Power Measurement for Performance Bicycles

IPRO 324 – Project Plan

Integrated Intelligent Torque Measurement System

'No Strain, No Gain'

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I. Team Information

The IPRO 324 Team Roster, complete with each individuals strengths and expectations can be found in **Appendix A**.

Team Purpose

The IPRO 324 team is working to develop a system that utilizes strain gauges to measure the applied torque on the crankset of a bicycle. The overall goal is to develop an inexpensive and accurate tool for measuring the power output of a professional cyclist. Current devices on the market are quite expensive, require the replacement of current parts that the cyclist has invented significant money, and can still be relatively inaccurate.

Therefore, our task is to find optimal configuration settings of strain gauges that will be retrofitted to the current crankset of various professional cyclists, and to develop an algorithm to process the strain gauge data in order to calculate an accurate measurement of the applied torque. This information will then be transmitted to the bicycle computer for display and storage.

The power measurement systems for aluminum alloy and carbon fiber cranksets developed in the spring 2010 IPRO need to undergo extensive testing with regards to accuracy and environmental stability, as well as mechanical and electromagnetic effects. Reducing power consumption of the current electronic processing unit is also desired. Ideally, a standard CR2032 lithium battery cell should be able to power the unit over an acceptable operating time on the order of a few hundred hours.

An improved encasement needs to be developed for the complete system that allows functioning in a realistic environment that is susceptible to dust and water. The encasement also needs to conform to the space requirements associated with a professional bicycle while still being aesthetically pleasing.

More efficient procedures for instrumentation and calibration of arbitrary cranksets must be developed. Currently, instrumentation and calibration of a single crankset requires tens of hours of work. This leads to unacceptable cost of a potential commercial product.

Finally, we hope to gain a better understanding of the competitive environment for this product in order to adapt the product and its packaging in a way that positions it favorably in the existing market.

Team Objectives

- Improve the current electronic circuitry.
- Construct a working model of the circuit board.
- Design and build a case to house the electronics.
- Develop improved methods for the calibration of arbitrary cranksets.
- Perform dynamic road testing.
- Analyze results and verify accuracy.
- Optimize code for better communication with ANT+ devices.
- Complete a comprehensive market analysis.

II. Background

History

The 2010 fall semester of IPRO 324's task is to continue the development of a power measurement device for bicycles. Since the late 1980s, companies have produced devices to address the need among professional cyclists and serious riders to track their variations in performance throughout a training session or a training period. However these devices are unlike heart rate monitors used by marathoners. This is because at varying heart rates, a cyclist's power output to the bike can remain constant, as the opposite can be true as well.

Power measurement systems initially came in two general forms, a handlebar-mounted model and a strain gauge based model, with the latter becoming more popular. Bottom bracket power meters rely on the torsional deflection of the bottom bracket shaft. Even though this technique was said to be the most accurate, it wasn't popular among cyclists because of the need for different bottom bracket units for each bike. Meters of this style were produced exclusively by a company named Ergomo, which declared bankruptcy in 2008.[1]

Free-hub-based devices came about as a solution to the problems posed by the need for unique bottom bracket units. Being mounted on the rear wheel, they were easily interchangeable. However, on a bicycle there is a power loss in the drivetrain between the crank set and the rear wheel. Therefore a rear wheel based system sees the power output of the cyclist minus the losses in the drivetrain, not his/her full power output. This leads to inaccurate readings with error typically around 1-2%.

The chain-based technique relied on technology similar to guitar pickups that converted the vibrations in the chain and mathematically converted the signal to the corresponding power. One problem with this model was that there was sometimes interference caused by possible and plausible external noises. Another issue was that the eigenfrequency of the chain is affected by friction, and thus by how well-oiled the chain is. External excitation (riding over a rough road) also had affects on the results.

The technique with the potential of being least expensive was the opposite force based (handheld mounted) technique. One disadvantage of this model was the complexity of the calculations needed to be performed by the system. There was also the issue of the accuracy of wind-speed and inclination of the road, and, most of all, the variation of the drag coefficient of the rider with posture (e.g. sitting upright versus riding in the drops). Results varied significantly and were easily influenced by irrelevant factors.

