ABSTRACT

Competitive rowing teams are often unable to train outdoors due to inclement weather conditions and limited access to proper equipment and waterways. Current indoor rowing solutions focus on strength and stamina training, but do not emphasize proper technique. RowTek addresses these issues by allowing rowers to practice technical rowing while training indoors. The RowTek solution incorporates the balancing difficulties associated with rowing, a port-side oar to practice sweep rowing, and a computer-controlled variable resistance mechanism. With the engagement of these three systems, RowTek more accurately portrays the on-the-water rowing experience.

1. INTRODUCTION AND BACKGROUND

According to Ted Nash, Olympic Gold medalist and current US National team coach, the greatest need currently facing rowing clubs across the country is the ability to train year round. There are several factors that prohibit athletes from being able to exercise on the water throughout the year. First, athletes and coaches alike find it unbearable to train outside during the winter months of cold climate areas. Second, coaches are faced with the difficulty of communicating and critiquing their students as they practice in several different boats. Coaches desire the ability to be able to help many athletes with their technique simultaneously. Crew Teams would highly value the ability to train in the winter months on an indoor machine that better simulates the rowing.

Additionally, there are high costs associated with the sport of rowing (predominantly the cost of the boat). A more affordable training device would reach out to a broader scope of socioeconomic groups. While current machines, such as the Concept2, may be considerably cheaper than buying a boat, they fail to provide valuable technical training. Other solutions, such as Durham's Indoor Tanks [3], are extremely expensive and require an institutional investment. With these issues to consider, the rowing community desires a training device that is affordable and more representative of on-water experience.

1.1 Existing Solutions

There are currently two popular solutions on the market that address the needs of the rowing community:
1. **Traditional Indoor Rowers** – The traditional indoor rower has roots stemming to the mid 19th century. However, it was not until the early 1900s that rowing machines would be mass-produced by a company called Narragansett Machine Company and used by crew teams across the country. In the 1960s, the rowing machine was improved with the invention of the ergometer, a machine that measured the work capacity of the rower. The ergometer uses straps and a fly wheel device to model the rowing experience. Typically, either a friction brake mechanism or a wheel fitted with plastic paddles is used to create resistance for the athlete to measure against [2]. Machines today are built in a variety of styles. They can differ in type of resistance, stationary vs. sliding seat/foot attachment, and type of handlebar. Most machines provide athletes with a monitor to gauge distance, speed, pace, calories burned, watts produced, and occasionally heart rate [1].

2. **Indoor Tanks** – The indoor rowing tanks are less common forms of equipment used by athletes. Indoor rowing tanks consist of a platform, oars, seats, and two tanks full of water. Athletes (typically 2 to 16) sit on sliding seats mounted atop the platform. The oars are positioned to move through the water in the tanks as the athlete takes his/her stroke. Indoor rowing tanks are typically custom designed and are extremely expensive. While these devices more accurately represent the stroke technique than the ergometer, they still fail to portray buoyancy and balance effects. Additionally, the water speed in the tank has little correlation to the actual average speed in a boat, making it hard for one to gauge athlete improvement and development. Moreover, the turbulence created when rowing in a water tank does not represent real on-water conditions, altering the feel an athlete has for the stroke [3].

The description of these existing products alone reveals several limitations in current designs. No indoor product has successfully reached a proper balance of cost and technical accuracy. Indoor tanks seem to provide rowers with better technique training, but are so expensive that only the top rowing clubs in the country can afford to install them. Traditional indoor rowers are a much more practical solution in terms of price, but lack the technical accuracy that is required for coaches to teach technique. In fact, in the paper “Comparison of On-Water Rowing with its Simulation on Concept2 and ROWPERFECT Machines,” Dr. Valery Kleshnev reports his findings when testing the technical accuracy of two popular existing products: the Concept2 and the ROWPERFECT. The Concept2 was the most popular training machine in the late 1990s and early 2000s. The ROWPERFECT simulator addressed some issues with the Concept2, such as increased probability of knee and low back injury due to stationary foot-rests. Dr. Kleshnev concluded that the forces and motion of the rower stationed in the machines is extremely different than those experienced on the water and affect the rowers’ motor control pattern and rowing technique. He then went on to claim that rowing on the water and rowing on a machine are two very different kinds of exercise. Dr. Kleshnev’s work, as well as the analysis of existing solutions, has led toward the recognition of the need for a better indoor rowing simulator for year round training.

