11	5V out
3	Phase B	12	No Connect
4	Phase B	13	Hall A
5	Phase C	14	0VDC
6	Phase C	15	Hall B
7	VHV	16	0VDC
8	VHV	17	Hall C
9	0VDC	18	PG OUT

P2:

Pin #	Description
19	Ready
20	No Connect
21	No Connect
22	Enable
23	Direction
24	0VDC
25	Current LIMIT
26	Vspeed

Motor Connection

Refer to the hookup diagram for typical driver applications. When connecting a motor for the first time, connect the hall sensor wires (5 of them) to the driver. **DO NOT CONNECT THE PHASES YET.** Turn on power and rotate the motor by hand. If the Ready output is a logic "0" (0V), the hall phases are incorrectly wired. If the Ready output is a logic "1" (5V) then the hall wires are connected correctly. Power the unit down and proceed to connect the motor phases. If the motor does not run or runs erratically, power down and make sure the phases are connected correctly. There are six different ways to connect the phase wires, and normally only two will allow the motor to rotate, but only one is correct. If the direction of the motor is changed and the no-load current of the motor is approximately the same and the motor runs smoothly in both directions then the phase wires are correct. The wiring of the motor phases should be separated from the hall and input connections to not allow a possible source of interference.

P1 Terminal Descriptions

VHV

This pin (P1 - pin 7,8) is the voltage supply for the driver with respect to 0VDC (P1 - pin 14, 16). A voltage from 6VDC (min) - 50VDC (max) is required to operate the driver.

5V OUT

This pin (P1 - pin 11) is the Hall Sensor Power Output: 5V @30mA maximum. Typical current draw from hall sensors in 20mA.

PG OUT

A 5V signal pulse out is available at a rate of 4 pulses for 1 revolution of an 8-pole motor, 3 pulses for 1 revolution of a 6-pole motor, and 2 pulses for 1 revolution of a 4-pole motor.
8-pole motor RPM = 15 * PG OUT (in Hz)
6-pole motor RPM = 20 * PG OUT (in Hz)
4-pole motor RPM = 30 * PG OUT (in Hz)

P2 Terminal Descriptions

Ready

When NO fault or disable occurs, this output will be a logic “1” (5V). When a fault occurs, this output will be a logic “0” (0V) under these conditions:

1. Invalid Sensor Input Code
2. Over Current. The driver is equipped with cycle-by-cycle current limiting or over current latch.

Enable

The motor enable feature allows the de-energized of the motor phases. A high input at this input causes the motor to run at the given speed, while a low (open) at this input causes the motor to coast to a stop.

Direction

The motor direction feature allows the changing of the rotation of the motor. This input should not be changed while motion is in progress. A high input causes the motor to turn in the CW direction, while a low (open) at this input causes the motor to turn in the CCW direction.

Current Limit

The current limit input is used for setting the motor current in the range of 0.5-10A peak (0.25-5A continuous). The current limit value should be set below the rated motor current (max continuous current). To set the current limiting value, an external resistor (at least 62.5mW) between current limiting input (P2 - pin 25) and ground (P1 - pin 14, 16) must be added as shown in table below.

Current Limit Resistor Values

Current Limit	Resistor
10A	Input Floating
9A	220Kohms
8A	91Kohms
7A	56Kohms
6A	36Kohms
5A	24Kohms

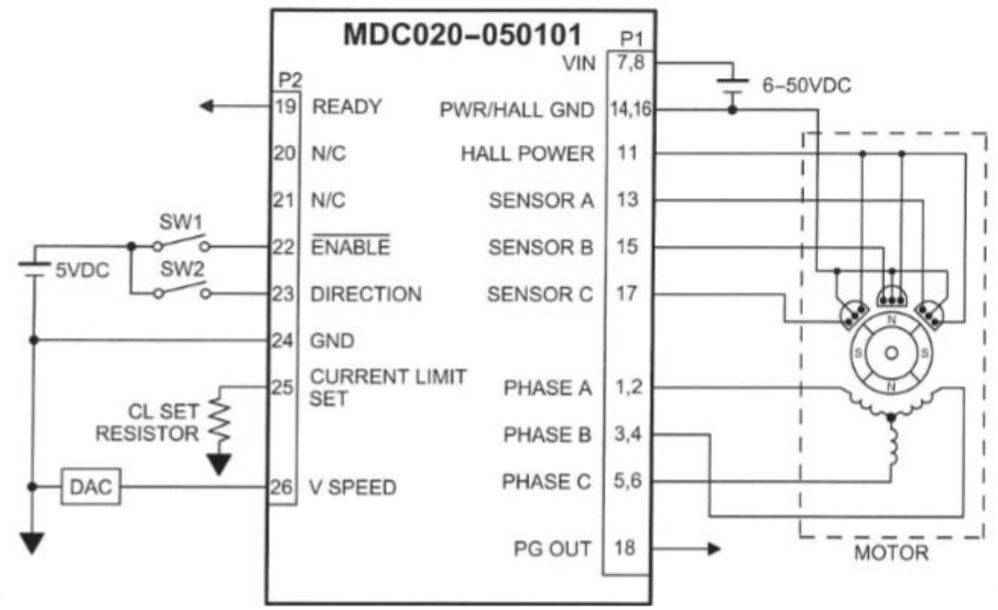
Current Limit Resistor Values

Current Limit	Resistor
4A	16Kohms
3A	10Kohms
2A	5.6Kohms
1A	2.7Kohms
0.5A	1.2Kohms

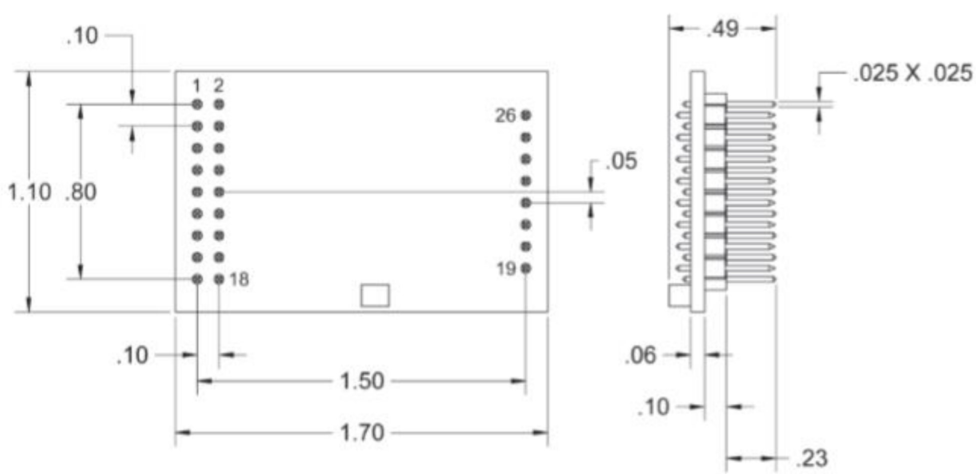
Vspeed

A voltage is used to control the speed of the motor, the 0.75V to 5V voltage can be tied on Vspeed (P2 - pin 26) with respect to 0VDC (P2- Pin 14, 16). The maximum voltage amplitude that can be placed on Vspeed is 5.5V. A voltage exceeding 5.5V will cause damage to the driver.

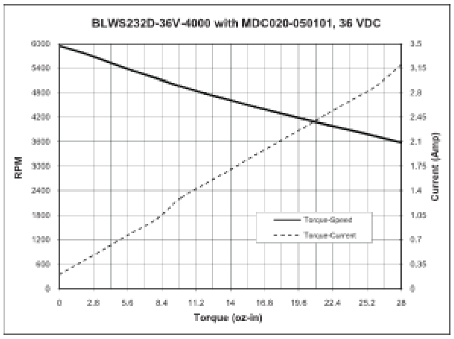
Typical Wiring Diagram



Dimensions



Torque Speed Curve



DISCLAIMER

Though every effort has been made to supply complete and accurate information in this manual, the contents are subject to change without notice or obligation to inform the buyer. **In no event will Anaheim Automation be liable for direct, indirect, special, incidental, or consequential damages arising out of the use or inability to use the product or documentation.**

Anaheim Automation's general policy does not recommend the use of its' products in life support applications wherein a failure or malfunction of the product may directly threaten life or injury. Per Anaheim Automation's Terms and Conditions, the user of Anaheim Automation products in life support applications assumes all risks of such use and indemnifies Anaheim Automation against all damages.

LIMITED WARRANTY

All Anaheim Automation products are warranted against defects in workmanship, materials and construction, when used under Normal Operating Conditions and when used in accordance with specifications. This warranty shall be in effect for a period of twelve months from the date of purchase or eighteen months from the date of manufacture, whichever comes first. **Warranty provisions may be voided if products are subjected to physical modifications, damage, abuse, or misuse.**

Anaheim Automation will repair or replace at its' option, any product which has been found to be defective and is within the warranty period, provided that the item is shipped freight prepaid, with previous authorization (RMA#) to Anaheim Automation's plant in Anaheim, California.

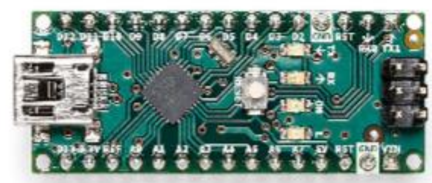
TECHNICAL SUPPORT

If you should require technical support or if you have problems using any of the equipment covered by this manual, please read the manual completely to see if it will answer the questions you have. If you need assistance beyond what this manual can provide, contact your Local Distributor where you purchased the unit, or contact the factory direct.

ANAHEIM AUTOMATION

Appendix G: Arduino Nano Datasheet

Product Reference Manual
SKU: A000005



Description

Arduino® Nano is an intelligent development board designed for building faster prototypes with the smallest dimension. Arduino Nano being the oldest member of the Nano family, provides enough interfaces for your breadboard-friendly applications. At the heart of the board is **ATmega328 microcontroller** clocked at a frequency of 16 MHz featuring more or less the same functionalities as the Arduino Duemilanove. The board offers 22 digital input/output pins, 8 analog pins, and a mini-USB port.

Target Areas

Maker, Security, Environmental, Robotics and Control Systems

Features

- **ATmega328** Microcontroller
  - High-performance low-power 8-bit processor
  - Achieve up to 16 MIPS for 16 MHz clock frequency
  - 32 kB of which 2 KB used by bootloader
  - 2 kB internal SRAM
  - 1 kB EEPROM
  - 32 x 8 General Purpose Working Registers
  - Real Time Counter with Separate Oscillator
  - Six PWM Channels
  - Programmable Serial USART
  - Master/Slave SPI Serial Interface
- **Power**
  - Mini-B USB connection
  - 6-20V unregulated external power supply (pin 30)
  - 5V regulated external power supply (pin 27)
- **Sleep Modes**
  - Idle
  - ADC Noise Reduction
  - Power-save
  - Power-down
  - Standby
  - Extended Standby
- **I/O**
  - 22 Digital
  - 8 Analog
  - 6 PWM Output

Contents

1 The Board

1.1 Application Examples

Arduino Nano is the first embedded microcontroller in the Nano series with minimum functionalities, designed for mini projects from the maker community. With a large number of input/output pins gives the advantage of utilizing several serial communications like UART, SPI and I2C. The hardware is compatible with Arduino IDE, Arduino CLI and web editor.

Security: The high-performance and low-power capabilities gives the chance to develop security based applications like access control systems using fingerprint sensors. The flexibility to interface sensors and external devices using serial communication has improved the scope of utility.

Environmental: The low-power feature of the microcontroller and the power supply options for the board has enhanced the ability to implement remote IoT projects related to environmental issues.

Robotics: Robotics has always been the favorite area of exploration for the Maker community and with this tiny embedded hardware you can now create complex and advanced robotic applications.

1.2 Accessories

1.3 Related Products

- Arduino Nano 33 BLE
- Arduino 33 IoT
- Arduino Micro

2 Ratings

2.1 Recommended Operating Conditions

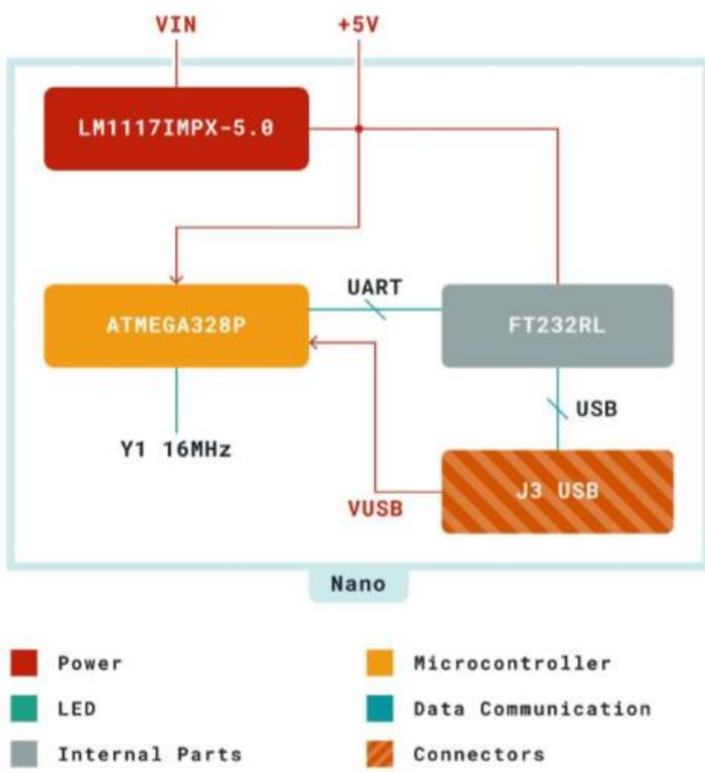
Symbol	Description	Min	Max
	Conservative thermal limits for the whole board:	-40 °C	85 °C

2.2 Power Consumption

Symbol	Description	Min	Typ	Max	Unit
USB VCC	Input supply from USB		TBC		mW
VIN	Input from VIN pad		TBC		mW

3 Functional Overview

3.1 Block Diagram

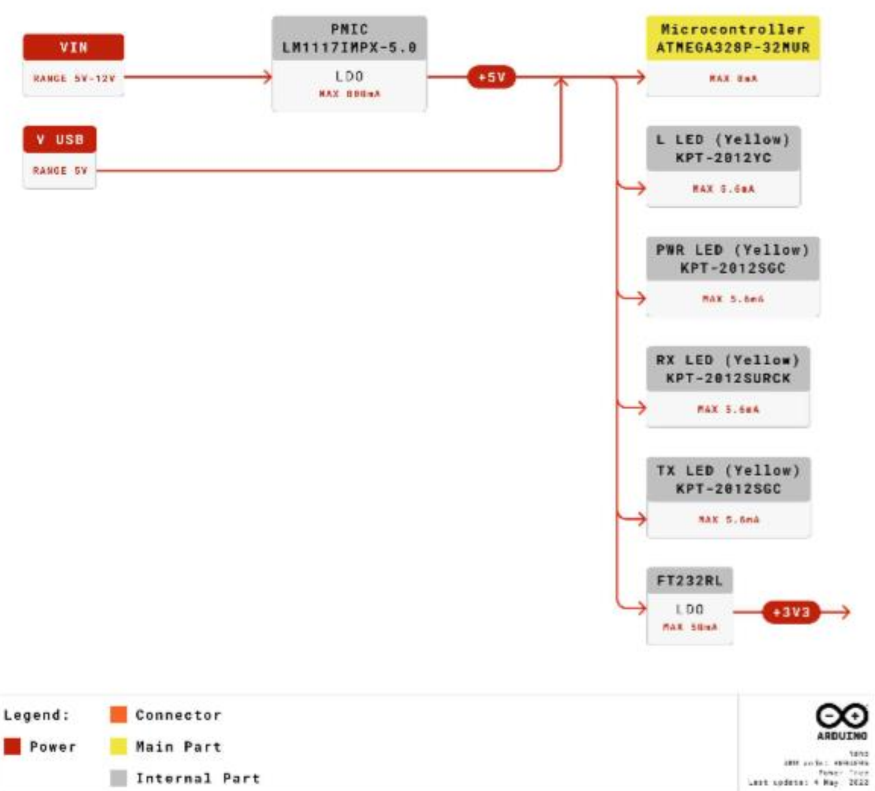


Block Diagram of Arduino Nano

3.2 Processor

The primary processor in the Arduino Nano v3.3 board is the high-performance and low-power 8-bit ATmega328 microcontroller that runs at a clock frequency of 16 MHz. The ability to interface external devices through serial communication supported by the chip with UART TTL (5V), I2C (TWI) and SPI. Arduino Nano can be programmed with Arduino software reducing the entry barriers for new users. Smallest dimension embedded hardware makes it a perfect choice for breadboard-friendly projects from the maker community.

3.3 Power Tree



Power Tree of Arduino Nano

The Arduino Nano can be powered by either the USB port or alternatively via VIN. The input supply of VIN is regulated by an LDO so the supply is limited to 5V for the optimal functioning of the board. There is also another regulator which limits the voltage to 3.3V for powrering the components with low voltage requirements.

4 Board Operation

4.1 Getting Started - IDE

If you want to program your Arduino® Nano while offline you need to install the Arduino® Desktop IDE **[1]** To connect the Arduino Uno to your computer, you'll need a Micro-B USB cable. This also provides power to the board, as indicated by the LED.

4.2 Getting Started - Arduino Web Editor

All Arduino® boards, including this one, work out-of-the-box on the Arduino Web Editor **[2]**, by just installing a simple plugin. The Arduino Web Editor is hosted online, therefore it will always be up-to-date with the latest features and support for all boards. Follow **[3]** to start coding on the browser and upload your sketches onto your board.

4.3 Sample Sketches

Sample sketches for the Arduino® can be found either in the "Examples" menu in the Arduino® IDE or in the "Documentation" section of the Arduino website **[4]**

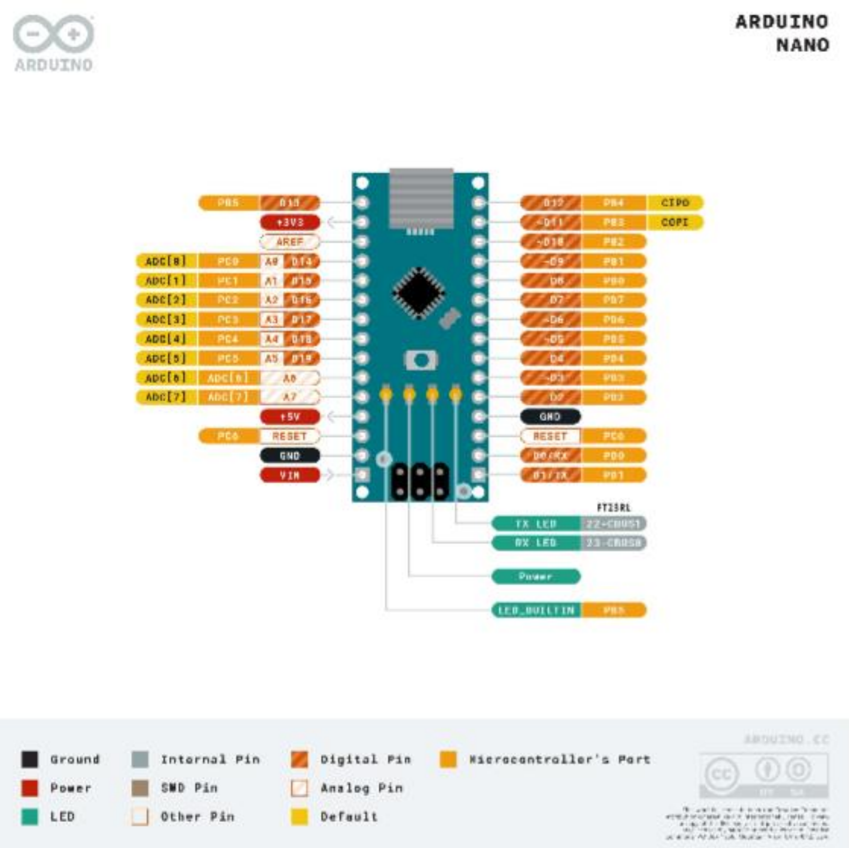
4.4 Online Resources

Now that you have gone through the basics of what you can do with the board you can explore the endless possibilities it provides by checking exciting projects on ProjectHub **[5]**, the Arduino® Library Reference **[6]** and the online store **[7]** where you will be able to complement your board with sensors, actuators and more.

4.5 Board Recovery

All Arduino boards have a built-in bootloader which allows flashing the board via USB. In case a sketch locks up the processor and the board is not reachable anymore via USB it is possible to enter bootloader mode by double-tapping the reset button right after power up.