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[1] Allen, Hunter, and Andrew Coggan. *Training and Racing with a Power Meter*. Boulder, CO: Velo, 2006. Print.

Finally, the most popular technique today is using a system based in the bike's crank set. Power output is measured here using the deflection of strain gauges[2] and the cadence of the pedals. Using one of three calculations to calculate the current torque on the system, power can then be easily determined.[3] There remains a disadvantage in the need of specific crank sets. However, though the total cost of a crank set/device is lower with higher accuracy compared to the other systems, changing the sets for each bike is considered a problem.

One similarity between most all of the devices on the market is that they wirelessly communicate to a display, often a Garmin watch or similar device. The system these devices use has been standardized and is called ANT+. Since 2008, ANT+ has been the accepted standard for short range wireless communication for sports devices. ANT+ runs on the free 2.4GHz band and requires very little power to send and receive information. All devices that support ANT+ have a built in power view, so our device will immediately be supported by a large number of watches and monitors. [4]

Previous IPROs

The previous IPRO 324s have determined the math behind calculating the power, given our system.[5] From their calculations they designed a method of gluing strain gauges to a crankset.[6] They designed a circuit, built it, and designed a layout to fit it onto a Printed Circuit Board (PCB); see Figure 1. Their programmers wrote and rewrote the code to complete the math and communicate with any ANT+ device, though it has proved difficult to get said code to function as intended. Then they began doing stationary tests to determine the correctness and error of the system; see Figure2.

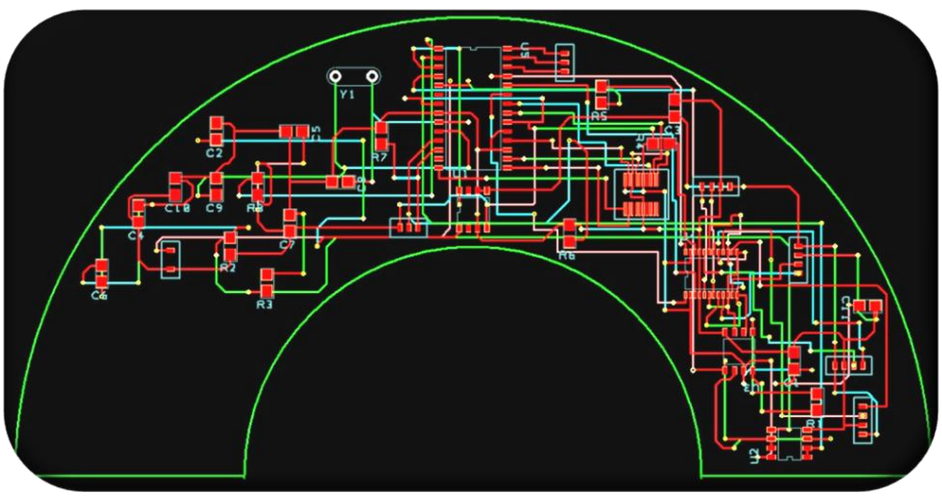


Figure 1: Current Circuit Design

[2] "The Strain Gage." *Sensors, Thermocouple, PLC, Operator Interface, Data Acquisition, RTD*. Web. 10 Sept. 2010. <http://www.omega.com/literature/transactions/volume3/strain2.html>.

[3] Walker, Jearl, David Halliday, and Robert Resnick. *Fundamentals of Physics.* Hoboken, NJ: Wiley, 2008. Print.

[4] Ant, By Using. "What Is ANT+?" *This Is ANT, the Wireless Sensor Network Solution*. Web. 10 Sept. 2010. <http://www.thisisant.com/pages/technology/what-is-ant-plus>.