2. **REQUIREMENTS AND OBJECTIVES**

   After understanding both the needs that exists in the rowing community and the existing products that try to satisfy such needs, our team developed the following requirements and objectives:

   *The RowTek solution must:*

   a. Replace the handle of a standard erg with a side-mounted oar, which will be free to rotate about a fixed oar-lock

   b. Accurately portray the “sweeping motion” present in rowing rather than the linear motion that exists in more current designs

   c. Simulate the forces on an oar that are felt by a rower during on-the-water rowing

   d. Allow the rower to roll laterally in order to portray the balancing effects of being in a boat

   e. Be robust in order to protect the safety of the user

   *The RowTek solution should:*

   a. Be portable in order to allow the machine to be transported between rooms

   b. Prevent the user from experiencing extreme angles of roll

3. **CANDIDATE CONCEPTS**

   Among the variety of formats under consideration for the final report, the following candidates emerged as distinct, realistic options:

   **Pool Mounting System** – A mounting system that connects a boat to the side of a pool. A spring and damper system, or hydraulic system, would be used to simulate the on-the-water forces.

   **Floating Platform** – Similar to the pool mounting system except a platform would be built as opposed to using an actual boat.

   **Modified Ergometer** – A standard concept II ergometer will be modified such that it will have a variable resistance mechanism, be able to roll, and require the user to row using a “sweep” motion.
3.1 Comparison and downselection

After coming up with several distinct design concepts, we decided to narrow our focus to the modified ergometer. We believe this is the most feasible project possible given our constraints and knowledge. The main issue for both the floating platform and pool mounting system design is that they both involve the extensive use of water in the testing process. Designing a system that has to sit in the water has a variety of issues. During a typical stroke a boat travels very large distances. Because of this the boat or platform would need to have ample room in the pool to operate. Also, at the end of each stroke the system would have to be returned to its initial state at the edge of the pool. This has the following problems:

1. The water will all be rushing in one direction while the boat/platform would need to go back the other way. If we were able to make the boat return to initial state that would have an adverse affect on the flow of water.
2. It is unlikely the boat could gently be returned to its initial state (since the second stroke would occur shortly after the first stroke). This indicates that the boat would likely have to experience a large force, which would jerk it back to the initial position. Obviously this type of motion would not realistically simulate what it is like to row in the open water.

The modified ergometer concept exhibits none of the issues involved in both the floating platform design and the pool mounting system. It is convenient that it will be a machine that remains in place since it will take up less room and be more portable. Also, since it does not involve water we will be able to replicate the forces on a boat by using a variable resistance mechanism (magnetic particle brake) to control the resistance against the rower. Similar to the previous designs this machine will make the user replicate the actual sweeping rowing motion (as opposed to the horizontal motion that exists in almost all of the common rowing machines). It is also significantly easier to test as the machine can be used anywhere while we would have to gain exclusive access to a pool to verify the other designs. All three designs should accurately reflect the balancing effects that occur in water and ensure the user is practicing the motion required when actual rowing. However, the modified ergometer concept has a higher chance of being successful since it does not have to deal with the problems that come from working with water.

Table 1 shows a comparison between these three designs.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Floating Platform</th>
<th>Pool Mounting System</th>
<th>Modified Ergometer</th>
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*Notes all products were rated on a 1-5 scale, with 1 being poor and 5 being excellent.

4. DESIGN DESCRIPTION

4.1 RowTek Design Concept

RowTek works through the combination of several subsystems:

1. **Balance system** - The wooden cradle is connected between two uprights by the use of a steel rod and extreme misalignment bearings. These bearings ensure that even if the uprights are to bend slightly the system will still be able to spin freely.
2. **Sweep Rowing** - The addition of a real oar, along with a pulley system, forces the user to row in the same manner as they would while on-the-water.
3. **Computer Controlled Resistance** - A magnetic particle brake is mounted on to the flywheel which receives commands in real time from LabView.