5 Connector Pinouts



Power Tree of Arduino Nano

5.1 Analog

Pin	Function	Type	Description
1	+3V3	Power	5V USB Power
2	A0	Analog	Analog input 0 /GPIO
3	A1	Analog	Analog input 1 /GPIO
4	A2	Analog	Analog input 2 /GPIO
5	A3	Analog	Analog input 3 /GPIO
6	A4	Analog	Analog input 4 /GPIO
7	A5	Analog	Analog input 5 /GPIO
8	A6	Analog	Analog input 6 /GPIO
9	A7	Analog	Analog input 7 /GPIO
10	+5V	Power	+5V Power Rail
11	Reset	Reset	Reset
12	GND	Power	Ground
12	VIN	Power	Voltage Input

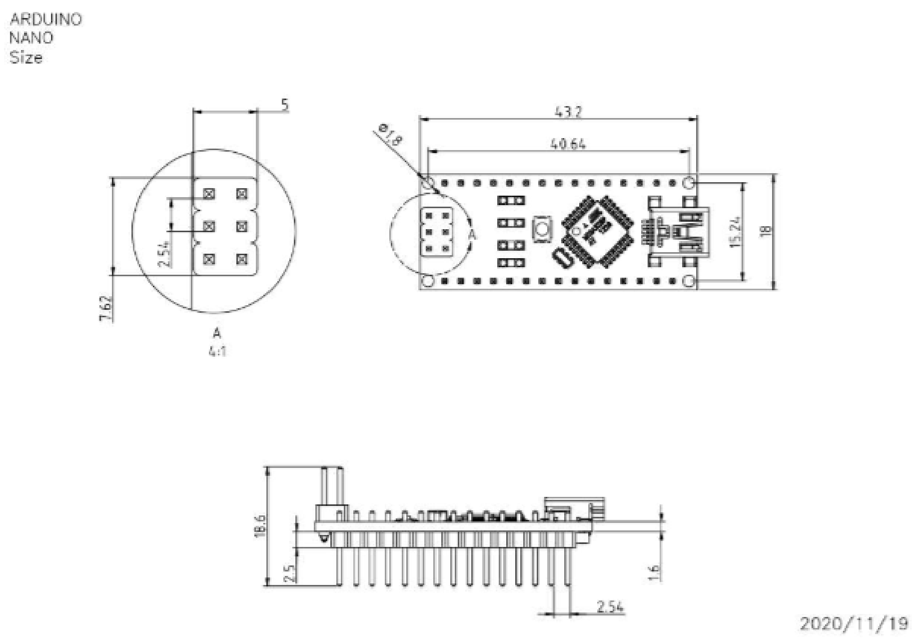
5.2 Digital

Pin	Function	Type	Description
1	D1/TX1	Digital	Digital Input 1 /GPIO
2	D0/RX0	Digital	Digital Input 0 /GPIO
3	D2	Digital	Digital Input 2 /GPIO
4	D3	Digital	Digital Input 3 /GPIO
5	D4	Digital	Digital Input 4 /GPIO
6	D5	Digital	Digital Input 5 /GPIO
7	D6	Digital	Digital Input 6 /GPIO
8	D7	Digital	Digital Input 7 /GPIO
9	D8	Digital	Digital Input 8 /GPIO
10	D9	Digital	Digital Input 9 /GPIO
11	D10	Digital	Digital Input 10 /GPIO
12	D11	Digital	Digital Input 11 /GPIO
13	D12	Digital	Digital Input 12 /GPIO
14	D13	Digital	Digital Input 13 /GPIO
15	Reset	Reset	Reset
16	GND	Power	Ground

5.3 ATmega328

Pin	Function	Type	Description
1	PB0	Internal	Serial Wire Debug
2	PB1	Internal	Serial Wire Debug
3	PB2	Internal	Serial Wire Debug
4	PB3	Internal	Serial Wire Debug
5	PB4	Internal	Serial Wire Debug
6	PB5	Internal	Serial Wire Debug

6 Mechanical Information



Mechanical dimensions of Arduino Nano

7 Certifications

7.1 Declaration of Conformity CE DoC (EU)

We declare under our sole responsibility that the products above are in conformity with the essential requirements of the following EU Directives and therefore qualify for free movement within markets comprising the European Union (EU) and European Economic Area (EEA).

7.2 Declaration of Conformity to EU RoHS & REACH 211 01/19/2021

Arduino boards are in compliance with RoHS 2 Directive 2011/65/EU of the European Parliament and RoHS 3 Directive 2015/863/EU of the Council of 4 June 2015 on the restriction of the use of certain hazardous substances in electrical and electronic equipment.

Substance	Maximum Limit (ppm)
Lead (Pb)	1000
Cadmium (Cd)	100
Mercury (Hg)	1000
Hexavalent Chromium (Cr6+)	1000
Poly Brominated Biphenyls (PBB)	1000
Poly Brominated Diphenyl ethers (PBDE)	1000
Bis(2-Ethylhexyl} phthalate (DEHP)	1000
Benzyl butyl phthalate (BBP)	1000
Dibutyl phthalate (DBP)	1000
Diisobutyl phthalate (DIBP)	1000

Exemptions : No exemptions are claimed.

Arduino Boards are fully compliant with the related requirements of European Union Regulation (EC) 1907 /2006 concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH). We declare none of the SVHCs (https://echa.europa.eu/web/guest/candidate-list-table), the Candidate List of Substances of Very High Concern for authorization currently released by ECHA, is present in all products (and also package) in quantities totaling in a concentration equal or above 0.1%. To the best of our knowledge, we also declare that our products do not contain any of the substances listed on the "Authorization List" (Annex XIV of the REACH regulations) and Substances of Very High Concern (SVHC) in any significant amounts as specified by the Annex XVII of Candidate list published by ECHA (European Chemical Agency) 1907 /2006/EC.

7.3 Conflict Minerals Declaration

As a global supplier of electronic and electrical components, Arduino is aware of our obligations with regards to laws and regulations regarding Conflict Minerals, specifically the Dodd-Frank Wall Street Reform and Consumer Protection Act, Section 1502. Arduino does not directly source or process conflict minerals such as Tin, Tantalum, Tungsten, or Gold. Conflict minerals are contained in our products in the form of solder, or as a component in metal alloys. As part of our reasonable due diligence Arduino has contacted component suppliers within our supply chain to verify their continued compliance with the regulations. Based on the information received thus far we declare that our products contain Conflict Minerals sourced from conflict-free areas.

7.4 FCC Caution

Any Changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.

This device complies with part 15 of the FCC Rules. Operation is subject to the following two conditions:

(1) This device may not cause harmful interference

(2) this device must accept any interference received, including interference that may cause undesired operation.

FCC RF Radiation Exposure Statement:

1. This Transmitter must not be co-located or operating in conjunction with any other antenna or transmitter.
2. This equipment complies with RF radiation exposure limits set forth for an uncontrolled environment.
3. This equipment should be installed and operated with minimum distance 20cm between the radiator & your body.

English: User manuals for license-exempt radio apparatus shall contain the following or equivalent notice in a conspicuous location in the user manual or alternatively on the device or both. This device complies with Industry Canada license-exempt RSS standard(s). Operation is subject to the following two conditions:

(1) this device may not cause interference

(2) this device must accept any interference, including interference that may cause undesired operation of the device.

French: Le présent appareil est conforme aux CNR d'Industrie Canada applicables aux appareils radio exempts de licence. L'exploitation est autorisée aux deux conditions suivantes :

(1) l' appareil nedoit pas produire de brouillage

(2) l'utilisateur de l'appareil doit accepter tout brouillage radioélectrique subi, même si le brouillage est susceptible d'en compromettre le fonctionnement.

IC SAR Warning:

English This equipment should be installed and operated with minimum distance 20 cm between the radiator and your body.

French: Lors de l' installation et de l' exploitation de ce dispositif, la distance entre le radiateur et le corps est d 'au moins 20 cm.

Important: The operating temperature of the EUT can't exceed 80℃ and shouldn't be lower than -20℃.

Hereby, Arduino S.r.l. declares that this product is in compliance with essential requirements and other relevant provisions of Directive 2014/53/EU. This product is allowed to be used in all EU member states.

8 Company Information

Company name	Arduino S.r.l.
Company Address	Via Andrea Appiani 25, 20900 MONZA MB, Italy

9 Reference Documentation

Ref	Link
Arduino IDE (Desktop)	https://www.arduino.cc/en/software
Arduino IDE (Cloud)	https://create.arduino.cc/editor
Cloud IDE Getting Started	https://create.arduino.cc/projecthub/Arduino_Genuino/getting-started-with-arduino-web-editor-4b3e4a
Arduino Documentation	https://docs.arduino.cc/hardware/nano
Project Hub	https://create.arduino.cc/projecthub?by=part&part_id=11332&sort=trending
Library Reference	https://www.arduino.cc/reference/en/libraries/
Online Store	https://store.arduino.cc/

10 Revision History

Date	Revision	Changes
08/03/2022	2	Reference documentation links updates
04/12/2022	1	First Release

Artifact ID: 017	Artifact Title: Motor and Gear subsystem definition
Revision: B	Revision Date: 18 April 2023
Prepared by: Joshua Vanderpool	
Purpose: *To document the detailed design of the control system.*	

Revision History			
Revision	Revised by	Checked by	Date
--	Joshua Vanderpool	**--**	**--**
A	Brinler Tanner	Joseph Edmund	17 April 2023
B	Isaac Sorensen	Joshua Vanderpool	18 April 2023

1. Design Summary

The control system will communicate with the motor controller board which will control the motor. With the motor securely mounted to the frame it will directly turn a custom 3D printed spool wrapped by the steel cable. The motor selected has an additional planetary gear box that provides 15:1 additional gear ratio. With the motor specs and the current spool diameter the angular speeds align well with the linear velocities and torque specs we need of 40-100rpm and 3-5Nm.

1.1 Recommendations for Improvement:

- The interface to the spool was difficult to install.
- Additionally, the alignment on the frame supports causes a warping of the plastic during each revolution. Make the attachment more robust.
- If not using an encoder, get only a single-shaft motor.

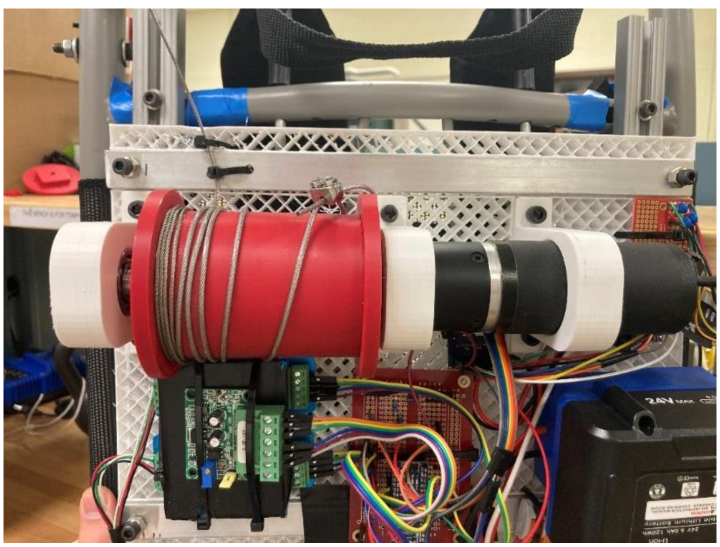


Figure 1. Mounted motor and cable spool

2. Design Details

2.1 General

All components used in this subsystem can be found in the Control Subsystem Section of the Bill of Materials. [022_DESIGN_Full_Bill_Of_Materials]

The 3D printed spool CAD file can be found here.

2.2 Motor Specs

Our chosen motor is a Brushless DC motor with a 24 V input and hall sensor control. We chose a BLWRPG173D-24V-4000-R15 from Anaheim Automation. It weighs approximately 2 pounds and has the following spec's:

Note: The only difference from the given table is that our motor is a 173D model, which stands for a dual shaft motor to allow for the mounting of an encoder. We did not use the encoder, but purchased the dual shaft model nonetheless.

Table 1	Output On Shaft of Motor Before Gear-Box												
Item	Rated Power (W)	Rated Voltage (V)	Rated Current (A)	Rated Motor Speed (RPM)	Rated Torque (oz-in)	Peak Torque (oz-in)	Line to Line Resistance (ohms)	Line To Line Inductance (mH)	Motor Back EMF Voltage (V/kRPM)	Torque Constant (oz-in/A)	Rotor Inertia (oz-in-sec^2)	Motor Weight (lbs)	"L2" Motor Length (mm)
BLWRPG172S-24V-1400	5.8	24	0.5	1400	5.66	25.5	11.90	15	8.45	14.92	0.000467	0.88	60
BLWRPG172S-24V-2100	11	24	0.8	2100	7.08	25.5	5.80	6.2	7.17	9.70	0.000467	0.76	60
BLWRPG172S-24V-4200	24	24	1.5	4200	7.93	25.5	1.60	1.94	4.44	5.45	0.000467	0.76	60
BLWRPG173S-24V-2000	31	24	2.1	2000	21.2	63.7	2.18	2.96	5.40	9.88	0.000821	0.88	85
BLWRPG173S-24V-4000	63	24	4.1	4000	21.24	63.7	0.71	0.86	4.00	5.21	0.000821	1.18	85

Table 2	Output On Shaft of Gear-Box			
Parameters/ Gear Box Ratio	Peak Torque (oz-in)	Number of Gear Trains	"L1" (Length of Gear Box in mm)	Gearbox Weight (lbs)
R3.8	208	1	35.0	0.43
R4.9	208	1	35.0	0.43
R15	833	2	45.5	0.58
R19	833	2	45.5	0.58
R24	833	2	45.5	0.58
R56	2083	3	55.5	0.58
R71	2083	3	55.5	0.58
R91	2083	3	55.5	0.58
R116	2083	3	55.5	0.58
R212	2083	4	66.0	0.89

Figure 2. Motor specs

The motor has 8 wires to power the phases and hall sensors. They are color coded and defined by the following specs:

Wire Color	Description
Green	Phase A
Red	Phase B
Black	Phase C

Wire Color	Description
Yellow	Hall Vc
Blue	Hall A
Orange	Hall B
Brown	Hall C
White	Hall Ground

Hall Sensor Specifications
Supply Voltage: 4.5VDC to 28VDC
Current, I_{off}: 10mA max
Current, I_{on}: 11.3mA max
Rated Sinking Current: 20mA
Saturation Voltage: 0.4VDC max @ 25°C
Output Leakage Current: 10µA
Output Switching Time @ 25°C Rise, 10% to 90% 1.5µs Fall, 90% to 10% 1.5µs
Output Type: Open Collector

Figure 3. Wiring table

Warning: The motor controller specifically states to not power the phases until you have ensured that the hall sensors have been hooked up correctly. This is indicated by a high signal on the READY pin of the controller board.

Complete datasheets are found in Appendix A and B. Dimensions of the motor are also given as follows:

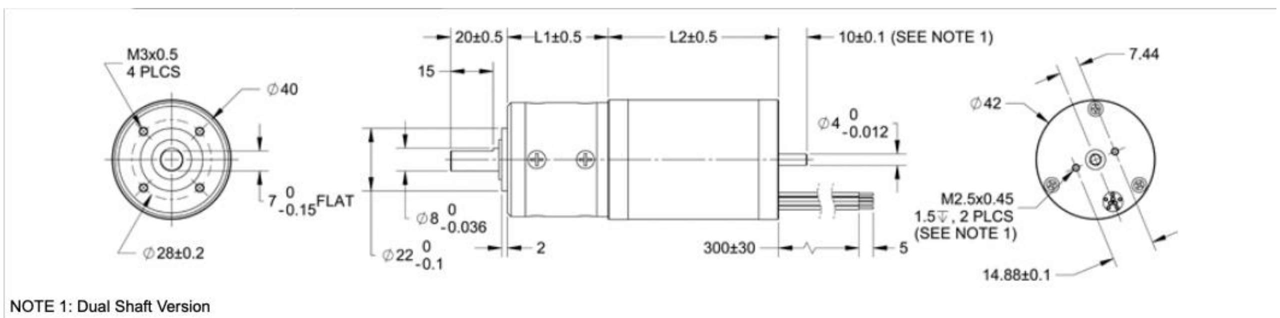


Figure 4. Anaheim motor and dimensions

https://www.anaheimautomation.com/products/brushless/brushless-gearmotor-item.php?sID=157&pt=i&tID=98&cID=47

2.2 Motor Spool

To interface with the motor shaft, we designed a custom 3D printed spool. It includes the following features:

1. Axis alignment holes for attachment to the frame.
2. Holes for cable connection.
3. An interchangeable end for easy replacement for different shaft sizes and connection points.
4. The interchangeable end attaches to the shaft via a keyed hole and set screw.

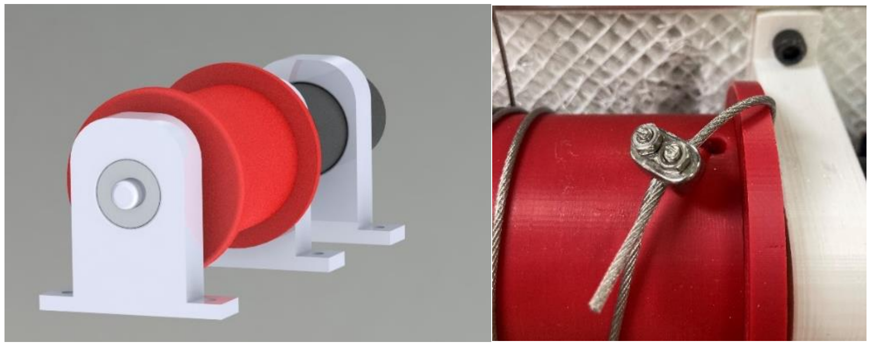


Figure 5. Cable spool frame attachment (left) and cable connection (right)

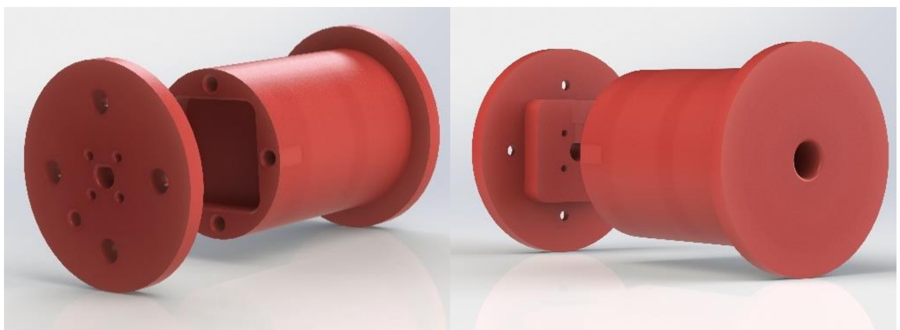


Figure 6. Motor spool detachable shaft attachment

3. Design Decisions

Q: What tests were run to confirm the function of this subsystem?

[028_TRES_Load_Offloading]

[033_TRES_Motor_Characterization]

Q: Why was a brushless motor chosen?

A: Brushless motors are more energy efficient than brushed DC motors. Its control is simple with an appropriate controller board. Through Anaheim Automations, we easily found lightweight motors with a high-power capacity and appropriate gearing.

Q: How was the motor spec'd out?

A: To find the power required by our motor, we use the fact that:

$$Power = Force * velocity$$

In this case, the force is the load we need to lift, and the velocity is how quickly we need to lift it.

The measured arm displacement required for our lifting is approximately 18 inches. Based on empirical measurement, we determine our needed cable speed is:

$$Velocity = 0.45m/s$$

Statically, the motor only will need to hold 11.25 lbs. With a safety factor of 2 to incorporate the accelerations and dynamics of the lift, we anticipate a max load of 22.5 lbs. on the motor. This is approximately **100 Newtons of force.**

Therefore, we require a motor with at least a **45-Watt** capacity.

To move the cable at 0.45 m/s a range of about **40-100 rpm** should be sufficient.

We designed our cable spool to have a 2–3-inch diameter. Thus, approximately **3-5 Nm (300-700 oz-in)** of torque will be required.

In summary, we determined that we would need a motor that:

- Runs efficiently at 45W.
- Spins at a rate of 40- 100 rpm.
- Provides approximately 3-5 Nm (300-700 oz-in) of torque.

After several iterations we selected the following motor: BLWRPG173D-24V-4000-R15 (BLWRPG17 - Brushless Motors with Planetary Gearboxes (anaheimautomation.com)). It had the following specs:

- 266 max RPM – rated for 318oz/in (Gearbox included in calculations)
- Peak torque of 955oz/in
- Rated power of 63W

This met all the specs we computed above and had a higher rated speed and power to allow us to stay well below our max thresholds to avoid overheating and maintain precise control of the motor speed.

Q: What inspired the spool design?

A: After frustration with many different types of motor shaft attachments (most would break after several minutes of use), we needed a more robust connection. It was printed in 2 separate parts to allow for an interchange of motor type. That is, a new shaft size would not require the entire reprint of the part.

Q: Were any other motors investigated?

A: Yes. We tested the BLWRPG112D-24V-10000-R51. It had enough torque to lift a 15 lbs weight, but it heated up significantly and so it was deemed that it could not sustain that amount of power for long periods of time. Although the newer BLWRPG173D was 1.1 lbs heavier, it did not struggle at all to lift the required weights and ran much more smoothly.

Additionally, we tried drill motors with drill chucks attached, but we abandoned the effort since most of these types of motors were lacking specs.

4. Interfaces

Subsystem:	Interface Description:

Frame	All elements of this system are fixtured to the frame.
Control	One motor of the control system will be attached to a transmission to pull on the cable attached to the shoulder system. There will also be a force sensor on this cable.
Wrist	The cable will be spooled on the spool attached to the gear.

BLWR17 - Brushless DC Motors

ANAHEIM AUTOMATION

FEATURES

- ***42mm Round Body***
- ***Compact Size and Power Density***
- ***Cost-Effective Replacement for Brush DC Motors***
- ***Long Life and Highly Reliable***
- ***Can be Customized for***
  - ***Maximum Speed***
  - ***Winding Current***
  - ***Shaft Options***
  - ***Cables and Connectors***

DESCRIPTION

The BLWR17 Series Brushless DC Motors come in a compact package with high power density. These motors are cost-effective solutions to many velocity control applications. The star wound motor comes in a standard 8-lead configuration. We can also customize the winding to perfectly match your voltage, current, and maximum operating speed. Special shaft modifications, cables and connectors are also available upon request.