[5] Gaulin, Nick, and Jeffrey Aigner. Spring 2010 IPRO 324 Data Calculation Documentation. (See **Appendix C**)

[6] Piediscalzi, Yoshio. Strain Gauge Applications. (See **Appendix C**)

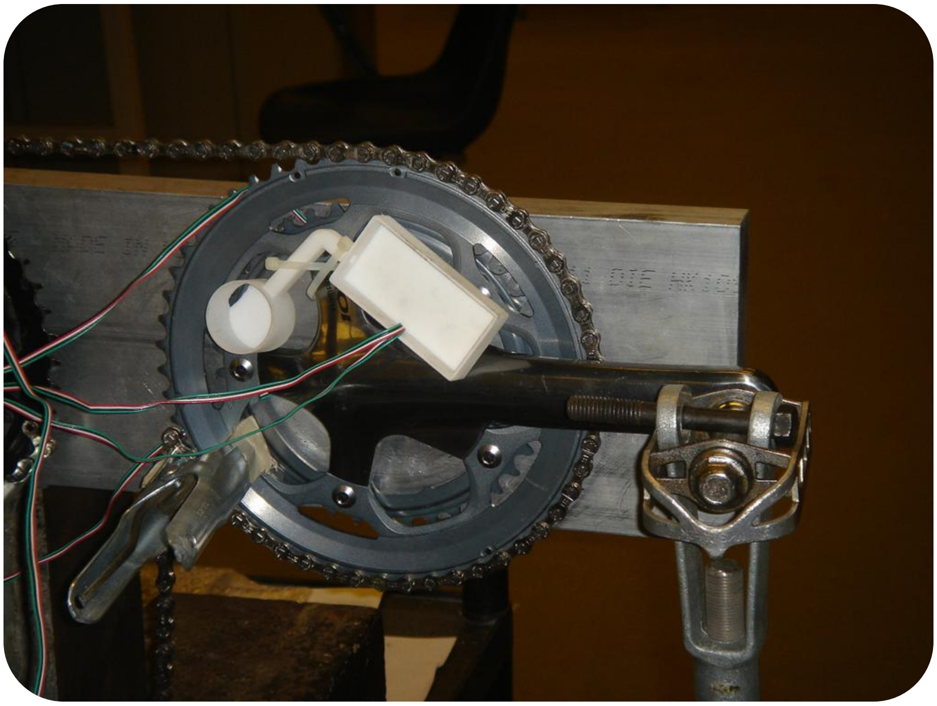


Figure 2: Testing the System

Ethical Considerations

The ethical considerations in this project primarily deal with the safety concerns for the end user. This product will be mounted on bicycles that could be traveling at speeds up to 40 miles per hour, which could have severe consequences for the cyclist if poorly designed. The prototype for this project needs to be extensively tested before it can be operated by an end user.

III. Team Values Statement

Desired Behavior

- Act professionally at all times
- Provide only constructive criticism
- Promptly attend all meetings and actively participate.
- Record detailed documentation on all research and design choices.
- Share all pertinent information with team members via iGroups.
- Be respectful towards one another.
- Fulfill assigned tasks in a timely manner.
- Ask a question when anything is unclear.
- Seek help if when necessary.

Conflict Resolution

In resolving conflict, we will adopt a "Get Over it, Move On" strategy. This method allows for us to overcome obstacles that hurt relationships, in which progress towards our desired goals is hindered. Professionalism and focus on finding solutions to the problems can only be maintained by separating the person from the problem.

The "Get Over it, Move On" strategy follows the following steps:

Get connected – How are you feeling?

Own your "problem" – What are the facts around your "problem"?

Make your decision – Are you willing to release your "problem"?

Opt for action – Let the "problem" go!

Replace the space – Move On with a piece of strength.

In cases where conflict is not resolved, the team will seek the advisor's counsel.[7]

[7] <http://www.execstrategies.com/Facilitator/ConflictResolutionStrategies.htm>

IV. Work Breakdown Structure

The team's primary objectives were determined in the first few meetings. A plan of action and a method for structuring the team was developed during these sessions.