![Figure 2. Cradle on misalignment bearings and port-side outrigger and oar](image)

The functions of the components in the sub-systems are as follows:

1. **Wooden cradle** – Balanced on two triangular stands (uprights) and allowed to rotate freely about steel cylindrical rods, each connected on the front and rear ends of the cradle.
2. **Sliding Seat** – Rolls on an I-beam from a standard Concept2 ergometer that is attached to the cradle.
3. **Oar** – A typical oar used while rowing however it has been shortened such that the machine will require less room to operate. The oar is attached to the cradle by a standard oar-lock.
4. **Pulley System** – Used to ensure that the sweeping motion of the oar is converted into the translational
motion of the flywheel chain. Involves four contact wheel chain points and two pulleys. One pulley with a custom made aluminum pulley block to accommodate the design is attached to the end of the oar. Another pulley with steel bearings is fastened to a U-bolt on vertical steel square tubing. This pulley sits on the bow end of the cradle and is fixed directly opposite the flywheel. A steel ball joint rod end connects the pulley system to the end of the oar. This smoothly rotating rod end ensures that the rower can feather/rotate the oar freely from any position.

5. **LabView** – A system design platform and development environment for a visual programming language from National Instruments™. It is commonly used for real time data acquisition, instrument control and industrial automation, all of which form the backbone of RowTek’s modulated resistance mechanism. The program performs a number of functions for RowTek including receiving voltage signals from the two primary sensors, filtering the signals, using signal to calculate boat speed and oar speed, deriving the ideal drag force on oar, and outputting the corresponding voltage to the brake. A diagram of the code and a flow chart of the process are shown in Appendix B. The force output by the code is based on the following drag force equation.

\[ F_{\text{water}} = \frac{1}{2} C_d \rho A_o ar (v_o - v_{\text{boat}})^2 \]

This force output is one of the major features that differentiates RowTek as a indoor training device. No current training device takes \( v_{\text{boat}} \) into account when outputting a resistance.

6. **Proximity Sensor** – To detect the RPM of the flywheel, a proximity sensor with three permanent magnets embedded in the flywheel is used. Upon detection of a changing magnetic flux, a current is induced in the solenoid sensor and a voltage signal is collected for processing in Labview.

7. **DC Motor** – A 9V Technic LEGO DC motor is used to detect the position and speed of the oar. When the motor shaft is rotated in a positive direction during the drive, a purely positive voltage signal is collected in Labview. When the motor is rotated in the opposite direction during the recovery, a purely negative voltage signal is collected in Labview. In this way, we are able to obtain a clear indication of whether the rower was in the drive or the recovery. The magnitude of the signal is proportional to the angular speed of the sprocket, and thus is proportional to the linear speed of the chain.

8. **Force Sensor** – There is no force sensor integrated into the current prototype. However, an explicit force measurement in the system may allow for simplified software code and faster reaction times from the resistance mechanism. A load cell integrated into the chain or a series of strain gauges on the oar could serve such a purpose.

9. **External PCI Boards** – Two PCI boards are used in the system to connect the sensor inputs and the brake outputs to the computer. One PCI board accepts the voltage spikes of the proximity sensor on the flywheel and outputs a voltage to the brake. Another PCI board is used to accept the voltage generated by the DC motor.

10. **Modified Flywheel** – This is the base resistance mechanism of the device. The blades of the original flywheel are removed (such that it is merely a flat circular disk) to minimize its moment of inertia and air drag resistance. This ensures that the air drag resistance and the moment of inertia of the flywheel are no longer the dominant opposing forces during each stroke.

11. **Magnetic Particle Brake** – The Montalvo PB-12 brake applies a torque to the flywheel based on the voltage output by Labview. The acceleration of the flywheel signals help control when to engage the brake (during the drive) and when not to (during the recovery). The speed (rpm) signals obtained from the magnets are correlated to the speed of the boat. The combined information from these signals allows us to control the voltage output to the brake using Labview. Since the current given to the brake is proportional to the torque applied by the brake, the resistance felt by the rower during the full length of the stroke can be modulated to simulate on-the-water rowing.

12. **Overall Unique Features of RowTek** – computer-controlled resistance, sweep motion and feathering capability of the oar (has no effect on force exerted by brake at this time, but it is still possible to do so), ability to roll from side to side.

### 4.2 Operation

To operate RowTek, the user will sit on the sliding seat and simulate strokes as if he or she was on the water.
The force applied during each stroke will cause the flywheel to accelerate and thus cause the rower to either gain or lose speed. While using the device the cradle will have the ability to rotate from side to side to simulate the roll of a boat while in water. Voltage signals generated by the three magnets attached to the flywheel will be detected in LabView to determine the instantaneous angular speed (in rpm) and acceleration of the flywheel. This data will then be used to manipulate the voltage output to the brake. Thus, the resistance of the flywheel and brake system will be constantly adjusting based on the inputs to and outputs from the LabView program to simulate on-the-water resistance.