SPECIFICATIONS

Model #	Rated Voltage (V)	Rated Speed (RPM)	Rated Power (W)	Rated Torque (oz-in)	Peak Torque (oz-in)	Rated Current (A)	Line to Line Resistance (ohms)	Line to Line Inductance (mH)	Torque Constant (oz-in/A)	Back EMF Voltage (V/kRPM)	Rotor Inertia (oz-in-sec²)	Weight (lbs)	"L" Length (mm)
BLWR171S-12V-4000	12	4000	8	2.8	8.4	0.89	1.50	2.26	3.36	1.47	0.000221	0.55	30
BLWR171S-12V-5000	12	5000	10	2.8	8.4	1.24	1.08	0.84	2.28	1.21	0.000221	0.55	30
BLWR172S-12V-4200	12	4200	25	7.9	29.7	2.87	0.48	0.44	2.79	1.46	0.000221	0.88	60
BLWR172S-24V-2000	24	2000	12	7.9	25.4	0.82	6.00	6.40	9.70	5.48	0.000467	0.88	60
BLWR172S-24V-4200	24	4200	25	7.9	25.4	1.45	1.60	1.94	5.45	3.84	0.000467	0.88	60
BLWR173S-12V-4000	12	4000	63	21.2	63.7	7.69	0.19	0.22	2.73	1.53	0.000821	1.54	85
BLWR173S-24V-2000	24	2000	31	21.2	63.7	2.15	2.18	2.96	9.88	5.60	0.000821	1.54	85
BLWR173S-24V-4000	24	4000	62	21.2	63.7	4.08	0.71	0.86	5.47	3.10	0.000821	1.54	85

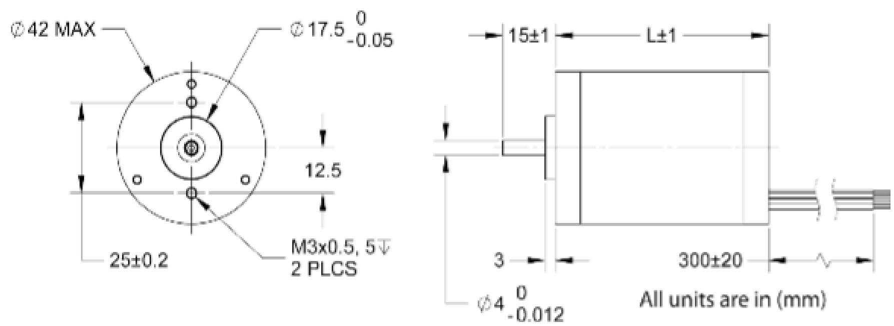
Note: Other speed options, custom leadwires, cables, connectors, and windings are available upon request.

Winding Type:	Wye, 8 Poles	Max. Radial Force:	15N @ 10mm from the flange
Hall Effect Angle:	120 degree electrical angle	Max. Axial Force:	10N
Shaft Run Out:	0.025mm	Insulation Class:	Class B
Radial Play:	0.02mm@450g	Dielectric Strength:	500VDC for one minute
End Play:	0.08mm@450g	Insulation Resistance:	100MOhm, 500VDC

L010411

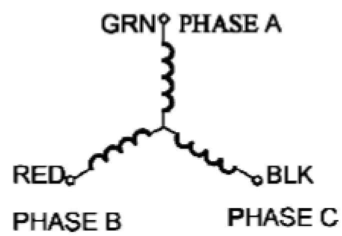
4985 E. Landon Drive Anaheim, CA 92807 **Tel. (714) 992-6990** Fax. (714) 992-0471 **www.anaheimautomation.com**

DIMENSIONS

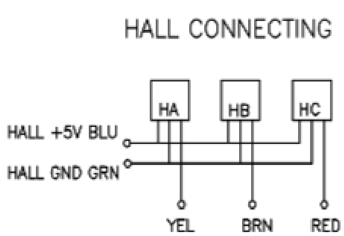


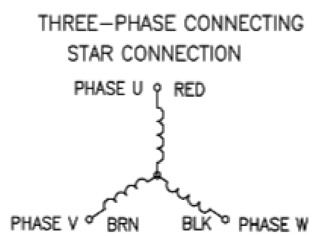
WIRING INFORMATION

Description	Motor Wire Color	Cable Adder Color
Hall Supply	Yellow	Red/White
Hall A	Blue	Orange/White
Hall B	Orange	Orange
Hall C	Brown	Yellow/White
Hall Ground	White	Black/White
Phase A	Green	Yellow
Phase B	Red	Red
Phase C	Black	Black

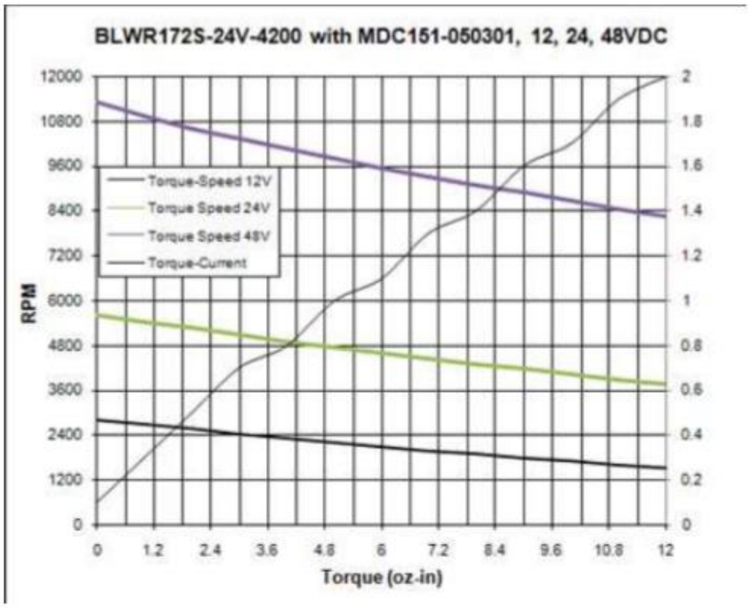


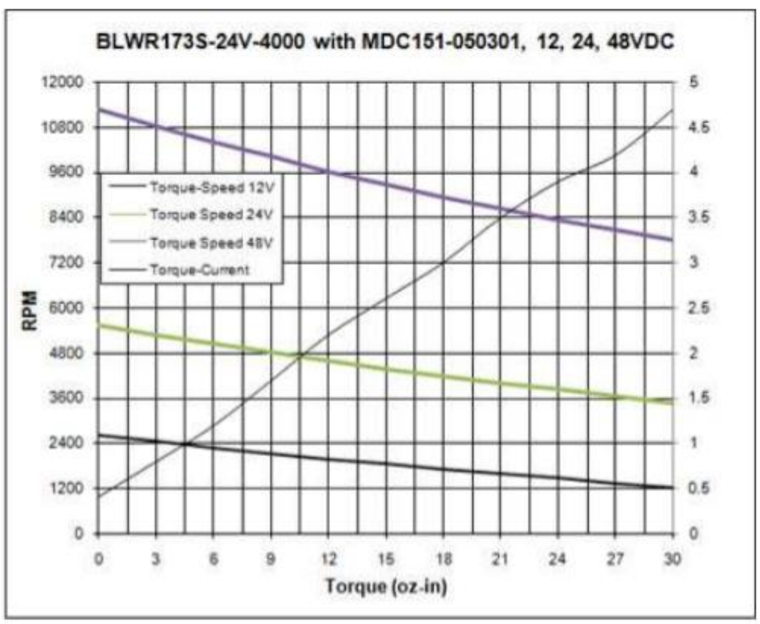
Wire Colors used for part number
BLWR173S-12V-4000 are as shown below.





Hall Sensor Specifications
Supply Voltage: 4.5VDC to 28VDC
Current, I_{off}: 10mA max
Current, I_{on}: 11.3mA max
Rated Sinking Current: 20mA
Saturation Voltage: 0.4VDC max @ 25°C
Output Leakage Current: 10µA
Output Switching Time @ 25°C Rise, 10% to 90% 1.5µs Fall, 90% to 10% 1.5µs
Output Type: Open Collector


BLWR172S-24V-4200 with MDC151-050301, 12, 24, 48VDC
RPM
Torque-Speed 12V
Torque Speed 24V
Torque Speed 48V
Torque-Current
0
1200
2400
3600
4800
6000
7200
8400
9600
10800
12000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1.2
2.4
3.6
4.8
6
7.2
8.4
9.6
10.8
12
Torque (oz-in)


BLWR173S-24V-4000 with MDC151-050301, 12, 24, 48VDC
RPM
Torque-Speed 12V
Torque Speed 24V
Torque Speed 48V
Torque-Current
0
1200
2400
3600
4800
6000
7200
8400
9600
10800
12000
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
3
6
9
12
15
18
21
24
27
30
Torque (oz-in)

Appendix B (BLWR with Planetary Gear Motor Specs)

BLWRPG17 Series - Brushless DC Planetary Gearmotors

ANAHEIM AUTOMATION

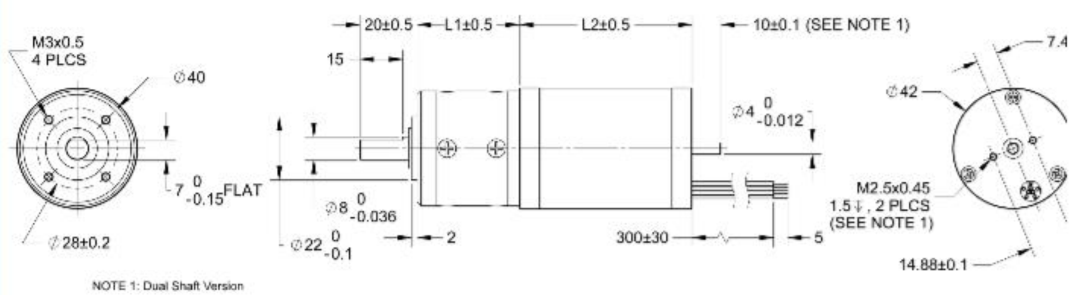
FEATURES

- *42mm Motor and Economy Gearbox*
- *Long Life - Over 3,000 Hour Operation*
- *Many Gear Ratios Available from 3.6 - 212*
- *Efficiency Up to 90%*
- *Backlash Less than 3°*
- *Can be Customized for*
  - *The Speed You are Running*
  - *The Winding Current You Need*
  - *The Shaft Options You Want*
- *CE Certified and RoHS Compliant*

DESCRIPTION

The BLWRPG17 Series are cost-effective Brushless DC Planetary Gearmotors. These motors we designed keeping the OEM in mind, using state of the art design parameters and low-co manufacturing. This allows us to offer there quality motors at exceptional prices. The BLWRPG Series include a planetary gearbox and a brushless DC motor in a compact fully integrated packa The brushless DC gearmotor is a perfect solution for applications requiring high torque or speeds und 500 RPM. These star wound motors come with integrated hall sensors for closed loop control velocity applications. If the off-the-shelf gearmotors do not match your application, a motor can wound or a gearbox can be selected to meet your specific requirements. V specialize in providing both off the self and custom solutions to handle any demanding applicati

DIMENSIONS/SPECIFICATIONS



NOTE 1: Dual Shaft Version

Winding Type:	Star, 8 Poles	Planetary Gear Radial Play of Shaft:	0.04mm
Planetary Gear Housing:	Metal	Planetary Gear Thrust Play of Shaft:	0.3mm
Planetary Gear at Output:	Ball Bearings	Planetary Gear Shaft Press fit force, max:	331lbs
Planetary Gear Radial Load:	10mm @ 22lbs	Planetary Gear Shaft Axial Load:	6.6lbs

L010402

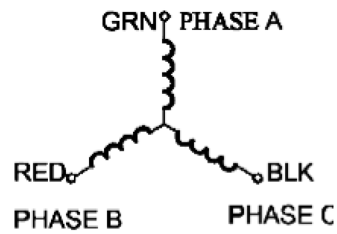
4985 E. Landon Drive Anaheim, CA 92807 **Tel. (714) 992-6990** Fax. (714) 992-0471 **www.anaheimautomation.com**

WIRING INFORMATION

Wire Color	Description
Green	Phase A
Red	Phase B
Black	Phase C

Wire Color	Description
Yellow	Hall Vc
Blue	Hall A
Orange	Hall B
Brown	Hall C
White	Hall Ground

Hall Sensor Specifications
Supply Voltage: 4.5VDC to 28VDC
Current, I_{off}: 10mA max
Current, I_{on}: 11.3mA max
Rated Sinking Current: 20mA
Saturation Voltage: 0.4VDC max @ 25°C
Output Leakage Current: 10µA
Output Switching Time @ 25°C Rise, 10% to 90% 1.5µs Fall, 90% to 10% 1.5µs
Output Type: Open Collector



SPECIFICATIONS

Create a complete Model Number by selecting a motor from Table 1 and Gear Box from Table 2

BLWRPG172S-24V-4200-R3.6

Table 1	Output on Shaft of Motor Before Gear-Box										
Model #	Rated Power (W)	Rated Current (A)	Line to Line Resistance (ohms)	Line to Line Inductance (mH)	Back EMF Voltage (V/kRPM)	Motor Weight (lbs)	Motor Length "L2" (mm)	Torque Constant (oz-in/A)	Rated Speed (RPM)	Rated Torque (oz-in)	Rotor Inertia (oz-in-sec^2)
BLWRPG172S-24V-1400	5.8	1.5	11.9	15	8.45	0.88	60	14.92	1400	5.66	0.00046
BLWRPG172S-24V-2100	11	2.6	5.8	6.28	7.17	0.76	60	9.70	2100	7.08	0.00046
BLWRPG172S-24V-4200	24	1.5	1.6	1.94	4.44	0.76	60	5.45	4200	7.93	0.00046
BLWRPG173S-24V-2000	31	2.1	2.18	2.96	5.40	0.88	85	9.88	2000	21.24	0.00082
BLWRPG173S-24V-4000	63	4.1	0.71	0.86	4.00	1.18	85	5.21	4000	21.24	0.00082

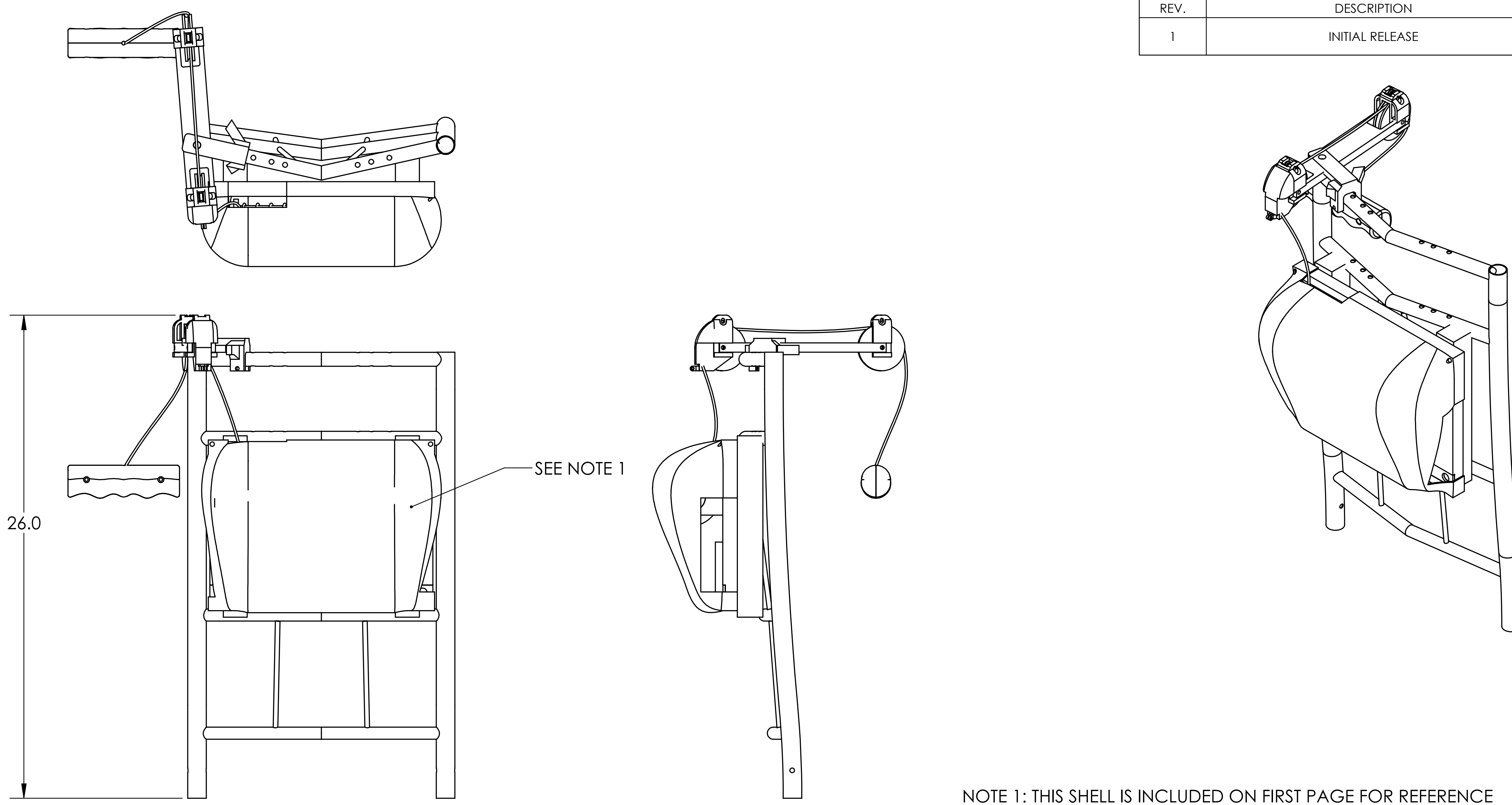
Table 2	Output on Shaft of Gearbox									
Parameters/Gear Box Ratio	3.8	4.9	15	19	24	56	71	91	116	212
Peak Torque (oz-in)	208	208	833	833	833	2083	2083	2083	2083	2083
Number of Gear Trains	1	1	2	2	2	3	3	3	3	4
"L1" (Length of Gear Box In millimeters)	35.0	35.0	45.5	45.5	45.5	55.5	55.5	55.5	55.5	66

** Weight will vary based on gear ratio selected.*
*** Length of gearmotor will vary based on gear ratio selected.*

Notes: Custom leadwires, cables, connectors, and windings are available upon request.

- Rated Speed of the output shaft (after gear-box) = (Rated Motor Speed)/(Gear Ratio)
- Torque of the output shaft (after gear-box) = (Peak Motor Torque) X (Gear Ratio)
- Rotor Inertia of the output (shaft after gear-box) = (Rotor Motor Inertia) X (Gear Ratio)^2

REVISIONS		
REV.	DESCRIPTION	DATE
1	INITIAL RELEASE	2023 APR 18



NOTE 1: THIS SHELL IS INCLUDED ON FIRST PAGE FOR REFERENCE
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MM: 0. = ± 0.50; 0.0 = ± 0.25; 0.00 = ± 0.15; 0.000 = ± 0.05	CHECKED	J. VANDER	2023 APR 19
ANGULAR: 0.0 = ± 1; 0.00 = ± 0.5	UNITS	IPS	
	MATERIAL	SEE PART DRAWINGS	
	FINISH		
DO NOT SCALE DRAWING	COMMENTS		

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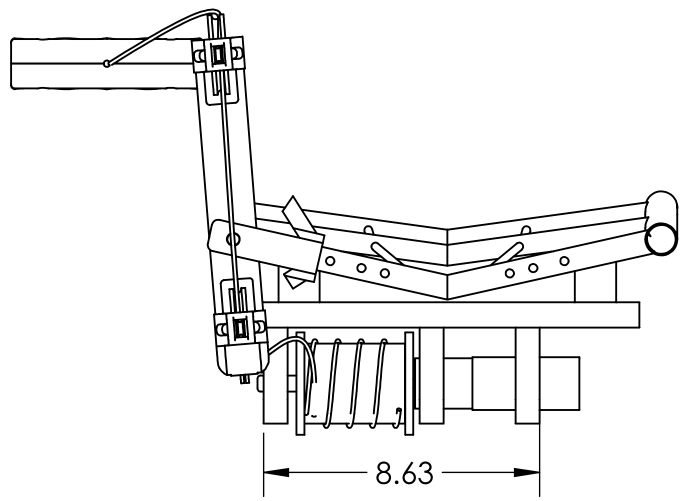
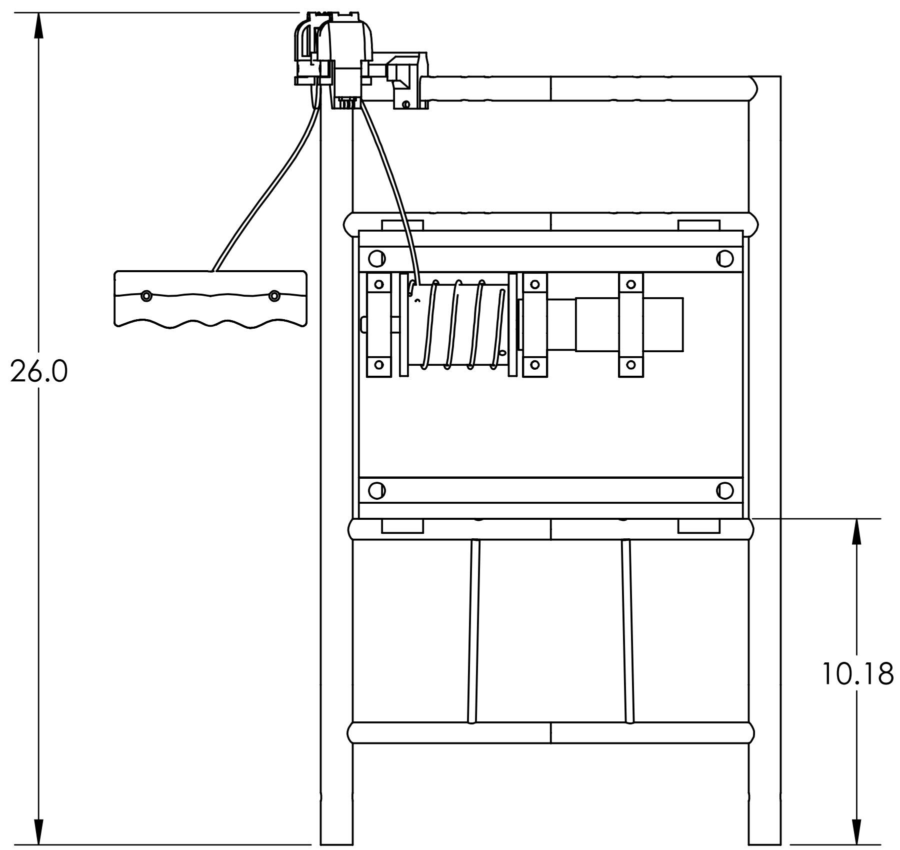
IRA A. FULTON COLLEGE OF ENGINEERING