Problem Solving Process

The electrical/programming team must initially build a working model of the current circuit design and become familiar with the ANT+ wireless standard that is currently used. This will provide wireless communication between the circuit and bicycle computer while allowing the mechanical team to perform comprehensive dynamic road testing. To ensure the accuracy of their current power calculation methods, the mechanical team must use a working commercial power measurement system for comparison. A comprehensive analysis of this recorded data must be performed, and more accurate methods must be developed in the event that the current formulae are inadequate. While this analysis is being performed, a final circuit board shall be designed which includes optimized technology and solves any issues encountered during testing. The mechanical team must also develop an aesthetically pleasing case design that fits into a wide variety of cranksets and provides a safe environment to house the circuit. In order to accomplish these tasks, the electrical/programming team must extensively research and understand the current circuit design, while also reading through the ANT+ documentation required to effectively implement this wireless technology into the final circuit. The mechanical team must also develop a more efficient method to quickly and accurately calibrate each system during production to make this product feasible. During this time, the research team will record detailed documentation of these tasks in order to facilitate the passing of this project to future semesters. They will also look into current competitors and the development of their products while conforming to all ethical and professional constraints. The research team will also perform market research to understand the equipment needed for the mechanical and electrical/programming applications to ensure the team stays within the projected budget.

Testing and Documentation Guidelines

All three sub teams are expected to write documentation that explains how they completed their tasks, their results, and their methodology. Documentation must then be uploaded to iGroups so that the other sub teams and future IPROs can understand and replicate the results. Each of the sub teams has further plans on how they are going to test and document their specific tasks.

Mechanical Team

The mechanical team shall complete extensive dynamic road testing to ensure the power calculation methods are both precise and accurate. This data will also be accompanied by a detailed documentation of the tasks performed and the results obtained. The designed casing will also be rigorously tested for reliability when protecting the circuit from both dust and water. Various manufacturing processes will also be tested to develop a more efficient and accurate method of calibrating the mechanical system during production. This method will be outlined in the documentation as well.

Electrical Team

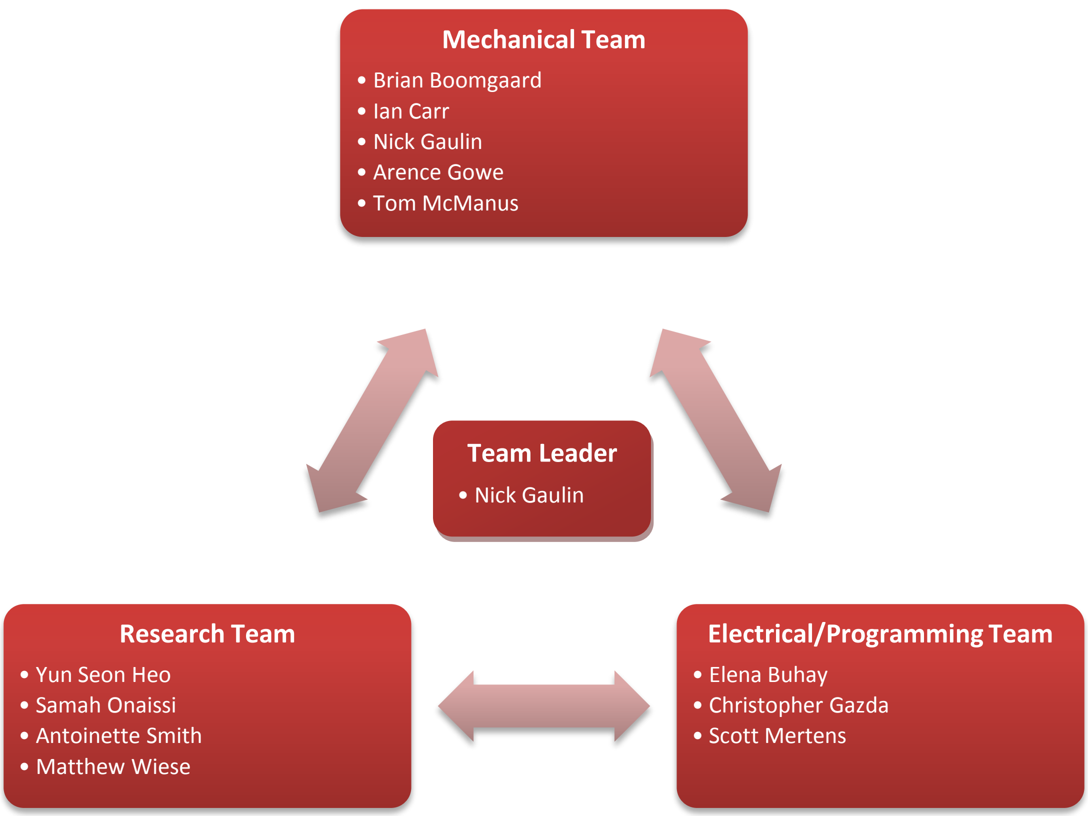
The electrical team must document the design choices used during the development of the circuit. This documentation will consist of the layout made within a circuit building application and the reasoning for the changes from the previous design. The code for the microprocessor will be fully debugged and tested using a logic analyzer, while the code itself will be commented for easy understanding. Comments are also expected to include some reasoning as to why a method of programming was used. Once the wireless communication issues are fixed, the circuit will then be tested again using a bicycle computer to ensure reliability. The results of these tests will also be extensively documented.