5. **Prototype Realization**

Most of our previously discussed design concepts were realized in the final prototype. A robust cradle was built which can freely rotate. This cradle has been tested with rowers that weigh up to 250lbs. A port-side oar was effectively integrated into the system through a pulley system with four contact points. Lastly, a brake was programmed in such a way that it reacts to the rower’s input with simulated on-the-water forces. In creating these systems, a few adjustments had to be made to achieve our final goal of better simulating rowing in water, which are as follows:

1. **Purely mechanical balance system** — We initially intended to integrate the balance system into our computer controls, so that the stability of the rower was directly proportional to the speed of the simulated boat. Unfortunately due to time and financial constraints, we were unable to implement a varying stability mechanism into the cradle. Instead, we fixed the stability of the cradle at a point which emulates the stability of an eight boat moving at a moderate pace.

2. **Limit on the angle of rotation** — Our initial prototypes did not successfully limit the rotation of the cradle. If the user pushed all of their weight to one side it would rock violently in that direction. We solved this problem by horizontally placing a piece of wood on each of the triangular uprights (such that when the cradle rotated approximately 10° in either direction it would collide with the stop and be prevented from rotating more).

3. **Resolution/timing trade-off with RPM sensor** — A typical rowing stroke lasts about 0.5 seconds for the drive and 0.5 seconds for the recovery. Since in this short time interval the force ranges from 0-600 N, we required data from the sensors every 10 ms and that we could send an output to the brake every 10 ms. With the proximity sensor collecting three peaks per revolution, a RPM range of 0-800 corresponded in Labview to a range of 0-4 peaks per 10ms. Given this discretization of the RPM data, we were unable to obtain sufficient resolution of the data for collection time intervals under 1s.

As a result, we lost the timing that was required (10ms) to appropriately engage the brake. It was crucial to collect data more quickly to know at what point the rower was in the stroke so that we could engage the brake with variable resistance during the drive and disengage the brake during the recovery.

4. **Improved sensors** — We attempted to modify the RPM sensor and add several new sensors to resolve the resolution/timing trade-off. An accelerometer solution proved untenable as a result of the inconsistent human input into the system. The Arduino-based accelerometers used for testing were too sensitive to uneven acceleration by the rower. Other sensor solutions were attempted. Our final solution was to attach a DC motor to the shaft that was directly connected to the chain and sprocket of the flywheel. With this second sensor, we could collect stroke position data and determine the chain velocity every 10 ms to engage and disengage the brake. In the future, it may be beneficial to add a load cell into the system to detect force exerted by the rower explicitly.

6. **Evaluation and Testing**

Extensive testing was done on all three of RowTek’s systems during and after construction/assembly.

**Balance System**

The cradle system was tested for stability and friction in the rotational motion. Through this testing, it was determined that approximately 24 pounds of weight needed to be added to the starboard-side of the cradle to compensate for the weight of the oar and outrigger on the port-side of the cradle. We accomplished this by adding 8 ft of steel trim and one 8 foot piece of 2 x 6 wood to the starboard wall of the cradle. The addition of this weight had the effect of making the cradle evenly balanced and more stable. Despite this increased stability, the cradle still roughly emulates the stability of an eight boat moving at a moderate pace.

**Sweep Motion**

Several current and former rowers were used as test subjects on the RowTek to ensure the sweep motion was natural and to ensure the pulley system could accommodate rowers of different lengths. No major problems arose during these tests. In addition, physical tests were run on the pulley system to ensure that all points in the multi-layered system could handle repetitive loading and impulse forces up to 200lbs. During this testing, it was discovered that one of the rod ends at the end of the oar was twisting while in use. The team decided to stop this twisting motion in order to reduce the friction added by the pulley system. A new design was implemented where a nut was used to tighten down the rod end.

One of the weaknesses in our final design is that
the oar will sometimes slip through the oarlock at the finish (end of stroke) for shorter rowers. This is due to the force applied by the pulley system in the port to starboard direction if the distance between the cradle and the flywheel system is not adjusted properly. The distance between the cradle and the flywheel can be easily adjusted with a wrench, and ideally this adjustment would be made for each rower based on their physique. However, it is not convenient to have this requirement when multiple rowers are using the machine sequentially.