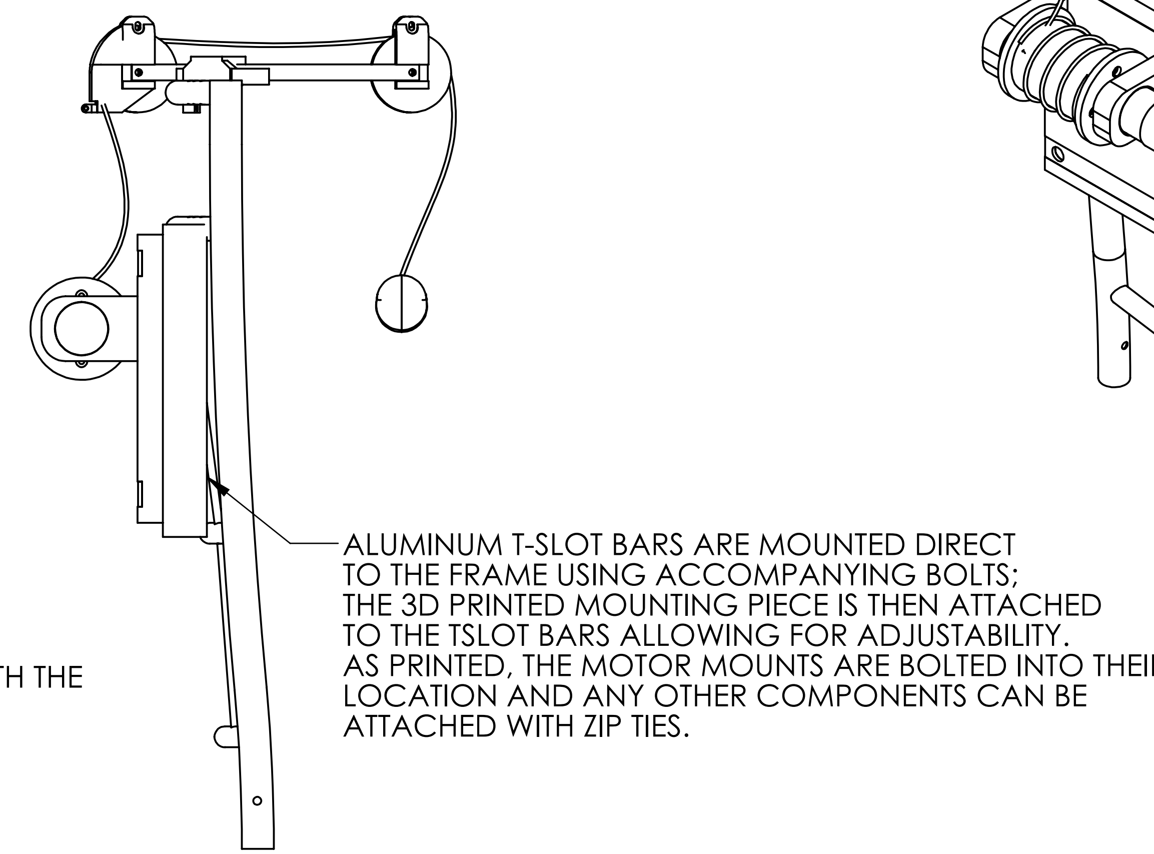
TITLE:
HERCULIFT ASSEMBLY

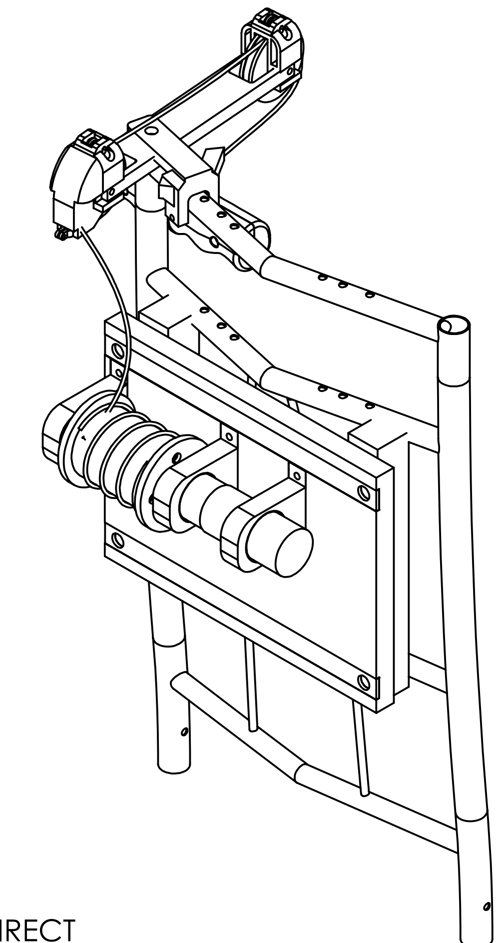
SIZE	DWG. FILE	REV
B	TOTALASSEMBLY	1
SCALE: 1:6	WEIGHT: 9.50	SHEET 1 OF 4

REVISIONS		
REV.	DESCRIPTION	DATE
1	INITIAL RELEASE	2023 APR 18

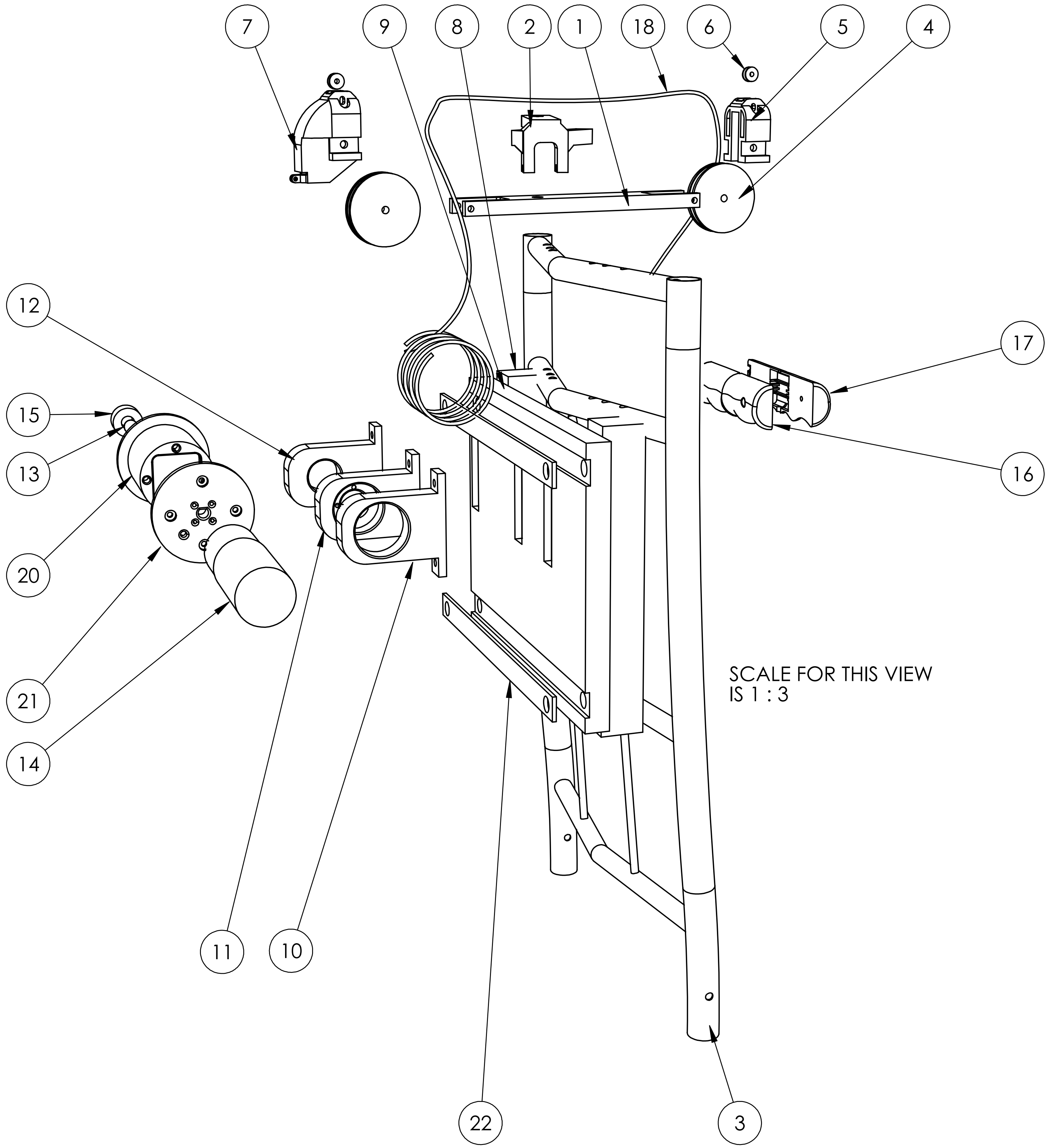








UNLESS OTHERWISE SPECIFIED TOLERANCES ARE		NAME	DATE	BYU ENGINEERING IRA A. FULTON COLLEGE OF ENGINEERING
INCH: 0.0 = ± 0.02; 0.00 = ± 0.01; 0.000 = ± 0.005	DRAWN	B. M. TANNER	2023 APR 18	
MM: 0. = ± 0.50; 0.0 = ± 0.25; 0.00 = ± 0.15; 0.000 = ± 0.05	CHECKED	J. VANDER	2023 APR 19	
ANGULAR: 0.0 = ± 1; 0.00 = ± 0.5	UNITS	IPS		TITLE: HERCULIFT ASSEMBLY
	MATERIAL	SEE PART DRAWINGS		
	FINISH			
DO NOT SCALE DRAWING	COMMENTS			SIZE B; DWG. FILE TOTALASSEMBLY; REV 1
				SCALE: 1:6; WEIGHT: 9.50; SHEET 2 OF 4



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Shoulder_Crane	Machined Aluminum Bar	1
2	Shoulder_Guard	Protects against swinging crane	1
3	Frame	Backpacking Frame	1
4	6284K53	Pulley	2
5	Pulley Gaurd.step	Front Pulley Guard	1
6	Small V Groove Bearing.step	Small Bearing	2
7	Bowden_Pulley_Guard_v8.step	Back Pulley Guard	1
8	Tbar	Aluminum T-slot	2
9	Mount	3D-printed part for mounting the other pieces to	1
10	BackMount	Motor Support	1
11	SpoolMounts	Motor Mount	1
12	BearingMount	Holds bearing for supporting the spool	1
13	SpoolBearingSupport	Aluminum Rod	1
14	Motorstandin	Motor	1
15	bearingstandin	1/2 " Bearing	1
16	Handle	1/2 of the handle	1
17	MirrorHandle	Mirrored half of the handle	1
18	Part4^TotalAssembly	Cable	1
19	Part5^TotalAssembly	Shell	1
20	Main Body.step	Spool main body	1
21	Cap.step	Spool Cap	1
22	AluminumBar	Aluminum Bars	2

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	NAME	DATE
DRAWN	B. M. TANNER	2023 APR 18
CHECKED	J. VANDER	2023 APR 19
UNITS	IPS	
MATERIAL	SEE PART DRAWINGS	
FINISH		
COMMENTS		

BYU ENGINEERING
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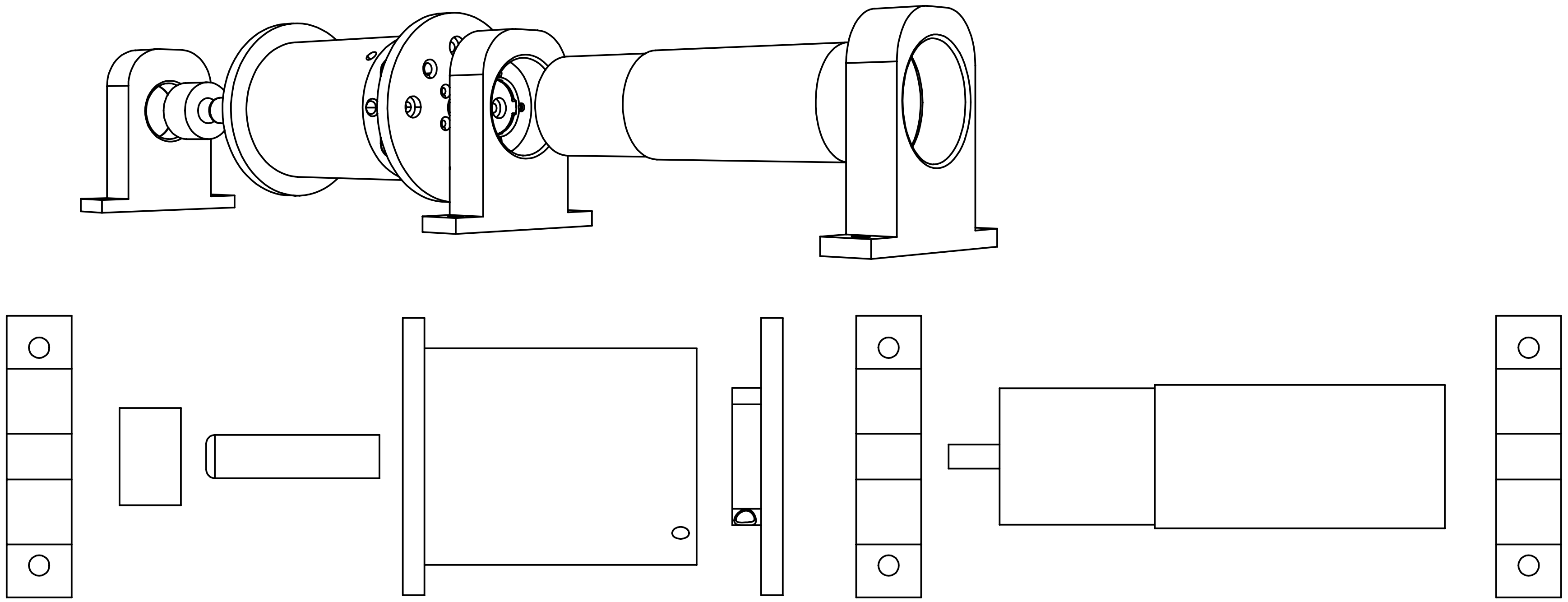
TITLE:
HERCULIFT ASSEMBLY

SIZE B | DWG. FILE TOTALASSEMBLY | REV 1

SCALE: 1:6 | WEIGHT: 9.50 | SHEET 3 OF 4

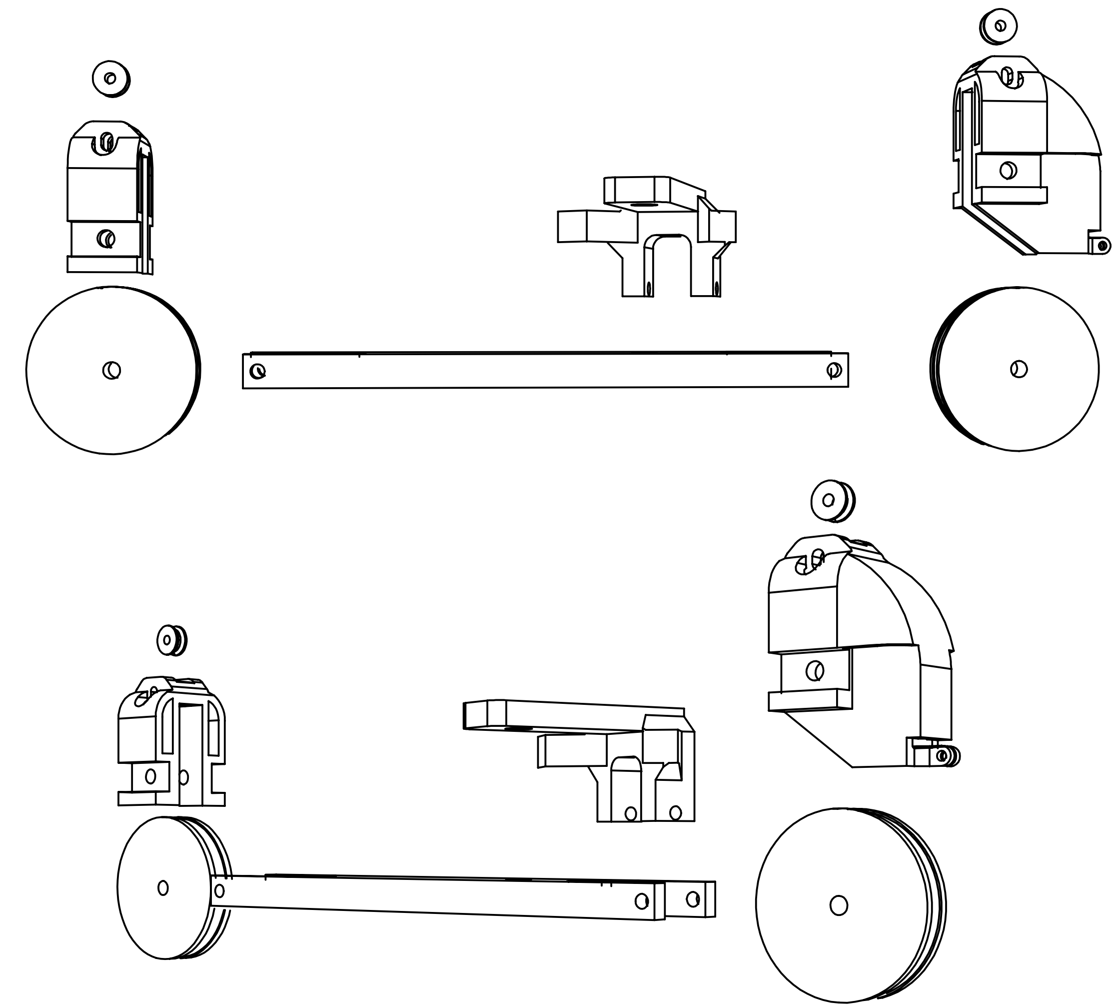
ISOLATED CLOSE UP OF THE MOTOR MOUNT PIECES

SCALE IS 1:2



ISOLATED CLOSE UP OF THE SHOULDER CRANE AND ACCOMPANYING PIECES

SCALE IS 1:2



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INCH:
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DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	B. M. TANNER	2023 APR 18
CHECKED	J. VANDER	2023 APR 19
UNITS	IPS	
MATERIAL	SEE PART DRAWINGS	
FINISH		
COMMENTS		

BYU ENGINEERING
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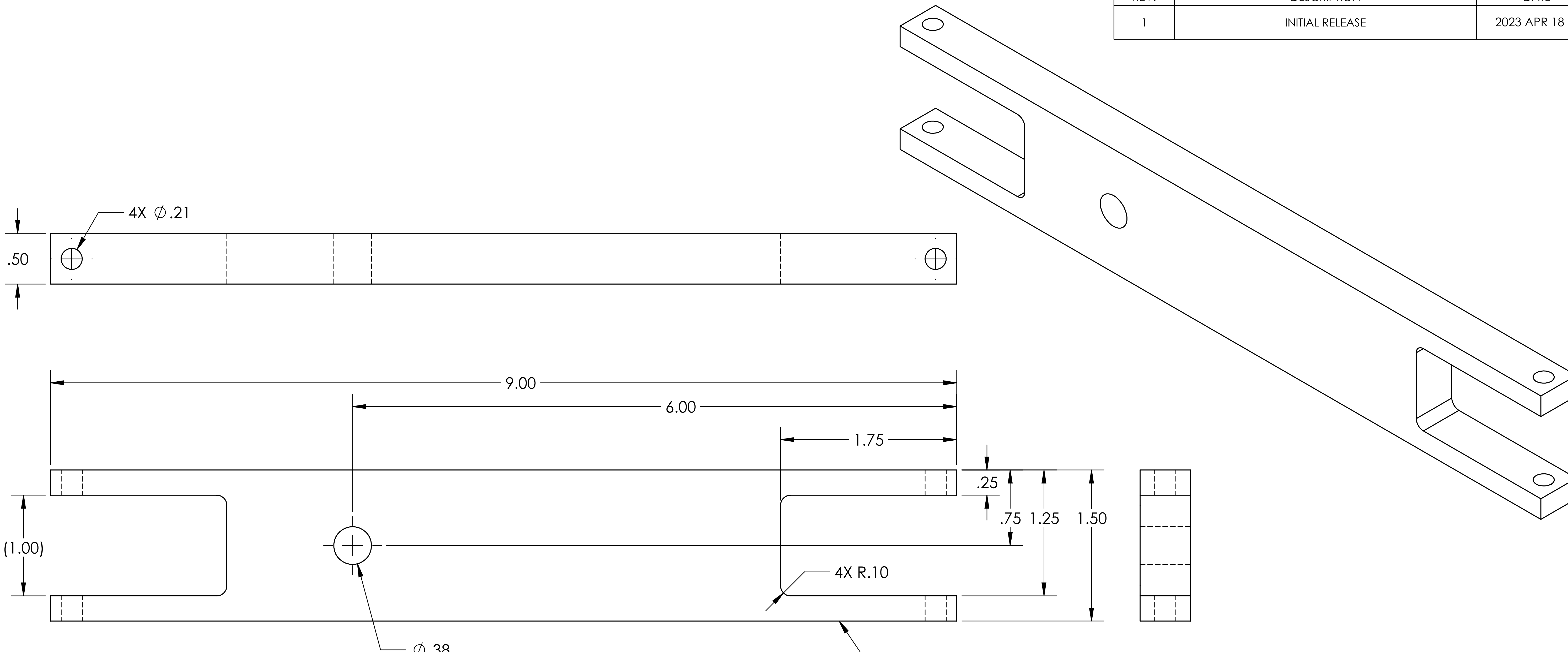
TITLE:
HERCULIFT ASSEMBLY