Research Team

The research team will stay on top of the mechanical and electrical team's documentation in order to ensure passing on this project for future semesters. They will specifically be looking for understandable documentation and sources. When compiling their market research the research team is expected to try contacting companies as well as using internet and paper sources to determine the product's viability and comparison to other similar products.

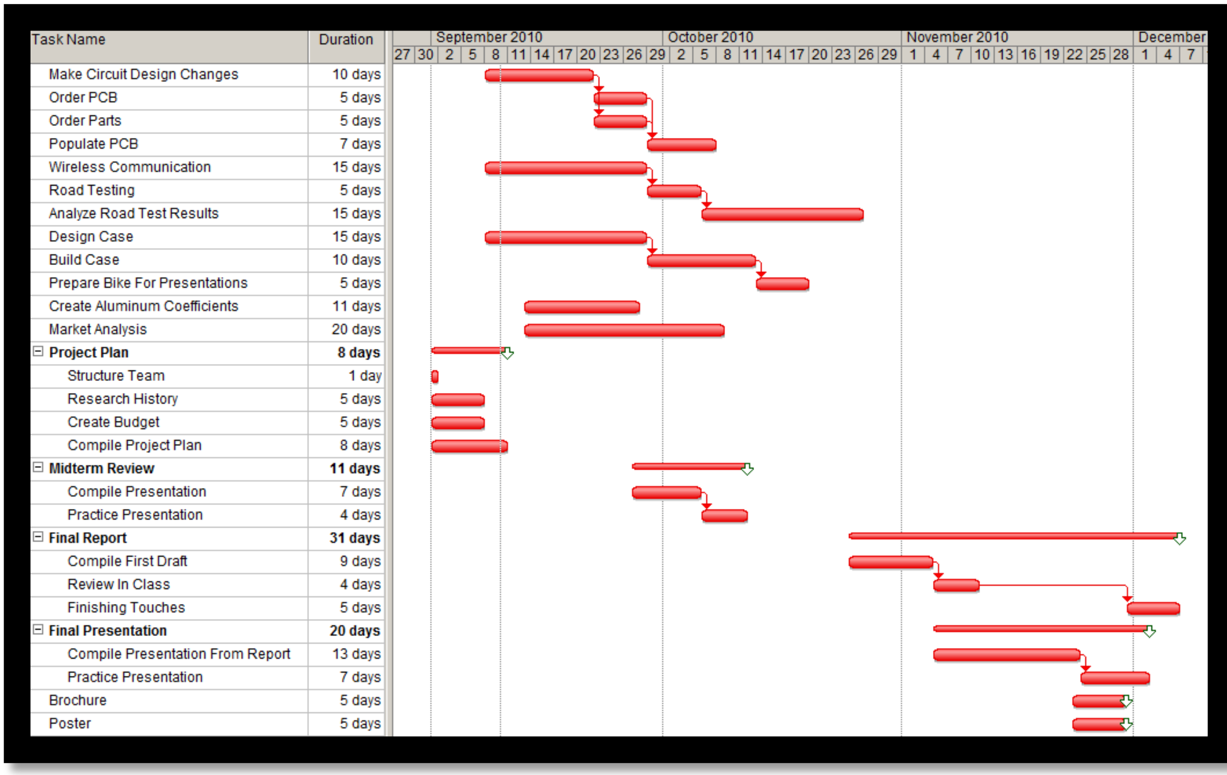
Team Structure

From the primary objectives, the group decided to split into three sub teams: mechanical, research, and electrical/programming. Each team has a subset of tasks that they are expected to complete. See **Distribution of Tasks**. Nick Gaulin was chosen to be the team leader because of his prior experience in this IPRO and his desire to gain leadership experience. Sub team leaders were determined to not be necessary at the time due to the small size of each group. If accountability becomes an issue, sub team leaders will be chosen to help keep group members on task. Most team members could have worked in two or even three of the groups. Therefore it is expected for each group to keep everyone informed of their current tasks to allow other sub team members the ability to assist if they are knowledgeable on a particular subject.



Gantt Chart

See **Appendix B** for more detail.



Distribution of Tasks

Tasks will be appointed to the proper sub team which will further assign each task to the necessary members. When scheduling and estimating the time, for each task, a few weeks of extra time was allotted to account for unforeseen difficulties. All tasks rely on the electrical team to complete the circuit changes in a timely manner so that a prototype can be completed. Until the new circuitry is finished, two circuit boards from last semester will be utilized to run tests and debug wireless communication code. The electrical team must also print the new PCB board and populate it before testing it for reliability. During this time, the mechanical team will perform dynamic road testing of the current system, while also creating a new casing to house the circuit. The research team will also perform a market analysis, order parts, and ensure that deliverables are completed on time.