Computer Controlled Resistance

The team exerted its most extensive evaluation and testing efforts on the resistance mechanism. Much calibration and testing had to be done to develop the Labview code. The brake needed to be calibrated to so that the ideal “force” outputted by the code could be translated into a voltage (0-10V) to be applied across the brake. Prior to testing we knew that the torque of the brake was proportional to the voltage applied, but we did not know the equation that governed this relationship. Our first test was a static calibration test. The brake was connected to the flywheel with a steel shaft coupling and set at a constant voltage. Then a digital hook scale was used to see how much force was required on the flywheel chain to overcome the brake’s torque. In this way, we were able to develop the following experimental equation relating the voltage applied to the brake and the force applied to the chain.

\[ F_{s, friction} = 6.67V^2 + 12.76V - 1.29 \]

The figure below shows the raw data and the best fit line from this static calibration.

The team decided to run its own tests on the standard Concept 2 ergometer (with the addition of the RowTek sensors) to have data to be used for comparison. Unfortunately the code was not in its final version at the time of this test. Therefore, the force had to be derived from a data set of the time locations of each voltage peak of the proximity sensor. This solution was completed by sending text files of time locations from Labview to Matlab. Based on the time locations, we found the average radians per second of the flywheel between each voltage peak. Then, this data was used to find the average radians per second squared between every other voltage peak. The result of these derivations is the average angular acceleration data for the flywheel. This data can theoretically be translated into the force exerted on the chain by the rower. However, in practice, the team was unable to determine the mass and moment of inertia of the objects that the chain is accelerating due to the complexity of the gear, shaft, and flywheel system which was all tightly integrated into the Concept 2 machine. As a result, we had to apply an approximate scale factor to produce the force curve for this test. We estimate that this scale factor could be off by ±10%.

The curve produced by this method is somewhat choppy, but gives a similar shape similar to the Concept 2 curve presented in the following chart.

The average patterns of biomechanical parameters of five female rowers at racing speed (32 stokes/min)
shown in the research. The magnitude of the force is lower than in the research curve, but this was expected since the research curve was produced by a rower at race pace (32 strokes per minute) whereas our curve was produced at a training pace (approximately 18 strokes per minute). All of this was verification to us that our method of deriving the curve was appropriate, and that our sensors were working properly.

After successfully running this test, the team prepared to run a similar test on RowTek. In the interim period, we were able to make changes to the code which allowed us to produce live force curves based on the output of the brake. We now had two methods of producing force curves. The first method took the time locations of the proximity sensor voltage peaks to derive the acceleration of the flywheel. The new method took the “ideal” drag force calculated in Labview (which controls output to the brake) and plotted it directly. Below are two graphs which were derived from the new method.

![Graph 1](image1.png)

**Figure 10.** Predicted handle force for moderate training speed of 22 strokes/min, corresponding to an average flywheel speed of 600 RPM

![Graph 2](image2.png)

**Figure 11.** Predicted handle force for slow training speeds of 18 strokes/min, corresponding to an average flywheel speed of 330 RPM

After analyzing these graphs, we realized that our resistance mechanism was not working well for faster strokes. The first graph shows the force output by the brake in response to someone rowing at a moderate pace, slightly faster than a training pace. The reason why the curve is not shaped similarly to the research curves is because the brake is reacting too slowly to the rower. At the beginning of the stroke at 0.25s, the rower is exerting a high impulse-like force. However, the brake does not spike until 0.4s in reaction to this force. Fundamentally, this delay in the brake is being caused by the lack of resolution of the proximity sensor on the flywheel. The sensor hardware on the final prototype limits the number of voltage peaks to 3 per revolution. This brings us back to the resolution/timing trade-off. If we want the brake to react quicker, we have to allow very poor resolution of the simulated “boat speed” or the rower has to stroke slower.

In the second graph output above, the rower took a slower stroke. The result is a curve that has more resemblance to the research curves. However, there are still problems with this curve as well. There is a large drop off in brake output right in the middle of the stroke. This is not ideal, as the rower should experience a smooth drag force against the oar. These discontinuities in the graphs are caused by, again, the lack of resolution of the proximity sensor. The RPM of the flywheel, which is translated into a theoretical boat speed to calculate ideal drag force, moves like a stepwise function. This causes the voltage applied to the brake to be choppy.