SIZE B | DWG. FILE TOTALASSEMBLY | REV 1

SCALE: 1:6 | WEIGHT: 9.50 | SHEET 4 OF 4

REVISIONS		
REV.	DESCRIPTION	DATE
1	INITIAL RELEASE	2023 APR 18



NOTE 1: RECOMMENDED TO FILE EDGES TO DESIRED SMOOTHNESS

UNLESS OTHERWISE SPECIFIED TOLERANCES ARE		NAME	DATE
INCH: 0.0 = ± 0.02; 0.00 = ± 0.01; 0.000 = ± 0.005	DRAWN	B. M. TANNER	2023 APR 18
MM: 0. = ± 0.50; 0.0 = ± 0.25; 0.00 = ± 0.15; 0.000 = ± 0.05	CHECKED	J. VANDER	2023 APR 18
ANGULAR: 0.0 = ± 1; 0.00 = ± 0.5	UNITS	IPS	
	MATERIAL	1060 ALLOY	
	FINISH		
DO NOT SCALE DRAWING	COMMENTS		

BYU ENGINEERING
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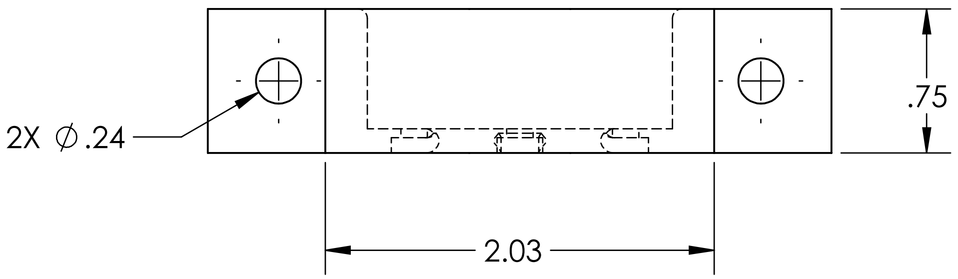
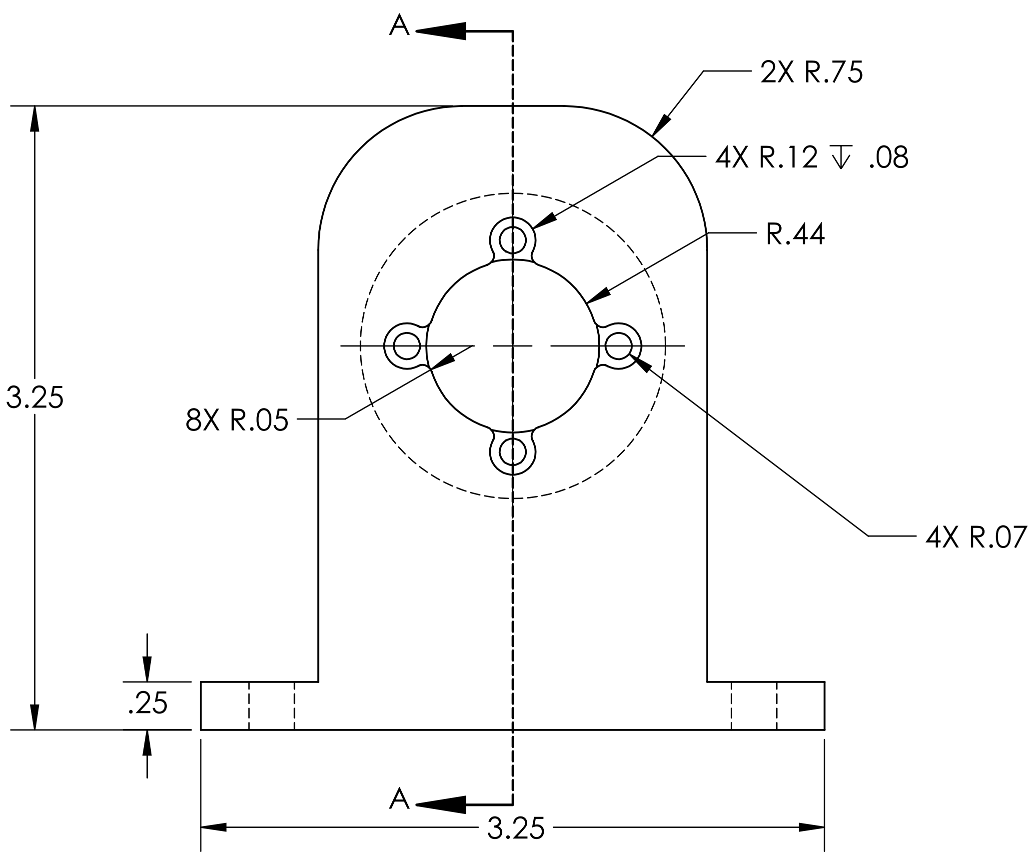
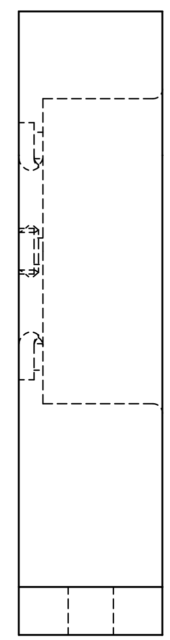
TITLE:
SHOULDER CRANE
(CAD_002)

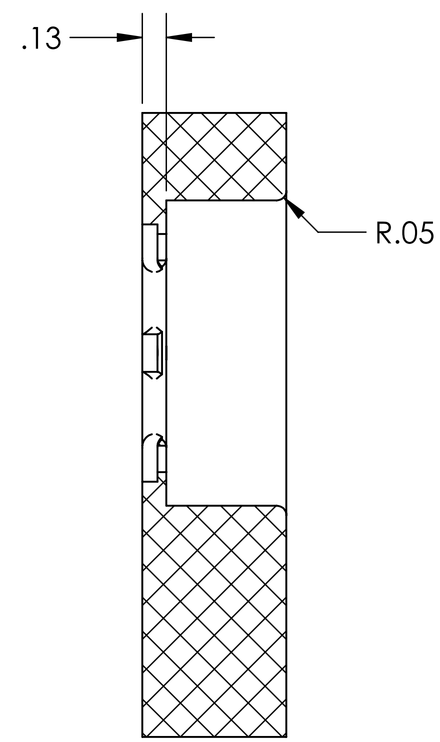
SIZE	DWG. FILE	REV
B	SHOULDER_CRANE	1
SCALE: 1:1	WEIGHT: 0.48	SHEET 1 OF 1

REVISIONS		
REV.	DESCRIPTION	DATE
1	INITIAL RELEASE	2023 APR 18

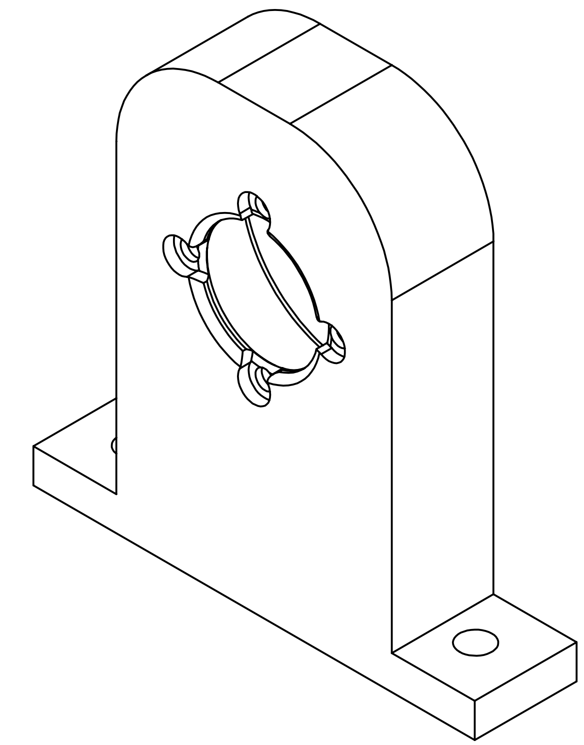


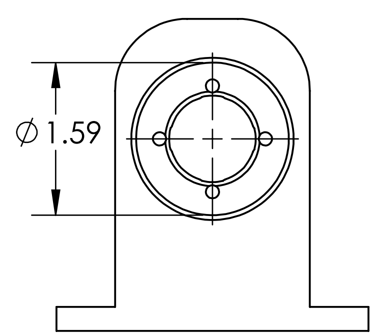






SECTION A-A





BACKSIDE VIEW
SCALE 1: 2

NOTE 1: THIS DRAWING IS ONLY FOR REFERENCE. SINCE THIS PART IS 3D PRINTED ALL SURFACES AND DIMENSIONS ARE DEFINED IN THE FILE SPOOLMOUNTS.SLDPRT

NOTE 2: THIS CONFIGURATION IS THE DEFAULT, THIS FILE CONTAINS 2 MORE CONFIGURATIONS THAT ARE ALSO 3D PRINTED

UNLESS OTHERWISE SPECIFIED TOLERANCES ARE

INCH:
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0.000 = ± 0.005

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0.00 = ± 0.5

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	B. M. TANNER	2023 APR 18
CHECKED	J. VANDER	2023 APR 18
UNITS	IPS	
MATERIAL		
FINISH		
COMMENTS		

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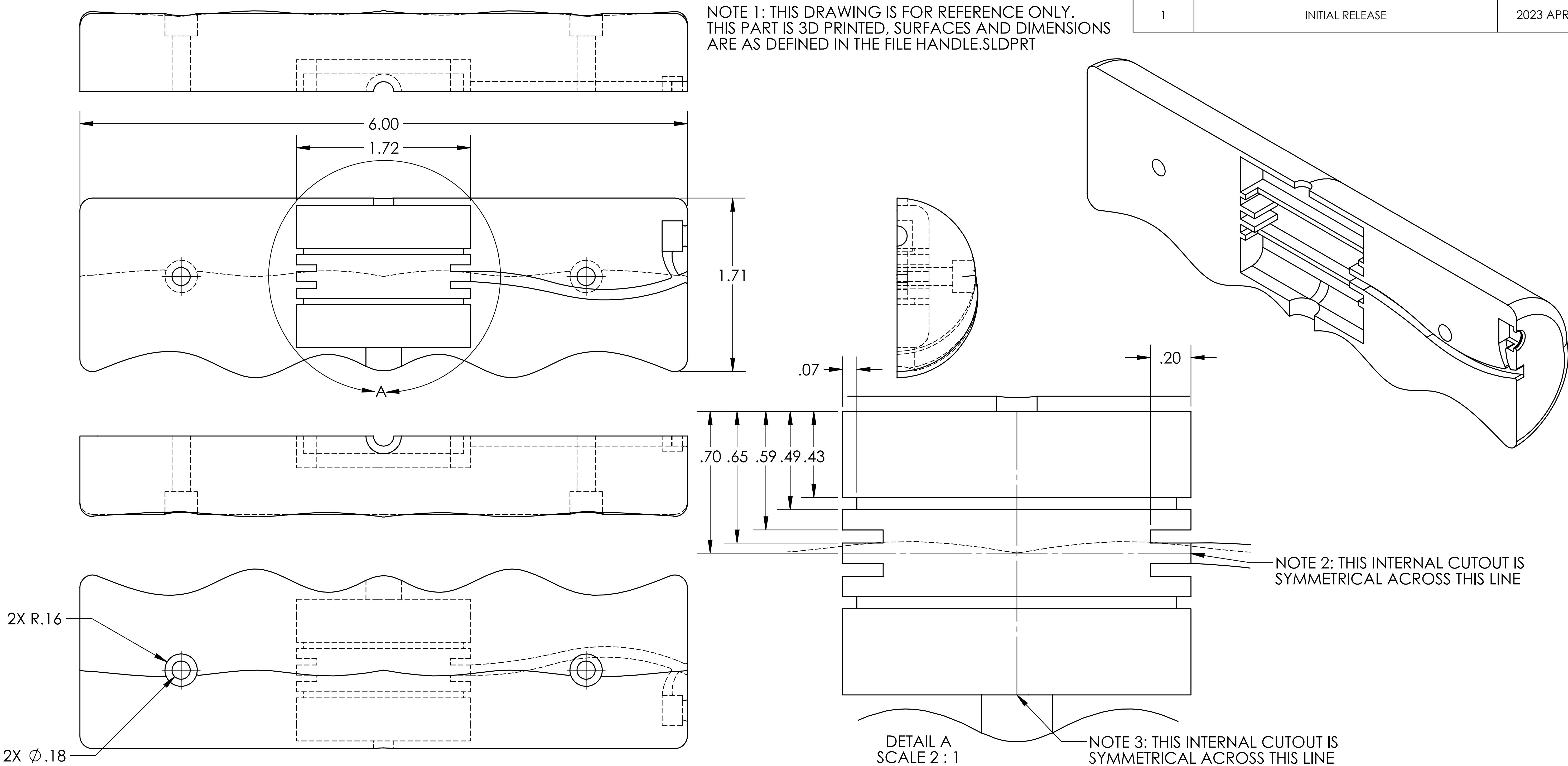
TITLE:
SPOOL MOUNTS
(CAD_003)

SIZE	DWG. FILE	REV
B	SPOOLMOUNTS	1
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

REVISIONS		
REV.	DESCRIPTION	DATE
1	INITIAL RELEASE	2023 APR 18

NOTE 1: THIS DRAWING IS FOR REFERENCE ONLY.
THIS PART IS 3D PRINTED, SURFACES AND DIMENSIONS
ARE AS DEFINED IN THE FILE HANDLE.SLDPRT



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DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	B. M. TANNER	2023 APR 18
CHECKED	J. VANDER	2023 APR 18
UNITS	IPS	
MATERIAL	PLA	
FINISH		
COMMENTS		

BYU ENGINEERING
IRA A. FULTON COLLEGE OF ENGINEERING

TITLE:
HANDLE (CAD_004)

SIZE	DWG. FILE	REV
B	HANDLE	1
SCALE: 1:1	WEIGHT: 0.19	SHEET 1 OF 1

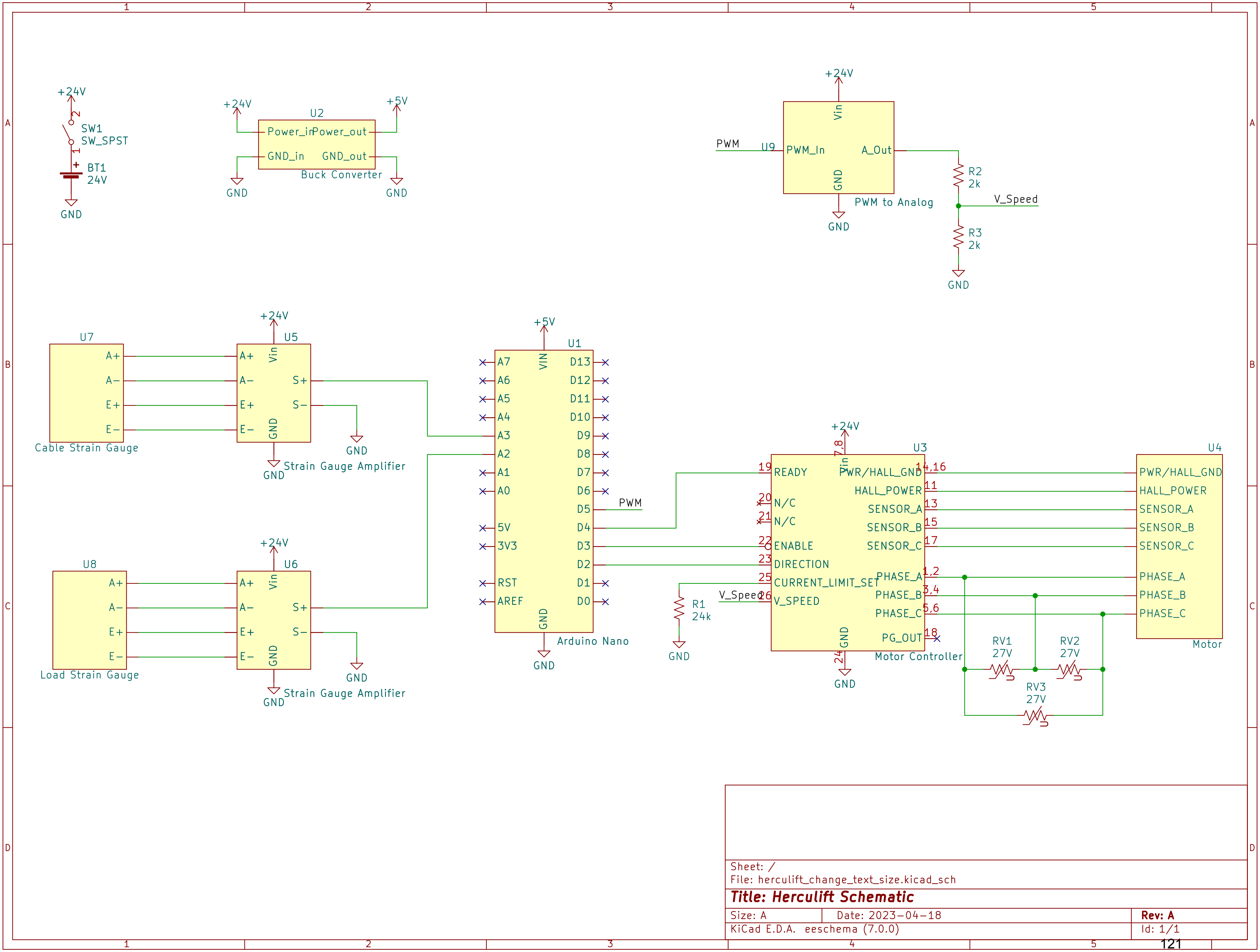
GA_007	**Bill of Materials**	**Date:**	1-Mar-23
Purpose:	To have one concise location for a total bill of materials		
Prepared by:	Joseph Edmund	**Checked by:**	Tyler Dickson

Revision History:	Revised By	Checked By	Date	Notes
	Tyler Dickson	Chris Payne	12/1/2022	Separate Cost and Description columns. Add Quantity and Total Cost columns.
	Brinler Tanner	Tyler Dickson	1/13/2023	Add Off the Shelf and Critical columns.
	Chris Payne	Isaac Sorensen	4/18/2023	Edited for final submission

Bill Of Materials

Sub Category:	Material:	Cost:	Quantity:	Total Cost	Description	Source (w/ Link):	Off the Shelf?	Critical?
Control System & Motor-Gearing	Arduino Nano	$12.00	1	$12.00	Microcontroller with digital I/O pins and analog input pins. Takes sensor inputs, output PWM to control motor.	Amazon	Yes	yes
	DC Brushless motor with planetary gearbox	$263.00	1	$263.00	BLWRPG173D-24V-4000-R15, 24 volt	Anaheim Automation	Yes	yes
	BLDC Motor Driver	$49.00	1	$49.00	MDC020-050101 - Board Mount Brushless Speed Controller, 50V, 10A Peak	Anaheim Automation	Yes	yes
	Strain gauge amplifiers	$30.00	2	$60.00	Amplifies the voltage signal from the strain gauges	Amazon	Yes	Yes
	PWM to anagol signal convertor	$20.00	1	$20.00	Takes our PWM signal and smooths it to the average voltage before going to the Motor	BYU Prototyping lab	Yes	no
	Proto Board	$2.50	2	$5.00		BYU Prototyping lab	Yes	No
	Resistors	$0.01	5	$0.05	Resistor values - 2k (4), 20k	BYU EE lab	Yes	No
	Varistors	$0.50	3	$1.50	27V 100A DISC 5MM	BYU EE lab	Yes	No
	Wires	$2.00	~35ft	$4.00	Wire connections, all stranded wire	BYU Prototyping lab	Yes	Yes
	Buck Convertor	$3.00	1	$3.00	(STPD01PUR)	Digikey	Yes	no
Power	Kobalt Battery	$48.99	1	$48.99	24 V 5.0 Ah	Amazon	Yes	yes
	Battery adapter	$16.39	1	$16.39	DIY battery to wire adapter	Amazon	Yes	no (determined by battery)
	KobaltBattery Charger	$49.99	1	$49.99	24-Volt Max Power Tool Battery Charger	Amazon	yes	no (determined by battery)
Frame	Hiking backpack frame	$5.00	1	$5.00	Standard metal frame with hip and arm straps	Deseret Industries	yes	no
	3D Printed Housing	$50.00	1	$50.00	$0.05 per gram.	BYU Prototyping lab	no	no
	Aluminum Stock	$5.00	1	$5.00	Aluminum bar stock for shoulder crane	BYU Prototyping lab	no	no
	Aluminum Bar	$16.19	1	$16.19	(2’’x24’’x1/8’’) is $16.19	McMaster Carr	yes with cutting to size	no
	1/16” Coated Cable	$0.19	2.5	$0.48	~6.5 feet needed $0.19 per foot	Amazon	yes with cutting to size	no

	Misc. Hardware	$0.50	28	$14.00	M5 bolts and nuts	BYU Prototyping lab	yes	no
	3D printed Shoulder Components	$25.00	1	$25.00	Shoulder guard and Pulley Cable guard	BYU Prototyping lab	no	yes
	Ball Bearing Collar	$16.15	1	$16.15	Supports the shouler cantilever and allows for rotation about the sagitall/transverse axis	McMaster Carr	Yes	Yes
	UHMW pulleys	$11.62	2	$23.24	Shoulder pulleys	McMaster Carr	yes	yes
Handle	Kill switch button and wiring	$5.00	1	$5.00	Simple button	BYU EE lab	yes with cutting to size	yes
	Force Sensors	$13.00	2	$26.00	Load Cell from fish scale sensor	Amazon	yes	yes
	3D printed handle	$15.00	1	$15.00		BYU Prototyping lab	no	yes
Total System				**$733.98**				


+24V
SW1
SW_SPST
BT1
24V
GND
+24V
U2
+5V
Power_in
Power_out
GND_in
GND_out
Buck Converter
GND
GND
+24V
Vin
PWM
U9
PWM_In
A_Out
GND
PWM to Analog
GND
R2
2k
V_Speed
R3
2k
GND
U7
A+
A−
E+
E−
Cable Strain Gauge
+24V
U5
A+
A−
E+
E−
Vin
S+
S−
GND
GND
Strain Gauge Amplifier
GND
+5V
U1
A7
A6
A5
A4
A3
A2
A1
A0
5V
3V3
RST
AREF
VIN
D13
D12
D11
D10
D9
D8
D7
D6
D5
D4
D3
D2
D1
D0
GND
PWM
Arduino Nano
GND
U8
A+
A−
E+
E−
Load Strain Gauge
+24V
U6
A+
A−
E+
E−
Vin
S+
S−
GND
GND
Strain Gauge Amplifier
GND
+24V
U3
7,8
Vin
19 READY
20 N/C
21 N/C
22 ENABLE
23 DIRECTION
25 CURRENT_LIMIT_SET
V_Speed
26 V_SPEED
GND
24
PWR/HALL_GND 14,16
HALL_POWER 11
SENSOR_A 13
SENSOR_B 15
SENSOR_C 17
PHASE_A 1,2
PHASE_B 3,4
PHASE_C 5,6
PG_OUT 18
Motor Controller
GND
R1
24k
GND
U4
PWR/HALL_GND
HALL_POWER
SENSOR_A
SENSOR_B
SENSOR_C
PHASE_A
PHASE_B
PHASE_C
Motor
RV1
27V
RV2
27V
RV3
27V
Sheet: /
File: herculift_change_text_size.kicad_sch
Title: Herculift Schematic
Size: A
Date: 2023-04-18
Rev: A
KiCad E.D.A. eeschema (7.0.0)
Id: 1/1

Artifact ID: 024	Artifact Title: Load Offloading
Revision: **A**	Revision Date: 18 April 2023
Prepared By: Isaac Sorensen	**Checked By:** Joseph Edmund
Purpose: *This test is to show how helpful our device is in offloading the weight felt by the user's arm.*	

Revision History			
Revision	Revised by	Checked by	Date
--	Isaac Sorensen	Joseph Edmund	17 April 2023
A	Tyler Dickson	Brinler Tanner	18 April 2023

Test Objective and Metric

The purpose of this test is to quantify how much our device is offloading from the arm to the trunk. This will be evaluated by measuring the force sensor at the hand and at the cable. By comparing these two force values, we can see how much the frame and motor are supporting the weight versus how much the user is feeling the weight.