A more detailed assignment of each task can be seen in **Appendix B**.

V. Expected Results

The electrical team expects to complete the construction of the PCB and the casing within the first few weeks. They will then be attached to a bicycle to perform dynamic road testing. The mechanical team expects the current power calculate methods to be relatively accurate, but must also prepare for the possibility that there are inaccuracies in the current prototype. Since the team is working with a prototype design by students from previous semesters, it can be difficult to infer why certain previous design decisions were made. This will require the team to extensively research and understand the current system, while also making any necessary changes to improve the reliability and performance during the course of the semester. However, the team expects to develop a sound design that builds on the work of these previous iterations and hopes to be successful in delivering an accurate prototype that meets the desired expectations.

VI. Budget

Item	Cost	Description
Printed Circuit Board	$130	A PCB is required to perform dynamic road testing and backups will be necessary in the event the current one is damaged.
Circuit Board Components	$130	Various components will be required to populate the PCBs.
Aluminum Crankset	$130	An aluminum crankset will be required to replace the damaged one from previous semesters.
Pedals	$150	New pedals will be required since the previous semester had to drill through the current ones to perform initial dynamic testing.
Total Cost:	$540	

VII. Designation of Roles

iGroups Moderator: Elena Buhay.

The iGroups Moderator is required to ensure that uploaded files are all placed into their proper folders and to make sure that deliverables are turned into the iKnow Nuggets area of the website.

Agenda Maker: Nick Gaulin.

The Agenda Maker is to prepare agendas for all meetings a day in advance and to upload them to iGroups. Sub teams are expected to notify the Agenda Maker of tasks and issues that they feel should be discussed.

Minutes Taker: Matthew Wiese.

The Minutes Taker is required to take notes on each meeting and upload them into their proper folder on iGroups in a timely manner. Sub teams are also expected to keep track of what occurs in their respective meetings.