As we attempted more tests to try to correct these issues, we tried the original method of calculating the force curves from the time locations. Unexpectedly the data produced from this method was extremely difficult to work with. The problem was that the lack of resolution of the proximity sensor was exacerbated by the averaging done to calculate the velocity and acceleration of the flywheel. The reason why the method was effective for the Concept 2 test was because the Concept 2 does not generate the same level of rotational speed that the RowTek generates. Due to the length of the RowTek’s lever arm, a 300N pull on RowTek gets the flywheel spinning faster than a 300N pull on the Concept 2. This multiplied the negative effects of the sensor’s low resolution. The graph below shows that the force calculation from the time location method frequently falls down to zero or below zero as a result of a lacking of sufficient quantity of data.
It is clear from our testing that our computer controlled resistance mechanism is effective, but requires sensors with greater resolution to be successful in perfectly emulating on-the-water forces. The addition of a force sensor may be exactly the hardware required to make this technology a very accurate training tool.

7. DISCUSSION

We believe RowTek is a revolutionary first-of-its-kind indoor rowing training technology, which offers distinct advantages for technique training over current options. RowTek’s balance mechanism and sweep oar offer the rower the unique opportunity to practice balance and coordination while off the water. Furthermore, the RowTek computer controlled resistance, with some additional investment, could become one of the most advanced technologies to be used as a training tool in world of athletics. In its current state, RowTek requires more sophisticated sensors to achieve the split-second reaction times demanded by the sport of rowing.

There are several updates that could be made to RowTek in the future, in addition to improving the hardware and software of the resistance mechanism, to advance its ability to train athletes for rowing on-the-water. One great addition to RowTek would be a variable balance mechanism for the cradle, as our team originally planned to implement. If a variable resistance mechanism were included and additional sensors were added to the oar, the rower could train in a completely computer-controlled environment. A mechanism could be added to exert forces on the oar in multiple dimensions. This would allow the system to simulate a real waterline, crabs, and back splash. It would be great if RowTek could eventually be extended to include multiple rowers sitting in the same cradle and connected to a resistance mechanism in which the actions of one rower affected the force on all other rowers.

8. CONCLUSIONS AND RECOMMENDATIONS

After spending extensive time working on and testing RowTek we believe it to be a significant improvement for the training of rowers. With the addition of RowTek rowers are now able to focus on improving their technique rather than just their strength during the winter months. However, it is important to note that RowTek is not yet a completely final design. Several improvements can be made in future years that would ensure RowTek is the “go-to” device for all rowers. We would like to see the stability and thus roll of the boat be a function of speed as was originally intending. It also would be beneficial to make the cradle out of a material other than wood such that it is stronger, easier to work with, easier to transport, and looks better. Additionally, we would like to have better sensors so it will be easier to acquire good data to generate force graphs. We recommend that RowTek be continued at least through 2013.

9. ACKNOWLEDGEMENTS

The RowTek team would like to thank several people and groups for their help with the project.

Montalvo, a company which generously donated us a magnetic particle brake that was used to control the resistance on the flywheel.

Dr. Bruce Kothmann, Dr. Robert Jeffcoat our advisor and instructor respectively, who were there to help us out whenever we had questions and were able to consistently provide advice.

John Martin, our TA, who helped us extensively with machining parts that we were unable to do ourselves.

Hitesh Sahoo, who spent a lot of his time working with us on the LabView code to make the brake respond appropriately.

Daniel Harbuck, former Penn student, who provided inspiration for the project.

Many other MEAM professors who were willing to meet with us and discuss the project and give us ideas.
11. REFERENCES

# APPENDIX A
## MATERIALS AND COST SUMMARY

Table A1 – Major Items

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<tr>
<td>Misalignment Bearings</td>
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<tr>
<td>500mm Steel Shaft</td>
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<td>Mounting Flanges</td>
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<tr>
<td>Pin</td>
<td>5</td>
<td>McMaster</td>
<td>7</td>
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<tr>
<td>Other Screws/Bolts</td>
<td>Many</td>
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<tr>
<td>Metal Connecting Plates</td>
<td>23</td>
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<td>120</td>
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<tr>
<td>Pulley</td>
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<td>McMaster</td>
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<tr>
<td>Rope</td>
<td>50 Feet</td>
<td>McMaster</td>
<td>16</td>
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<tr>
<td>Metal Rods</td>
<td>20 Feet+</td>
<td>McMaster/Home Depot</td>
<td>50</td>
</tr>
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</table>

**TOTAL** 1341
APPENDIX B
LABVIEW CODE AND FLOW CHART

Figure 13. Labview DC motor data collection and brake voltage output loop. Continuous collection and output of 100 samples @ 1000 Hz

Figure 14. Labview flywheel data collection loop. Continuous collection: 1000 samples at 1000 Hz
Figure 15. Flow chart of Labview data processing