The following metric ranges will be used.

Metric	Upper Limit	Ideal	Lower Limit
Percent of load at hand offloaded by actuated cable tension (%)	75	50	20

Test Materials

- The dynamic lift-assist device.
- Laptop with Arduino IDE and Excel, or some other spreadsheet software
- Long USB-mini cable for connection to the Arduino Nano.
- 15 lb. Weight with attachment for device hook (wire or hook).
- 2 ft shelf, 4 ft shelf, 5 ft shelf or elevated platform.
- Ensure there is enough space for the test subject to walk 6ft.

Test Procedure

Instruct the test subject to:

1. Don frame and device with the power off.
2. Ensure that the microcontroller is running the controller logic with Kp_UP and Kp_DOWN set to 0.5 and the I and D values set to 0. (See code attached in Appendix A)
3. Connect the USB cable to the Arduino on the frame and ensure that the force sensors are outputting to the serial plotter and monitor.
4. Turn the device on and begin recording with the Arduino IDE serial monitor.
5. Repeat the following steps for each of the following phases: Lifting, Carry w/ Weight, and Lowering:
    a. Press the reset button on the Arduino Nano to clear the serial monitor output.

b. Complete the phase movement at a normal pace. Do one of the following in this sub-step:
    i. Lift the 15 lbs from the ground to chest height.
    ii. Hold the 15 lbs at chest height for ~4 seconds. Test subject may walk a few paces to simulate the force sensors while walking.
    iii. Lower the 15 lbs from the chest to the ground at a natural speed.

c. Once each phase movement is completed, stop the serial monitor and copy the force values outputted to a labeled excel sheet.

6. Process the data. This includes the following:
    a. Use the text to columns feature in the 'Data' tab to separate the values of the force sensors.
    b. Convert the analog values (between 0 and 1023) to pound force. 15 lbs reads about 600 on the force sensor and 0 lbs reads about 0 on the analog output. Assuming a linear relationship, multiple the sensor output by 15lbs/600.
    c. Plot load force vs. time and cable force vs. time on the same plot.
    d. In the excel spreadsheet, subtract the cable force from the load force and divide it by the load force to produce a % offloading metric. *[1 -* (*load lbf – cable lbf*)/*(load lbf)]*
7. Analyze the data and draw conclusions.

Artifact ID: 025	Artifact Title: User Comfort Test Procedure	
Revision: **C**	Revision Date: 18 April 2023	
Prepared by: Isaac Sorensen		**Checked by:** Joshua Vanderpool
Purpose: *This is a test to evaluate device comfort for users. The focus is on the physical aspects of the device.*		

Revision History			
Revision	Revised by	Checked by	Date
--	Isaac Sorensen	Joshua Vanderpool	**--**
A	Joshua Vanderpool	Tyler Dickson	8 December 2022
B	Joseph Edmund	Isaac Sorensen	10 April 2023
C	Tyler Dickson		18 April 2023

Test Objective and Metric

To determine if the total device is reasonably comfortable for a test subject to wear. To provide some confidence that the device would actually be used and preferred by the DOE workers.

The measures of this test are all subjective. While there are multiple measures for this one test, all would logically be taken at the same time as the test subject is walked through several aspects of the device.

To more objectively rate the comfortability of our device use over time, we adapt the use of the scale and terms from Cardello, Winterhalter & Schultz, 2003: we reduced the total number of categories to 5 to simplify our future surveys and test of device comfort. We also provide a more thorough description of each.

Term	Description	Quantitative Score
Very Comfortable	Device feels soft, secure, cooling. Does not cause rubbing, irritation, or heating of the skin.	5
Moderately Comfortable	A mixture of the above characteristics, but still positively weighted.	4
Neither Comfortable nor Uncomfortable	Does not cause pain or discomfort but is not particularly enjoyable for the wearer to use.	3
Moderately Uncomfortable	A mixture of characteristics, but with a larger majority of negative aspects.	2
Very Uncomfortable	Causes direct pain or discomfort.	1

Pass/Fail Criteria

This test includes several performance measures that are subjectively scored by a test subject. Thus, each measure may pass or fail. Below is a table for the minimum and ideal scores for each measure. There is no maximum to the quality of experience of a test subject.

Performance Measure	Minimum Value	Ideal Value	Maximum Value
Discomfort after 15 mins	Very Comfortable (5)	Neither comfortable nor uncomfortable (3)	Very uncomfortable (1)
Time to don device (sec)	N/A	30	120
Time to doff device (sec)	N/A	30	120
Time required to learn the device. (mins)	N/A	10	20
Perceived exertion with device on (qualitative percentage)	0%	50%	80%
Response Time	Delay is an impediment to task (1)	Functional despite delay D & actuation discontinuities (3)	Input delay can be easily adjusted to (5)

Test Materials

Consumables: None

Durables:

- The dynamic lift-assist device
- 15 lb. Weight with attachment for device hook (wire or hook)
- 2 ft shelf, 4 ft shelf, 5 ft shelf or elevated platform

Test Equipment:

- Video camera for recording footage. It is preferrable to not use a smart phone so that test subject data is kept private and confidential.
- Ensure there is enough space for the test subject to walk 6ft.

Test Procedure

1. Present the device to the testing subject. Demonstrate the following to the testing subject:
    a. Don the device. And fit it to the tester's size as an example.
    b. Keep the device off.
    c. Lift an object from the ground to a shelf 4 ft above the ground. The object should be placed on the ground at least 6 ft from said shelf so there is a period of walking and carrying the object.
    d. After letting go of the object, grab it again and lower it to the floor.

   e. Turn the device on.
   f. Run the activation/calibration procedures on the device.
   g. Repeat steps c and d with the device on.
   h. Show the test subject the kill switch function.
   i. Turn the device off.
   j. Doff the device.
2. If the test subject is comfortable repeating the same motions with the device, you may proceed. Have the test subject consent to video recording, a post-test survey, and collecting some information about their body.
3. Adjust the device to the size of the test subject.
4. Allow the test subject to don the device on their own. Time and record the process from when they first touch the device for when it is ready to use.
5. Instruct the test subject to pick the object from 1c off the ground onto the same shelf mentioned in 1c. However, have them use all shelves, as described below. Record with video how the test subject choses to move in the device.
   a. Start with the 2 ft shelf, set the object, let go, then grab again and bring back to ground.
   b. Pick up the object off the ground, set the object on the 4ft shelf, let go, grab again, bring to ground.
   c. Pick up the object off the ground, set the object on the 5ft shelf, let go, grab again, bring to ground.
6. Repeat step 5 five times per test subject.
7. Turn the device on and walk the test subject through the activation/calibration procedure.
8. Repeat steps 5 and 6 with the device on.
9. For a select group of test subjects, have them take turns going through these test procedures.
10. Thank the test subject and ask them to doff the device.
11. Ask the test subject complete the post-test survey.

Feedback survey after testing: Ask the test subject the following questions.

1. What is your height?
2. What is your weight?
3. How would you rate your comfort during the testing?
   a. Very uncomfortable, moderately uncomfortable, neither comfortable nor uncomfortable, moderately comfortable, very comfortable?
   b. After 10 minutes, 1 hour, 4 hours?
4. How long did you wear the device?
5. How long did it take you to feel intuitive on the device?
6. On a scale of 1-10, how intuitive is the device?
   a. When off?
   b. When on?
7. How intuitive is the device when on?
8. What was your perceived exertion?
   a. While the device was off? (Was it similar to no device?)
   b. While the device was on?

9. What was the most difficult part of the test? Picking up off ground, carry, lift up, lift down, set down?
    a. While off?
    b. While on?
10.

Non-performance questions for device improvement.

11. What was your favorite part about the device?
12. What was your least favorite part about the device?
13. What specific areas are most uncomfortable or painful?
14. How would you improve the device?

Artifact ID: 026	Artifact Title: System Weight Test Procedure	
Revision: A	Revision Date: 10 April 2023	
Prepared by: Brinler Tanner		**Checked by:** Joshua Vanderpool
Purpose: *To test if our entire system meets the weight requirements*		

Revision History			
Revision	Revised by	Checked by	Date
--	Brinler Tanner	Joshua Vanderpool	--
A	Isaac Sorensen	Joseph Edmund	10 April 2023

Test Objective and Metric

The purpose of this test is to identify the total weight of our prototype for comparison against target and acceptable values.

The following metric ranges will be used.

Metric	Upper Limit	Ideal	Lower Limit
Total Device Weight (lbs)	20	10	NA

Test Materials

1 HEETA MAX 110lb/50kg luggage scale

Device Prototype

Test Procedure

1. Gather entire system prototype.
2. Secure handle to ensure it does not swing during measurement.
3. Hang the entire system on the luggage scale and wait approximately 5-10 seconds for the scale to settle.
4. Record the weight and repeat the previous step 3 times to ensure accurate reading.
5. Take the average of the 3 weight measurements and record as the final weight.

Artifact ID: 027	Artifact Title: Predicted Battery Life Test Procedure	
Revision: **A**	Revision Date: 11 April 2023	
Prepared by: J. Edmund and T. Dickson		**Checked by:** Joshua Vanderpool
Purpose: *To define how we will measure and test the predicted battery life of our system.*		

Revision History			
Revision	Revised by	Checked by	Date
--	Joseph Edmund	Isaac Sorensen	2 March 2023
A	Isaac Sorensen	Joseph Edmund	11 April 2023

Test Objective and Metric

Our objective is to determine how much current is drawn by our system during a representative period of use and then estimate how long our battery power will last.

We will measure the current versus time of our system and then compute an estimated battery life, in hours.

Measure	Upper limit	Ideal	Lower Limit
Battery life under normal work conditions (hrs)	N/A	8	4

Test Materials

For this test, you will need to access the following materials:

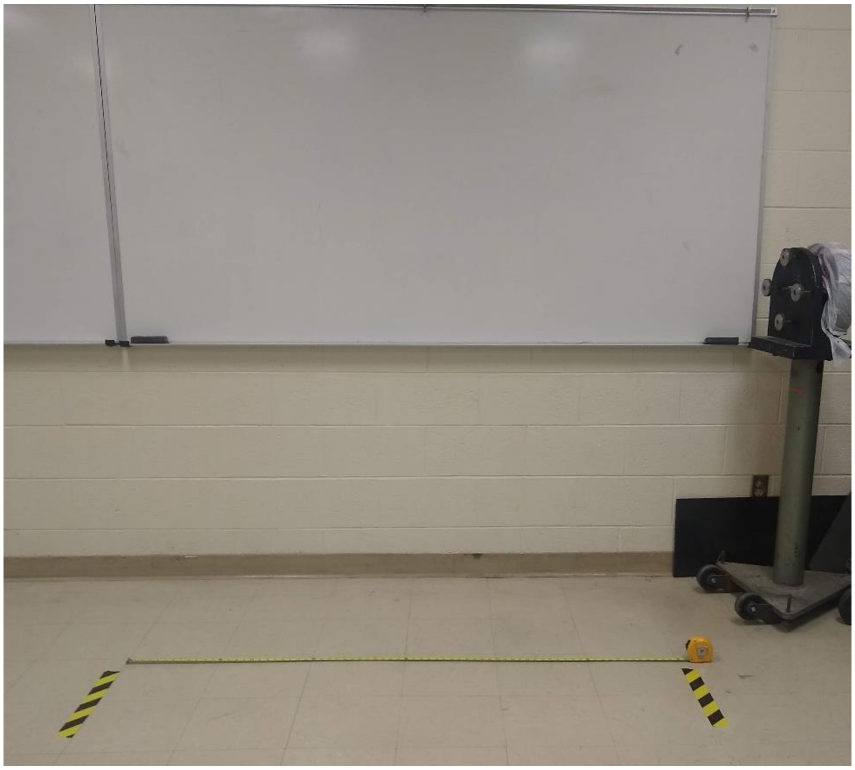
- 1 human test subject
- The Entire lifting system with a fully charged 24v 5.0ah Kobalt battery
- 1 Fluke 77 Series II multimeter with 10A DC current measuring capacity
- 2 lever blocks
- One long, 16-gauge wire
- 1 tape measure
- Colorful tape
- 1 15 lbs weight with attachment for hook.
- 1 Video recording device, such as a phone.

Test Procedure

The following procedure is broken up into 2 sections: (1) Normal lifting cycle estimation, and (2) Current Estimation for each part of the lifting cycle.

Normal Lifting Cycle Estimation

1. Measure out a 6 ft space on a hard floor.
2. Tape each end to mark the start and finish of the 6 ft length.



3. Instruct the test subject to don the device. Ensure the code in Appendix A is uploaded to the Arduino Nano. (*Kp_UP and Kp_DOWN gains both set to 0.5 and the I and D values set to 0)*
4. Place the 15lbs weight on one end of the marked path.
5. Instruct the test subject to stand by the tape next to the weight, facing the other tape marking.

6. Begin videoing the test subject.

   a. *Note: Video the subject at a wide enough distance that you can clearly see them pick up the weight, carry the weight for the 6 ft path, lower the weight, and then walk to return to the initial position.*
7. Instruct the test subject to:
   a. *Note: All of the following steps should be down in order, with the left hand, and while using the handle of the device to lift the weight.*
   b. Lift the 15 lbs weight at the starting point.
   c. Carry it in a stable natural position to the other end of the 6 ft walking length.
   d. Once they have reached the other tape mark, lower the weight to the ground.
   e. Walk back naturally to the original starting place without the weight.
8. Once the user has reached the original tape mark, stop the video.
9. Watch the video (perhaps at a slower speed) and note the starting and ending times of each of the following phases of the lifting cycle:
   a. Lifting the weight.
   b. Carrying the weight in a stable position for 6 feet.
   c. Lower the weight to the ground.
   d. Walk and return back to the original starting location with no weight on the handle.
10. Using those starting and ending times, fill out the following table and compute the approximate duration for each phase of the cycle.

Phase	*Start Time (s)*	*End Time (s)*	*Total Duration (s)*
Lift			
Carry			
Lower			
No weight			

You have now completed the lifting cycle estimation phase of this procedure.

Current Estimation

1. Instruct the test subject (preferably the same as the one used for the first portion of this procedure) to don the entire system device.
2. Ensure that the code attached in Appendix A is uploaded to the Arduino Nano.
3. Using the lever blocks and extra wire, connect the multimeter in series with the main battery such that you are measuring the entire current draw of the system. This is shown in the figure below.
4. Ensure the red multimeter lead is plugged into the 10A fuse and the black lead is plugged into the COM.
5. Turn the multimeter on to the DC current measurement setting.

We will now measure the estimated current draw for each of the phases, but without the test subject walking across the floor. (i.e. the test subject will simply stand statically in place with and without the weight for the carrying and no weight phases)

6. Carefully watch the current reading on the multimeter and instruct the test subject to pick up the 15 lbs weight at a normal pace.

7. Record the maximum current observed on the multimeter in a table like one formatted below.
8. Repeat measurements when the test subject simply carries the 15 lbs. weight stably, when they lower the weight, and when no weight is present.

Phase	*Max Current Draw (A)*
Lift	
Carry	
Lower	
No Weight	

9. Now take a weighted average of the current using the times from the table in Step 10. Plug into the following formula:

$$i_{average} = \frac{\left(t_{lift} \cdot i_{lift} + t_{carry} \cdot i_{carry} + t_{lower} \cdot i_{lower} + t_{no-weight} \cdot i_{no-weight}\right)}{t_{total}}$$

10. Take your battery's amp-hour rating and divide it by the average current draw. **This is your predicted battery life.** Alternatively, you can plug those values into the battery life calculator from Digi key. [Battery Life Calculator | DigiKey Electronics]

Conclusion

The value obtained from step 10 should be reported as the predicted battery life.

Artifact ID: 028	Artifact Title: Percent Offloading Results
Revision: --	Revision Date: 17 April 2023
Prepared by: Isaac Sorensen	**Checked by:** Joseph Edmund
Purpose: *To measure the effectiveness of our overall device in offloading the load felt by the user's arm.*	

Revision History			
Revision	Revised by	Checked by	Date
--	Isaac Sorensen	Joseph Edmund	17 April 2023

Test Procedure Used

[024_TPRO_Load_Offloading]

Test Metric and Objective

Our goal is to ensure that our device is offloading a significant portion of the load felt by the user's arm (ideally 50%). We measure this offloading to the trunk by comparing the force sensors' measurement of the load and of the cable tension. Ideally, the cable tension should be ½ of the load felt at the hand.

Test Data/Results

Lifting

First, we tracked these force sensor readings when the 15 lbs. weight was placed on the handle all at once.