VIII. Appendix A

Contact List

Name	Phone Number	Email
Boomgarrd, Brian	[redacted]	bboomgaa@iit.edu
Buhay, Elena	[redacted]	ebuhay@iit.edu
Carr, Ian	[redacted]	icarr@iit.edu
Gaulin, Nick	[redacted]	ngaulin@iit.edu
Gazda, Christopher	[redacted]	cgazda@iit.edu
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Mertens, Scott	[redacted]	smerten1@iit.edu
Onaissi, Samah	[redacted]	sonaissi@iit.edu
Rempfer, Dietmar	[redacted]	rempfer@iit.edu
Smith, Antoinette	[redacted]	smitant@iit.edu
Wiese, Matthew	[redacted]	mwiese@iit.edu

Strengths and Expectations

Boomgaard, Brian has some level of skills related to machining as well as minimal composite layup experience. He can also use CAD competently. He would like to learn how to use more data gathering systems as well as communicate productively and hopes to help this IPRO become a future ENPRO.

Buhay, Elena has computer programming experience in C, circuit experience, and trained presentation skills. She wishes to enhance her programming skills and learn more about cycling and bicycles in general. She expects to develop a finished product that could actually be sold on the market by the end of this semester.

Carr, Ian has extensive knowledge of bicycles and the cycling community. He hopes to apply his interpersonal skills and improve his knowledge of electrical systems. He hopes to learn something that he can apply later in life.

Gaulin, Nick specializes in computer programming and web design. After starting his own software company in 2004, he has developed many applications and websites for a wide variety of businesses in the Northeastern Illinois and Southwestern Missouri areas. His project management skills will be a valuable asset to the team, and he hopes to gain engineering experience from this program.

Gazda, Christopher brings strong circuit design and analysis. He also has strong technical communications skills to offer and hopes to develop his interpersonal communication skills. He hopes to see a fully functional prototype by the end of the semester.

Gowe, Arence has a Mechanical Engineering background, has skills soldering, and knowledge of Electrical Engineering. She hopes to strengthen her team work and communication skills during this project. Her expectations are to develop a working prototype of the power measurement device.

Heo, Yun Seon is a Material Sciences and Engineering major who has intimate knowledge of strain gauges. She hopes to improve on her research skills and help improve inter-team communications.

McManus, Tom is a team player with strong math skills and MATLAB experience. He hopes to learn how to solder, work with strain gauges, and be more efficient in a team. Overall he expects our team to come together and achieve our goal of creating a dynamic testable prototype.

Mertens, Scott has a wide range of skills to offer, including: soldering, research, programming, electrical engineering. He hopes to develop his electronics skills and learn more about bikes. It is his hope to learn how to use and apply strain gauges.

Onaissi, Samah comes to this IPRO with both programming skills and research experience. He intends to develop his communication and presentation skills and hopes to achieve each and every project goal this semester.

Smith, Antoinette has skills in editing, presenting, and programming. She hopes to work on a traditional engineering team in order to relate it to application development.

Wiese, Matthew has skills in programming, research, and design. He hopes to improve his communications skills and gain some experience in working with the ANT+ technology. He hopes to see the group achieve its goals and come together as a whole and succeed in the IPRO.