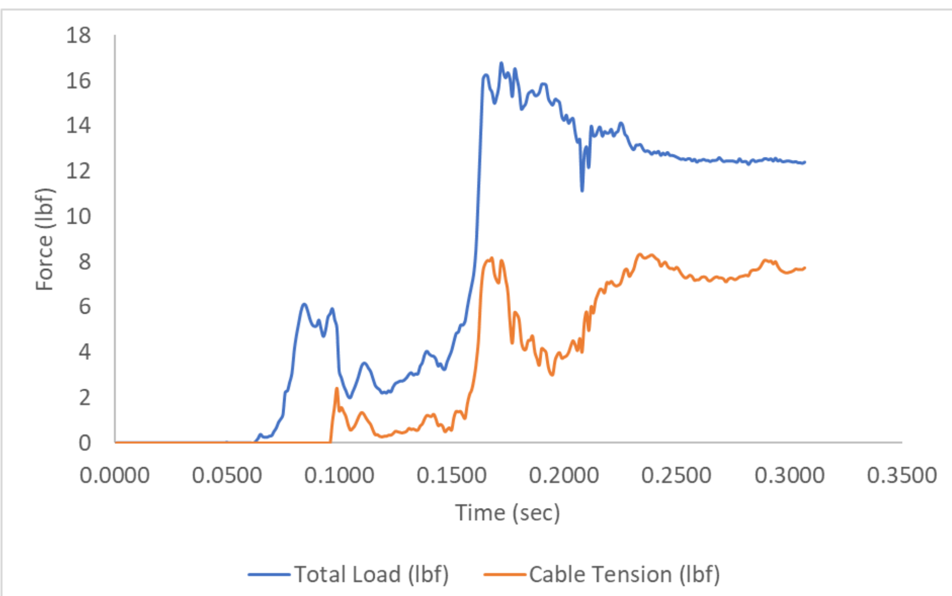
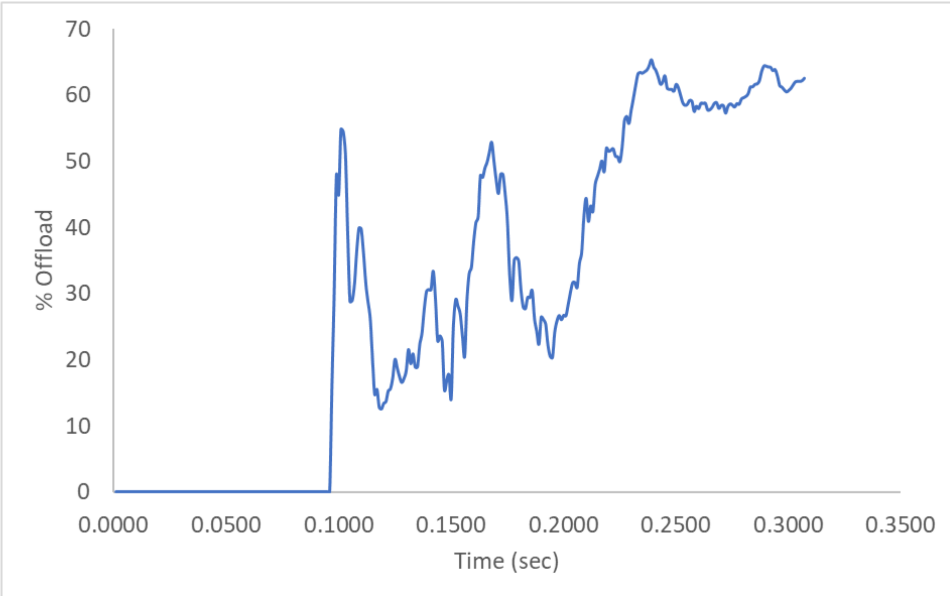
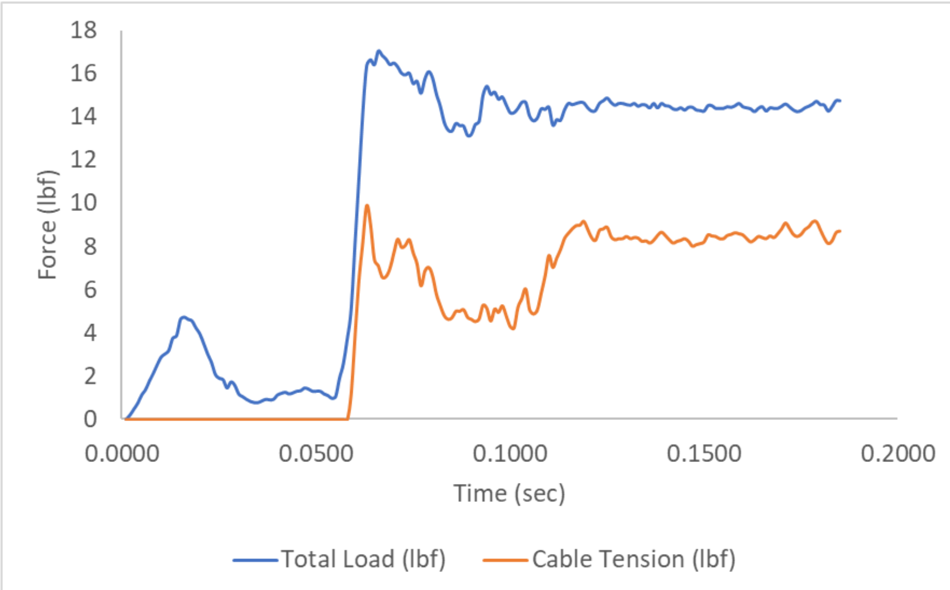
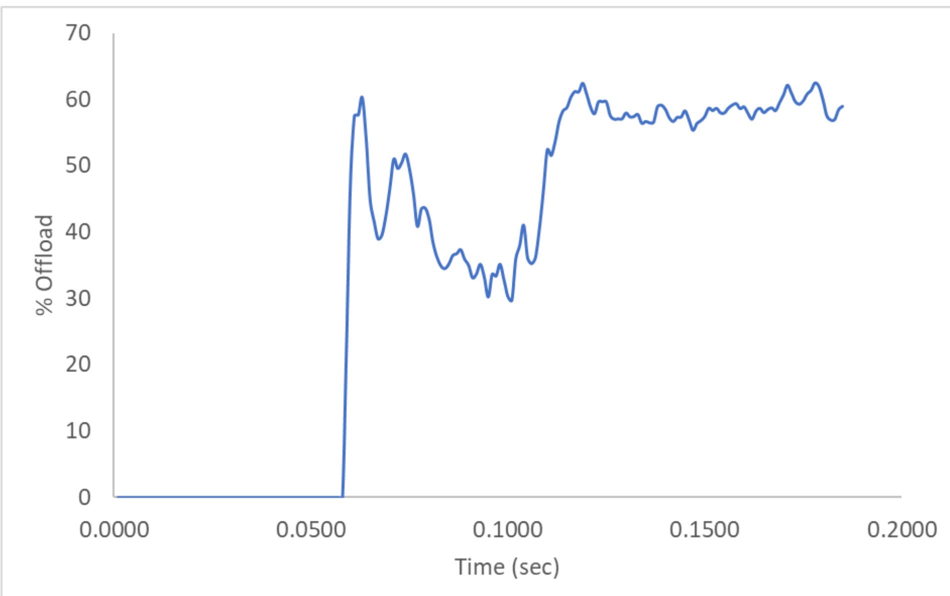


Figure 1



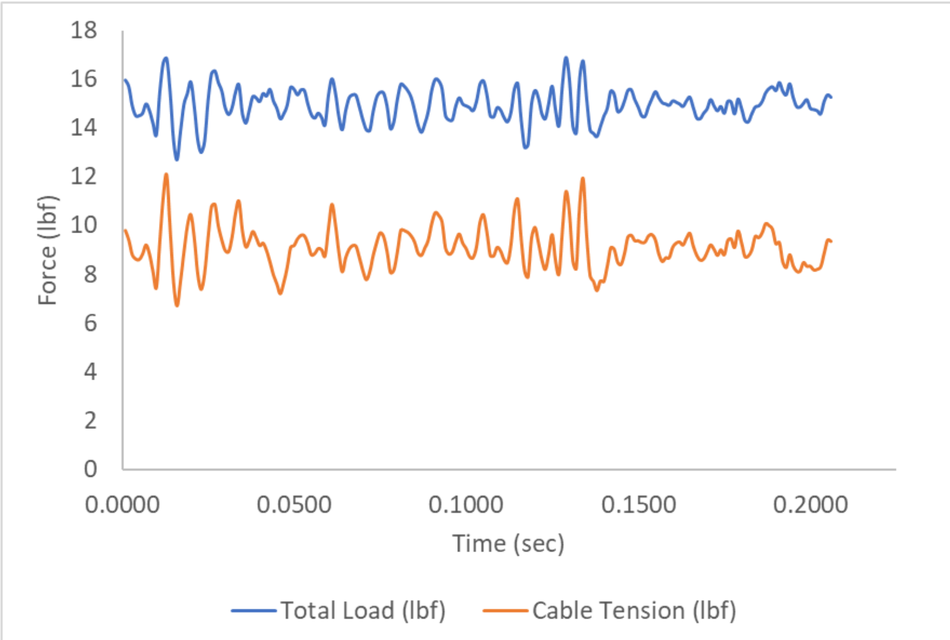
Then, we measured the forces when the load was picked up from the ground. Note that the beginning shows some lag because the cable was slackened when the test subject bend down to pick up the weight.

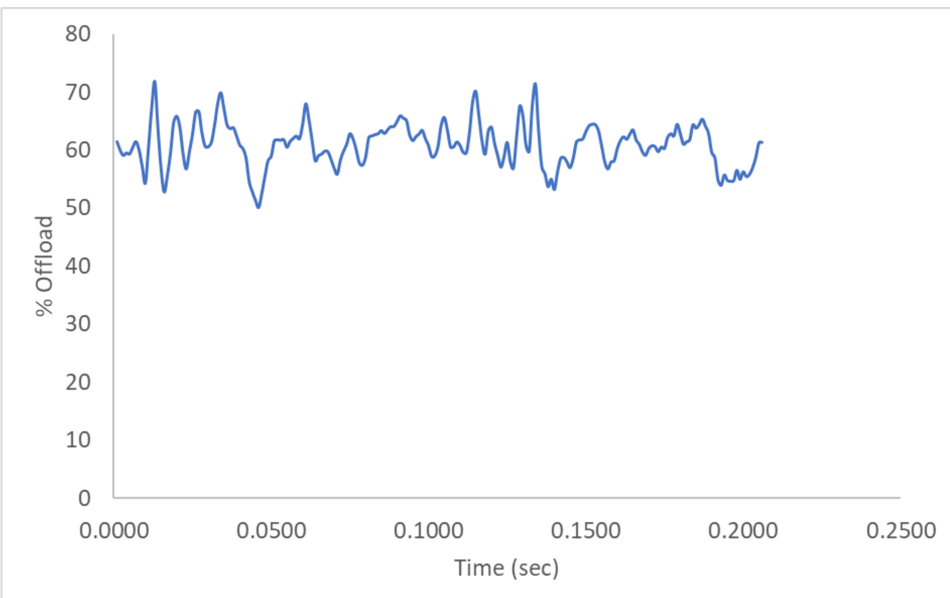




Carrying with Weight

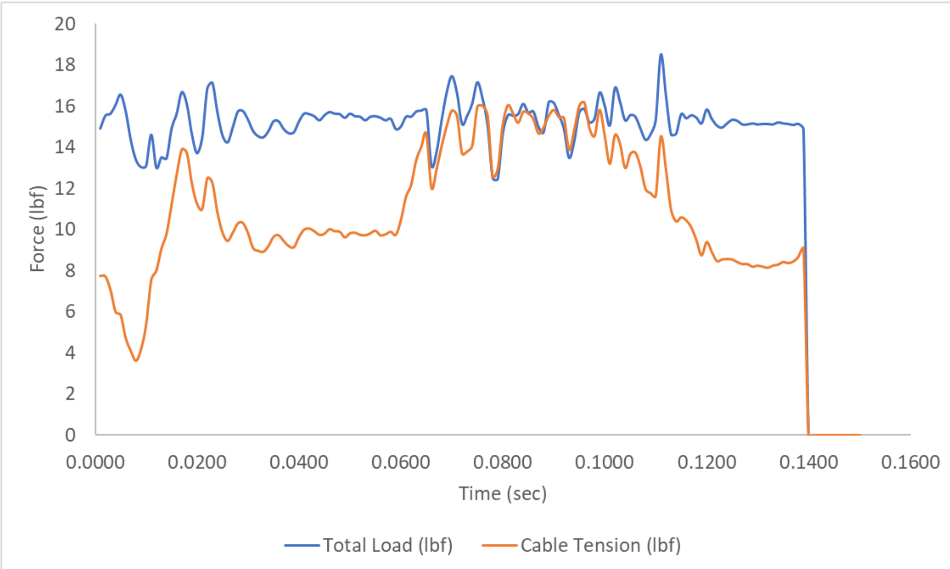
Next, we measured the force sensor when the test subject carried the weight at chest-height. We asked the test subject to walk around to simulate some of the bumps in normal walking.

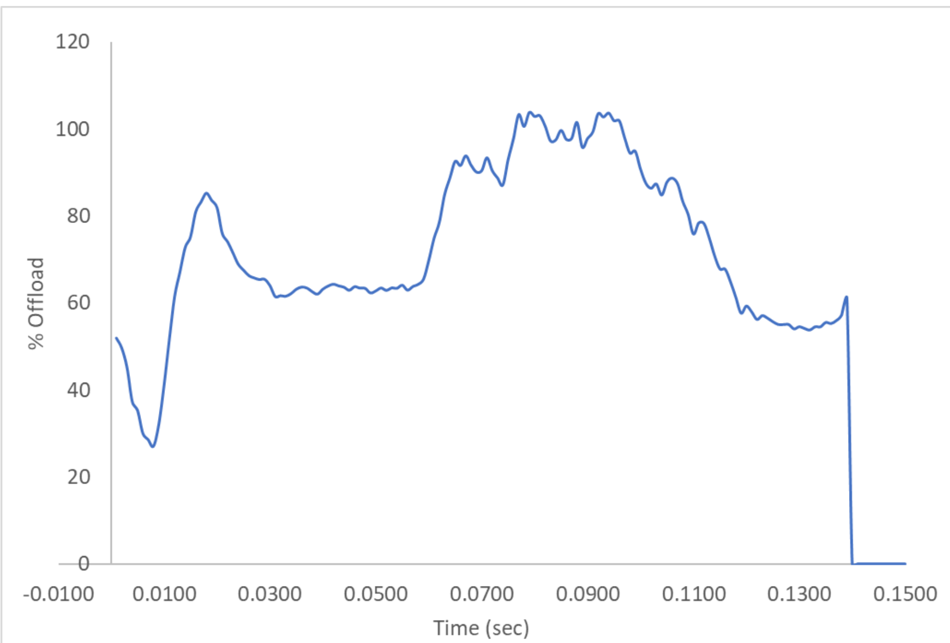




Lowering

Lastly, the test subject lowered the weight. The force sensor output is shown in Figure 4.





Analysis

Overall, although our offload to the trunk is not a constant 50%, in the majority of the stable positions, we are exceeding 50% offload. Yet, on average we are above 50%. Notably, in the lowering phase, it seems that we have a small lag that causes the motor to take nearly all of the load, but this may not be undesirable.

Future Recommendations

Future work could focus on better understanding the initial lifting lag and increasing the response time of the system. Additionally, a longer continuous test would add more insight in the evolution of the support during each of the phases—particularly during sharp transitions.

Artifact ID: 029	Artifact Title: User Comfort Test Results	
Revision: B	Revision Date: 10 April 2023	
Prepared by: Isaac Sorensen		**Checked by:** Joshua Vanderpool
Purpose: *This document has been revised to encapsulate the user testing experience with the physical aspects of the device. TR_004 tests the user experience with the control system, thus this test procedure is intended for only the physical aspects of the device. This is performance testing.*		

Revision History			
Revision	Revised by	Checked by	Date
--	Isaac Sorensen	Joshua Vanderpool	29 November 2022
A	Joshua Vanderpool	Tyler Dickson	8 December 2022
B	Joseph Edmund	Chris Payne	10 April 2023

Test Procedure Used

[025_TPRO_User_Comfort]

Pass/Fail Criteria

This test includes several performance measures that are subjectively scored by a user. Thus, each measure may pass or fail. Below is a table for the minimum and ideal scores for each measure. There is no maximum to the quality of experience of a user.

Performance Measure	Minimum Value	Ideal Value	Maximum Value
Discomfort after 15 mins	Very Comfortable (5)	Neither comfortable nor uncomfortable (3)	Very uncomfortable (1)
Time to don device (sec)	N/A	30	120
Time to doff device (sec)	N/A	30	120
Time required to learn the device. (mins)	N/A	10	20
Perceived exertion with device on (qualitative percentage)	0%	50%	80%
Response Time	Delay is an impediment to task (1)	Functional despite delay D & actuation discontinuities (3)	Input delay can be easily adjusted to (5)

Test Metric and Objective

The objective of this test is to determine whether the design meets predetermined performance measures. Once again, the measures of this test are all subjective. While there are multiple measures for this one test, all would logically be taken at the same time as the user is walked through several aspects of the device.

To more objectively rate the comfortability of our device use over time, we adapt the use of the scale and terms from Cardello, Winterhalter & Schultz, 2003: we reduced the total number of categories to 5 to simplify our future surveys and test of device comfort. We also provide a more thorough description of each.

Term	Description	Quantitative Score
Very Comfortable	Device feels soft, secure, cooling. Does not cause rubbing, irritation, or heating of the skin.	5
Moderately Comfortable	A mixture of the above characteristics, but still positively weighted.	4
Neither Comfortable nor Uncomfortable	Does not cause pain or discomfort but is not particularly enjoyable for the wearer to use.	3
Moderately Uncomfortable	A mixture of characteristics, but with a larger majority of negative aspects.	2
Very Uncomfortable	Causes direct pain or discomfort.	1

See 003_TPRO_User_Wearability_Procedure_and_Test_Metrics for a detailed description of test procedures and materials

Test Results

We adjusted our test procedures to be simplified for a quick testing of user comfortability. Below is the table from above with our performance measures. With the added question of response time to the user. There will be 6 values in each category representing the values gained by testing the system on each of our 6 team members. Following that there will be an avg value from the group given.

Performance Measure	Recorded Values	Ideal Value
Discomfort after 15 mins	4, 3, 3, 4, 3 **Avg: 3.4**	3
Time to don device (sec)	20, 30, 10, 12, 20 **Avg: 18.4**	30

Time to doff device (sec)	15, 15, 7, 6, 12 **Avg: 11**	30
Time required to learn the device. (mins)	3, 1.5, 15, 5, 5 **Avg: 5.9**	10
Perceived exertion with device on (qualitative percentage)	30%, 20%, 40%, 30%, 40% **Avg: 32%**	50%
Response Time	3, 4, 4, 3.5, 3 **Avg: 3.5**	3

Artifact ID: 030	Artifact Title: System Weight Test Results		
Revision: **A**	Revision Date: 10 April 2023		
Prepared by: Brinler Tanner		**Checked by:** Joshua Vanderpool	
Purpose: *To test if our entire system meets the weight requirements*			

Revision History			
Revision	Revised by	Checked by	Date
--	Brinler Tanner	Joshua Vanderpool	**--**
A	Isaac Sorensen	Joseph Edmund	10 April 2023

Test Procedure Used

[026_TPRO_System_Weight]

Test Results Summary

Weighting Iteration	Measured System Weight (lbs)
1	10.91
2	10.89
3	10.90
Average	**10.90**

Notes

This weight could be significantly reduced with design changes to the frame, wiring, and shell.

Largest contributor to the weight is the frame (~3-4 lbs), the motor with planetary gearbox (~2 lbs), and cable spool (~1 lbs). While the motor weight is fixed, the spool and the frame could be significantly reduced.

Recommended Future Tests

Our design includes several 3D printed parts. Therefore, one could adjust the infill settings to reduce weight and compare that to the strength of the parts.

Artifact ID: 031	Artifact Title: Predicted Battery Life Test Results	
Revision: C	Revision Date: 18 April 2023	
Prepared by: J. Edmund and T. Dickson		**Checked by:** Joshua Vanderpool
Purpose: To define how we will measure and test the predicted battery life of our system.		

Revision History			
Revision	Revised by	Checked by	Date
--	J. Edmund and T. Dickson	Joshua Vanderpool	--
A	Joseph Edmund	Isaac Sorensen	2 March 2023
B	Isaac Sorensen	Joseph Edmund	11 April 2023
C	Tyler Dickson	Brinler Tanner	18 April 2023

Test Procedure Used

[027_TPRO_Predicted Battery Life]

Test Objective and Metric

Our objective is to determine how much current is drawn by our system during a representative period of use and then estimate how long our battery power will last.

We will measure the current versus time of our system and then compute an estimated battery life, in hours.

Measure	Upper limit	Ideal	Lower Limit
Battery life under normal work conditions (hrs)	N/A	8	4

Results

We ran the lifting simulation as described in the procedure. A video of our simulations is stored here: https://byu.box.com/s/xdqrrjszsenyw8t5theugo710uh6ddt7

We extracted times as follows:

Table 1. The time stamps of the various phases of the cyclic lifting video.

Phase	*Start Time (s)*	*End Time (s)*	*Total Duration (s)*
Lift	0:05	0:07	2
Carry	0:07	0:11	4
Lower	0:11	0:13	2
No weight	0:13	0:17	4

We measured the maximum currents as follows:

Table 2. The measured average current draws for each of the phases.

Phase	Max Current Draw (A)
Lift	1.15
Carry	0.35
Lower	-0.75
No Weight	0.05

Note that the lowering phase indicated a –0.75 current draw due to the back EMF.

Average current draw: **0.2 Amps** (if battery can recharge), or **.325 Amps** (if battery cannot recharge).

At these current levels, this battery could last approximately **25 hours or 15 hours**, depending on the rechargeability of battery. This is for our one-arm device.

Thus, for a two-armed device, we could reasonably assume that the battery could last up to **12.5 or 7.5 hours**. A more refined estimate would require a better understanding of the particular battery.

Artifact ID: 032	Artifact Title: Strain Gauge Characterization
Revision: A	Revision Date: 17 April 2023
Prepared by: Joshua Vanderpool	**Checked by:** Brinler Tanner
Purpose: his is a small test to characterize the strain gauges in this device.	

Revision History			
Revision	Revised by	Checked by	Date
--	Joshua Vanderpool	Brinler Tanner	--
A	Tyler Dickson	Brinler Tanner	17 April 2023

Pass/Fail Criteria

There are no pass/fail criteria. This is exploratory.

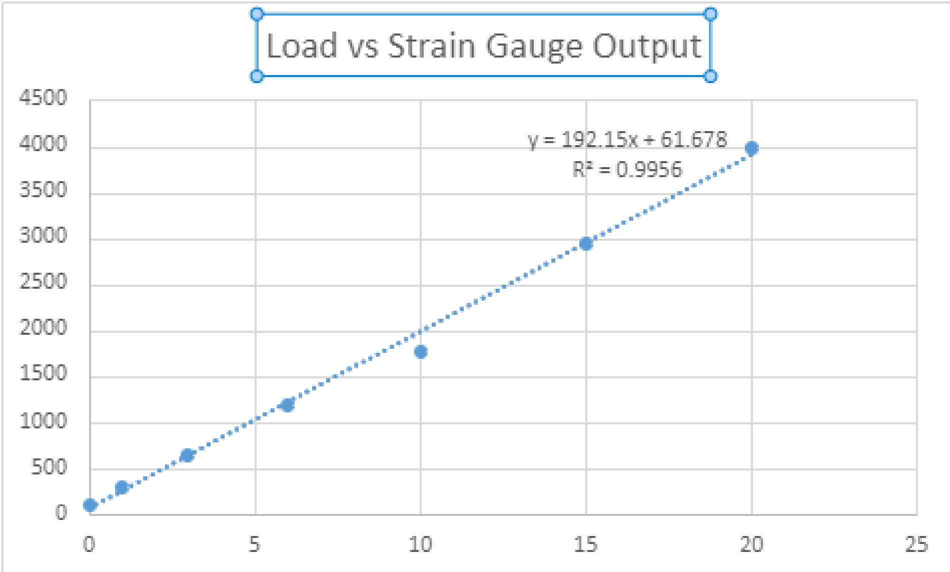
Test Metric and Objective

The strain gauges were loaded with select loads indicated in the table and outputs the output value in the Arduino code. The calibration factor was the same as the final version of the code. The exact values are unitless and meaningless, this test is only to test the linearity of the output.

Test Results

The test shows the strain gauges behave linearly.

Weight (lbs)	Output (diff from 0)
0	100
1	310
3	660
6	1200
10	1780
15	2950
20	4000


Load vs Strain Gauge Output
y = 192.15x + 61.678
R² = 0.9956
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25

Artifact ID: 033	Artifact Title: Motor Characterization
Revision: A	Revision Date: 18 April 2023
Prepared by: Joshua Vanderpool	**Checked by:** Brinler Tanner
Purpose: *This testing was to understand the behavior of the motor controller and motor.*	

Revision History			
Revision	Revised by	Checked by	Date
--	Joshua Vanderpool	Brinler Tanner	--
A	Tyler Dickson	Brinler Tanner	18 April 2023

Pass/Fail Criteria

This test is exploratory and will not have a goal to be reached. This testing was to understand the behavior of the motor controller and motor.

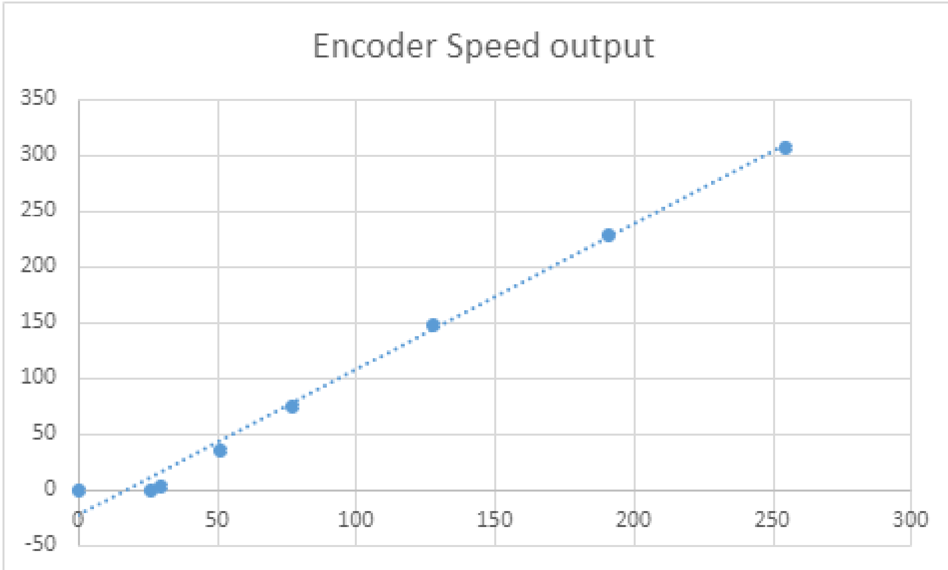
Test Metric and Objective

We tested various PWM inputs on the motor with no load. We recorded the current draw and encoder voltage, as well as the motor encoder speed output. We then graphed various elements to see the trends of the graphs.

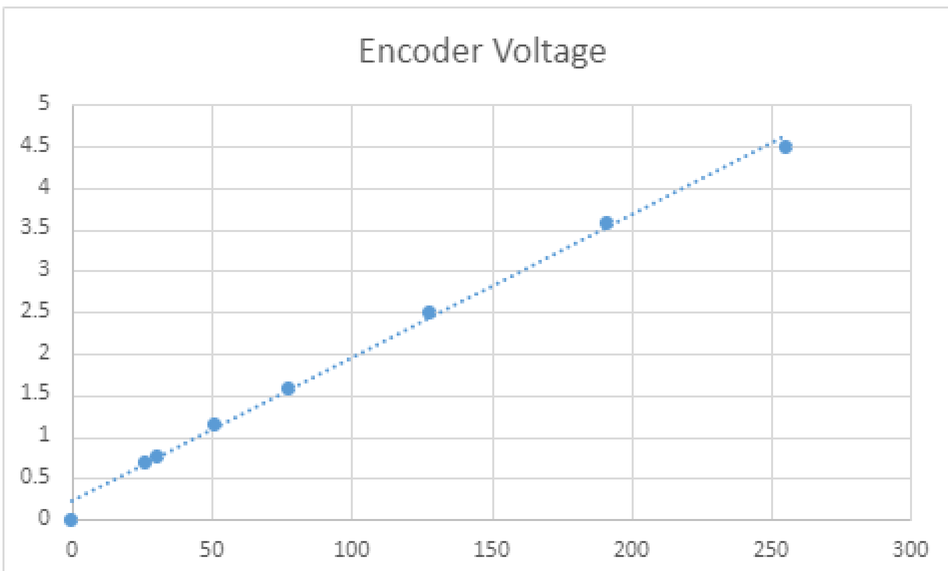
Test Results

PWM Arduino Input (approximate)	Duty Cycle	Load	Current Draw	Encoder Voltage	Encoder Speed output
0	0.00	0	0.01	0.01	0
26	10.20	0	0.01	0.702	0
30	11.76	0	0.01	0.777	5
51	20.00	0	0.04	1.15	36
77	30.20	0	0.07	1.6	76
128	50.20	0	0.14	2.5	149
191	74.90	0	0.24	3.6	230
255	100.00	0	0.27	4.5	308

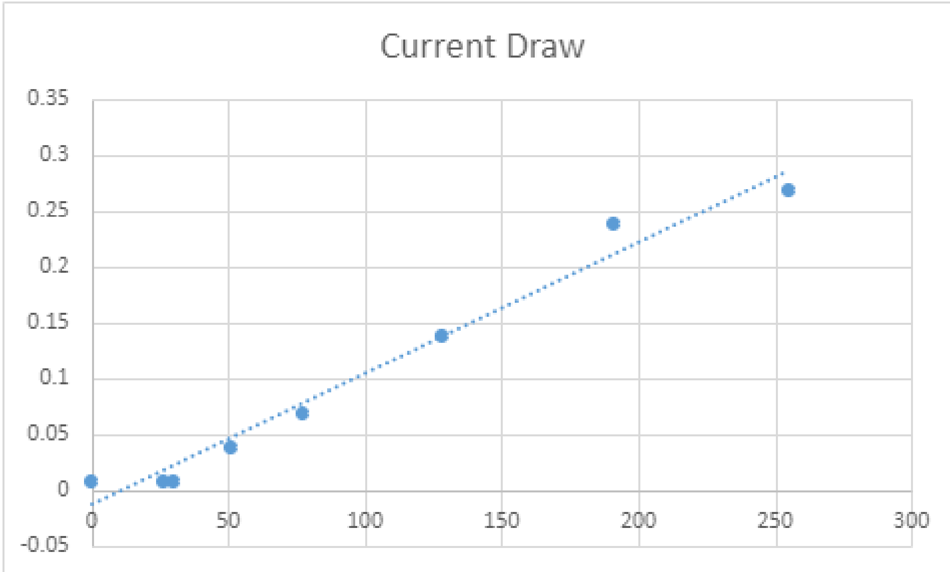
Each of the below graphs has the PWM input on the x axis. The title is the y axis. All of these are roughly linear.



Encoder Speed output
350
300
250
200
150
100
50
0
-50
0
50
100
150
200
250
300



Encoder Voltage
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300


Current Draw
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
50
100
150
200
250
300

034	System FMEA	Revision	Date
			3/1/2023
Team	Herculift		
Prepared by	Joshua Vanderpool and Brinler Tanner		
Checked by	Isaac Sorensen		

Failure Modes and Effects Analysis

Product/subsystem:

Component	Functional Purpose	Failure Mode	Failure Effect	Failure Cause	Current Situation				Assigned Action	Improved Situation			
					S	L	D	RPN		S	L	D	RPN
Shoulder crane	Redirect cable from back, over shoulder, to handle	Lever arm bends or shears when load is applied	Bent or broken cantile	Aluminum yield stress reached	7	2	3	42					0
		Cable gets loose and falls out of pulley track	Increased friction in cable as cable falls off of pulley and into groove	Pulley guide failed	5	2	6	60					0
Frame	Attach other subsystems to user and provide a location for other subsystems to interact	Frame bends due to applied load	Bent and uncomfortable frame, no longer usable	Yield stress reached	6	1	4	24					0
		Parts detach from back mounting	Tension released, flying parts, alignment failure	Yield stress reached	9	3	8	216	Add housing designed with safety factor, inspect before use	6	3	1	18
Cable Stop	Prevent cable from extending or retracting past comfortable limits	Cable stop slips and does not stop cable	Allows the cable to reel in excessively, could cause injury to user	Cable load above 110 lb and at a maximum displacement	3	4	2	24					0
Shoulder Stop	Prevent shoulder crane from toucing face.	The stop breaks, slips, or otherwise malfunctions	Allow the cantilever beam to contact the user, could cause injury	Yield stress reached	8	2	2	32					0
Handle	Attach hook to cable, and sensing the load in the hook and the cable separately	Strain gauge does not calibrate well, gives incorrect readings	Controller will drive motor based on incorrect readings, causing instability	Sensor hysteresis, instability, positive feedback in motor actuation	7	4	4	112					0
		Handle breaks, splits open, cable attatchments break throuhg plastic	The tarp will drop, excessive force to the hand, could cause variety of injures of user's face and or hand	PLA material yielding, fracture, or failure of bolts keeping handle together	9	3	7	189	Increase factory of safety, more ductile material	7	1	7	49
Motor	Take input from controller and output appropriate toqrue to gears for assisted dynamic lifting.	Motor controller board burns out or pulls excessive current	Motor will burn out and no longer have any control.	Overheating of components, current limiting resistor burns out	5	3	5	75					0
		Gear teeth on gear box break	Cable goes slack, support suddenly gone, motor spins uncontrollably	Yield stress of gear teeth reached	5	5	9	225	Add passive system, Check system before donning, Harder material	4	3	7	84
		Motor overheats and melts	Burn user, cable stops or goes slack	Over use, lack of heat transfer or cooling	5	6	3	90	Indicator for overuse				0
		Battery dies	System shutoff, loss of cable actuation	Extreme temperatures, over use, drained battery	2	4	1	8	Press Battery indicator Periodically				0
Controller	Measure input forces and output appropriate current to motor	Controller overshoots assist	Difficult to lower handle	Sensor noise, code errors	5	9	7	315					0
		Controller undershoots assist	User overuses muscles	Sensor noise, code errors	5	9	7	315					0
		Cable moves too quickly	Cable slack	Sensor noise, code errors, incorrect default values in code	5	8	7	280					0
		Turns off suddenly	Cable can't move, user may pull and break it	Controller logic error	7	3	8	168					0
		Turns on suddenly	Undesired motion	Controller logic error, too small of error band	7	3	8	168					0
		Incorrectly calibrated	Device consistently over or undershoots	Inproper user calibration	3	5	2	30					0

S: Severity of failure effect

L: Likelihood of failure occurring

D: Dectability of cause before failure occurs

RPN: Risk Priority number (S*L*D)

Revision History

Rev.	Date	By	Approval	Description
--	3/1/2023	J. Vanderpool	I. Sorensen	Initial Release

FMEA Worksheet Template Rev A 1/26/2019

Project Success Agreement

Wearable Assisted-Lift Device

Sponsor: Sandia National Laboratories

Date: 13 March 2023

Revision D

Capstone Team 37: Herculift

Revision:	Date:	Notes:
--	26 Oct 2022	Initial release
A	11 Nov 2022	Preparation for architecture review, refining of scope and background
B	17 Nov 2022	Before Architecture Review Submission, refining of requirements section
C	06 Dec 2022	Revisions after Sponsor and Pod Leader Feedback—Key Success Requirements
D	13 Mar 2023	Revisions on end-of-semester performance measure wording

Approval Signatures:

Tyler Dickson	Date:
Christian Payne	Date:
Isaac Sorensen	Date:
Joshua Vanderpool	Date:
Brinler Tanner	Date:
Joseph Edmund	Date:
13 March 2023	
Rob Cloward – Team Coach	Date:
David Wood David Wood (Mar 15, 2023 12:15 MDT)	Mar 15, 2023
David Wood – Sandia National Labs	Date:
Jason W. Wheeler Jason W. Wheeler (Mar 15, 2023 12:16 MDT)	Mar 15, 2023
Jason Wheeler – Sandia National Labs	Date:
Carl D. Sorensen Carl D. Sorensen (Mar 15, 2023 13:12 MDT)	Mar 15, 2023
Professor Carl Sorensen – Capstone Instructor	Date:

Project Background

Department of Energy workers are periodically tasked with lifting heavy lead blankets for several days at a time. These workers are at risk of experiencing fatigue injuries in their biceps and shoulders due to this repetitive lifting. Capstone Team 37 is tasked with creating the preliminary design and prototype of a dynamic lift-assist device to be worn by DOE workers. This project is an expansion of the current exoskeleton market because it will assist with dynamic (as opposed to static) loads. Upon completion of this capstone project, the design will be turned over to Sandia National Laboratories for further testing and development.

Project Scope

Capstone team 37 will design and test a preliminary prototype for a wearable dynamic lift-assist device that can be transferred to Sandia Labs for further refinement and testing.

The device, wearable on the user's back, will assist in offloading ideally half of stress felt by the user's shoulder and bicep and transfer it to the hips and trunk of the user. This assistance will dynamically adapt to the impulses and inertia of regular work.

Specific Project Deliverables

- A prototype of the device for a single arm. This prototype will fulfill the following functional needs:
    - Sense and dynamically adjust the actuation for load assist.
    - Redirects a significant portion of the load force to the user's trunk.
    - An appropriately sized motor and cable-transmission system.
    - Be battery powered and contained in a wearable frame that offloads the weight to the hips.
- A well-documented control system, including:
    - A control diagram indicating inputs, outputs, and feedback loops.
    - A bill of materials with specific sensors used for sensing the load at the hand and in the cable and controlling the motors.
    - A diagram that maps the connections of electrical components in the system.
    - Robust and thoroughly commented code that integrates inputs and drives the device actuation.
- A compilation of models and test documentation that analyzes the system effectiveness.

Expected Schedule

March-April:

- Refinement of subsystems and interfaces with documentation
- Implementation of control system and refinement of sensing/actuation
- Test procedures and test results for battery life, load offloading, device response time, device comfort, the control system, and device range of motion. We expect further testing and testing refinement by Sandia.

- Documentation and final report of product for delivery to Sandia National Labs.

Current and Expected Resources

We anticipate the full use of the rest of this budget as well as the further $1,500 budget that has been approved by Sandia for our further prototype development and system refinement.

Project Objective Statement

Develop a test-ready electronically-controlled one-arm device to reduce fatigue during repetitive heavy lifting delivered by April 06, 2023 using less than $3000, and within 1800 man-hours.

Product Requirements Summary

Here, we summarize our finalized market requirements with their specified rating of importance. See the full requirements matrix (GA_001_Herculift_Requirements_Matrix) for all success measures, ideal values, and further detail.

	Market Requirement	**Rating of Importance (3 is most, 1 is least)**
1	Reduce fatigue, specifically biceps and deltoid fatigue	3
2	Device assisted lifting is task-agnostic	2
3	The device can be used continuously for half a work shift	2
4	The device can be used comfortably for multiple days of work	2
5	Device fails safely and protects against injury from cables and actuating parts.	3
6	The device permits use of site equipment (Whites, PPE, Tools, Lifts, Etc)	2
7	Device aids in repeatedly lifting 45 lbf tarps (with two hands) by redirecting a portion of the load to the trunk	2
8	Device support adapts to tarp weight and dynamic stresses	3
9	The device is intuitive to the user	1

Key Success Measures

Here, we summarize our key success measures. Any measure that evaluates in the ‘Poor’ category has crossed the lower/upper acceptable limit for that evaluation.

Measure	Stretch Goal	Excellent	Good	Poor
Response time of system	No perceptible delay	Input delay can be easily adjusted to	Functional despite delay & actuation discontinuities	Delay is an impediment to the task
Percent of load at hand redirected to the trunk (%)	50-70%	40-50%	20-40%	<20%

Average user discomfort during normal work use (See TRES_001_User Testing Physical	Very Comfortable (4.2+)	Moderately Comfortable (3.6-4.2)	Neither Comfortable nor Uncomfortable (2.6-3.5)	Moderately Uncomfortable (1.5-2.5)
Total Weight of System	0-10 lbs	10-12 lbs	12-20 lbs	20+ lbs
Predicted Battery Life Under Expected Working Conditions	>5 hrs	4-5 hrs	2-4 hrs	<2 hrs

Change Management Procedures

Once this agreement has been agreed on the following method will have to be followed by any group wishing to change any aspect of it.

The party desiring the change will send a notice to email to the other two parties indicating which section of the agreement they want to change, and why they feel the current agreement fails to meet their needs. Additionally, they will include a preliminary draft of the specific changes they would like to have made. The other two parties will have a week to consider and send their initial response to the change request.

After email correspondence, and once the change is agreed on by all three parties, the student team will create the change in the official documentation and send it to BYU Capstone officials for final signatures.

A note on the student team: agreement among the student team will require 4 out of 6 votes in the affirmative from the students and a vote in the affirmative from the team coach.

BYU Capstone Team37 - Project Success Agreement Revision D

Final Audit Report 2023-03-15

Created:	2023-03-15
By:	Lisa Barrager (lc38@byu.edu)
Status:	Signed
Transaction ID:	CBJCHBCAABAAlfcmvdFKqeHiuHW1Wr8rRDQgj0iqoZz9

"BYU Capstone Team37 - Project Success Agreement Revision D" History

Document created by Lisa Barrager (lc38@byu.edu)
2023-03-15 - 5:34:58 PM GMT- IP address: 128.187.112.6

Document emailed to dswood@sandia.gov for signature
2023-03-15 - 5:35:56 PM GMT

Email viewed by dswood@sandia.gov
2023-03-15 - 6:11:23 PM GMT- IP address: 104.47.64.254

Signer dswood@sandia.gov entered name at signing as David Wood
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Document e-signed by David Wood (dswood@sandia.gov)
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Signer jwwheel@sandia.gov entered name at signing as Jason W. Wheeler
2023-03-15 - 6:16:15 PM GMT- IP address: 198.102.151.244

Document e-signed by Jason W. Wheeler (jwwheel@sandia.gov)
Signature Date: 2023-03-15 - 6:16:17 PM GMT - Time Source: server- IP address: 198.102.151.244

Document emailed to c_sorensen@byu.edu for signature
2023-03-15 - 6:16:19 PM GMT

Email viewed by c_sorensen@byu.edu

2023-03-15 - 7:11:21 PM GMT- IP address: 128.187.112.26

Signer c_sorensen@byu.edu entered name at signing as Carl D. Sorensen

2023-03-15 - 7:12:10 PM GMT- IP address: 128.187.112.26

Document e-signed by Carl D. Sorensen (c_sorensen@byu.edu)

Signature Date: 2023-03-15 - 7:12:12 PM GMT - Time Source: server- IP address: 128.187.112.26

Agreement completed.

2023-03-15 - 7:12:12 PM GMT

Artifact ID: 036	Artifact Title: Initial Power Requirement Calculations
Revision: C	Revision Date: 18 April 2023
Prepared by: Brinler Tanner	**Checked by:** Tyler Dickson
Purpose: Calculate Overall Power for general reporting.	

Revision History			
Revision	Revised by	Checked by	Date
--	Tyler Dickson	Josh Vanderpool	28 October 2022
A	Tyler Dickson	Isaac Sorensen	2 November 2022
B	Tyler Dickson	Isaac Sorensen	8 November 2022
C	Tyler Dickson	Brinler Tanner	18 April 2023

Outcome:

Energy = 100 J/cycle

Time to lift = 0.75 s

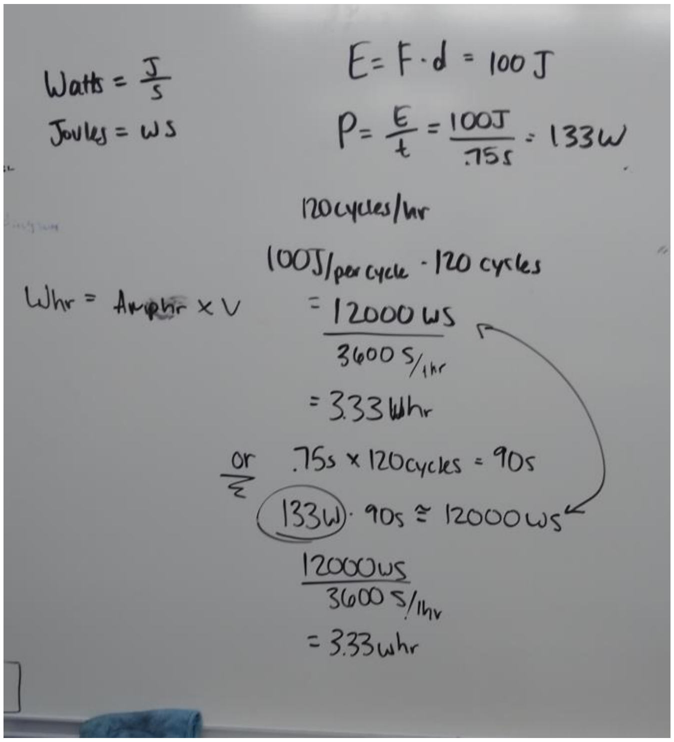
Power for lift = 133 W

Active time = 0.75 s * lifts per hour = 90 seconds of on time

Active time in 5 hours = 0.125hr

Total capacity = Power for lift * Active time in 5 hours = 16.625 Whr

Required Battery Capacity = Total Capacity / Battery Volts = 0.8 Ahr



Assumptions:

Lift Speed = 2 m/s

Weight (N) = 15lb * 4.4 (conversion factor)

Lift distance = 1.5 m

Work time = 5 hours

Lifts per hour = 120 (this assumes a lift rate of about 2 per minute)

Battery Voltage = 20 V

Reason for decision:

Equation for work: W = F * d

Equation for power: P = W / t (where t is time in seconds)

Time = Lift Distance / Lift Speed

Equation for watt hours: Wh = P * t (where t is time in hours?)

Equation for amp hours: Ah = Wh / V (where V is voltage)

Variable	**Definition**
W	Work
F	Force
t	Time
d	Distance
P	Power
Wh	Watt Hours
Ah	Amp Hours