IX. Appendix B

Gantt Chart Details

Task Name	Duration	Start	Finish
Make Circuit Design Changes	10 days	Wed 9/8/10	Tue 9/21/10
Order PCB	5 days	Wed 9/22/10	Tue 9/28/10
Order Parts	5 days	Wed 9/22/10	Tue 9/28/10
Populate PCB	7 days	Wed 9/29/10	Thu 10/7/10
Wireless Communication	15 days	Wed 9/8/10	Tue 9/28/10
Road Testing	5 days	Wed 9/29/10	Tue 10/5/10
Analyze Road Test Results	15 days	Wed 10/6/10	Tue 10/26/10
Design Case	15 days	Wed 9/8/10	Tue 9/28/10
Build Case	10 days	Wed 9/29/10	Tue 10/12/10
Prepare Bike For Presentations	5 days	Wed 10/13/10	Tue 10/19/10
Create Aluminum Coefficients	11 days	Mon 9/13/10	Mon 9/27/10
Market Analysis	20 days	Mon 9/13/10	Fri 10/8/10
Project Plan	8 days	Wed 9/1/10	Fri 9/10/10
Structure Team	1 day	Wed 9/1/10	Wed 9/1/10
Research History	5 days	Wed 9/1/10	Tue 9/7/10
Create Budget	5 days	Wed 9/1/10	Tue 9/7/10
Compile Project Plan	8 days	Wed 9/1/10	Fri 9/10/10
Midterm Review	11 days	Mon 9/27/10	Mon 10/11/10
Compile Presentation	7 days	Mon 9/27/10	Tue 10/5/10
Practice Presentation	4 days	Wed 10/6/10	Mon 10/11/10
Final Report	31 days	Mon 10/25/10	Mon 12/6/10
Compile First Draft	9 days	Mon 10/25/10	Thu 11/4/10
Review In Class	4 days	Fri 11/5/10	Wed 11/10/10
Finishing Touches	5 days	Tue 11/30/10	Mon 12/6/10
Final Presentation	20 days	Fri 11/5/10	Thu 12/2/10
Compile Presentation From Report	13 days	Fri 11/5/10	Tue 11/23/10
Practice Presentation	7 days	Wed 11/24/10	Thu 12/2/10
Brochure	5 days	Tue 11/23/10	Mon 11/29/10
Poster	5 days	Tue 11/23/10	Mon 11/29/10

Summary of Tasks

Make Circuit Design Changes - Christopher Gazda is in charge of reworking the circuit board design to both make it more reliable and to add a feature to make it easier to install the device.

Order PCB - The research team will use last year's recommendations and order PCB(s) as soon as their design is finished.

Order Parts - As Christopher Gazda needs parts to build the circuit board the Research team is in charge of making sure he gets what he needs as quickly as possible.

Populate PCB - Scott Mertens and Christopher Gazda are in charge of soldering components to the PCB(s).

Wireless Communication - Elena Buhay is tasked with fixing the C code and documenting her changes and findings.

Road Testing - The Mechanical team is in charge of running tests once wireless communication is fixed. Tests will be conducted both indoors and outdoors, in varying weather and track conditions.

Analyze Road Test Results - Once the Mechanical team has finished gathering their data, they will work on finding the correctness and percent error our device has.

Design Case - Ian Carr and Brian Boomgaard are to design a casing for our finalized PCB to fit into.

Build Case - Once the case has been designed Ian Carr and Brian Boomgaard will get it printed in 3D.

Prepare Bike For Presentations - Once we have a PCB and case created we will prepare our bike for presentation and double check everything.

Create Aluminum Coefficients – The Material team will work on determining the coefficients needed when using an aluminum crankset.

Market Analysis - The Research team will be working on a market analysis to see the viability of our product.

***Project Plan** - Due 9/10/10*

Structure Team - The entire team worked together to split into sub teams and elect a leader. Research History - Samah Onaissi and Matthew Wiese worked on looking into the history of cycling power measuring devices and what previous iterations of IPRO 324 completed.

Create Budget - The entire team with worked together to determine what we need to complete our goals.

Compile Project Plan - The rough draft of the Project Plan was completed by the Research team and was reviewed by the entire team.

Midterm Review *- Due 10/11/10*

Compile Presentation - The Research team will monitor what the other teams have completed and put together a presentation.

Practice Presentation - The entire team will practice presenting and answering questions for the Midterm Review.

Final Report *- Due 12/6/10*

Compile First Draft - Each sub team will be tasked with compiling a summary of what they completed and learned. The Research team will then flesh out the rest of the rough draft.

Review In Class - The rough draft will be reviewed and fixed by the entire team.

Finishing Touches - The final touches be completed by the Research team.

Final Presentation *- Due 12/2/10*

Compile Presentation From Report - From the final report the Research team will put together a presentation. The entire team will then help review and fix the presentation.

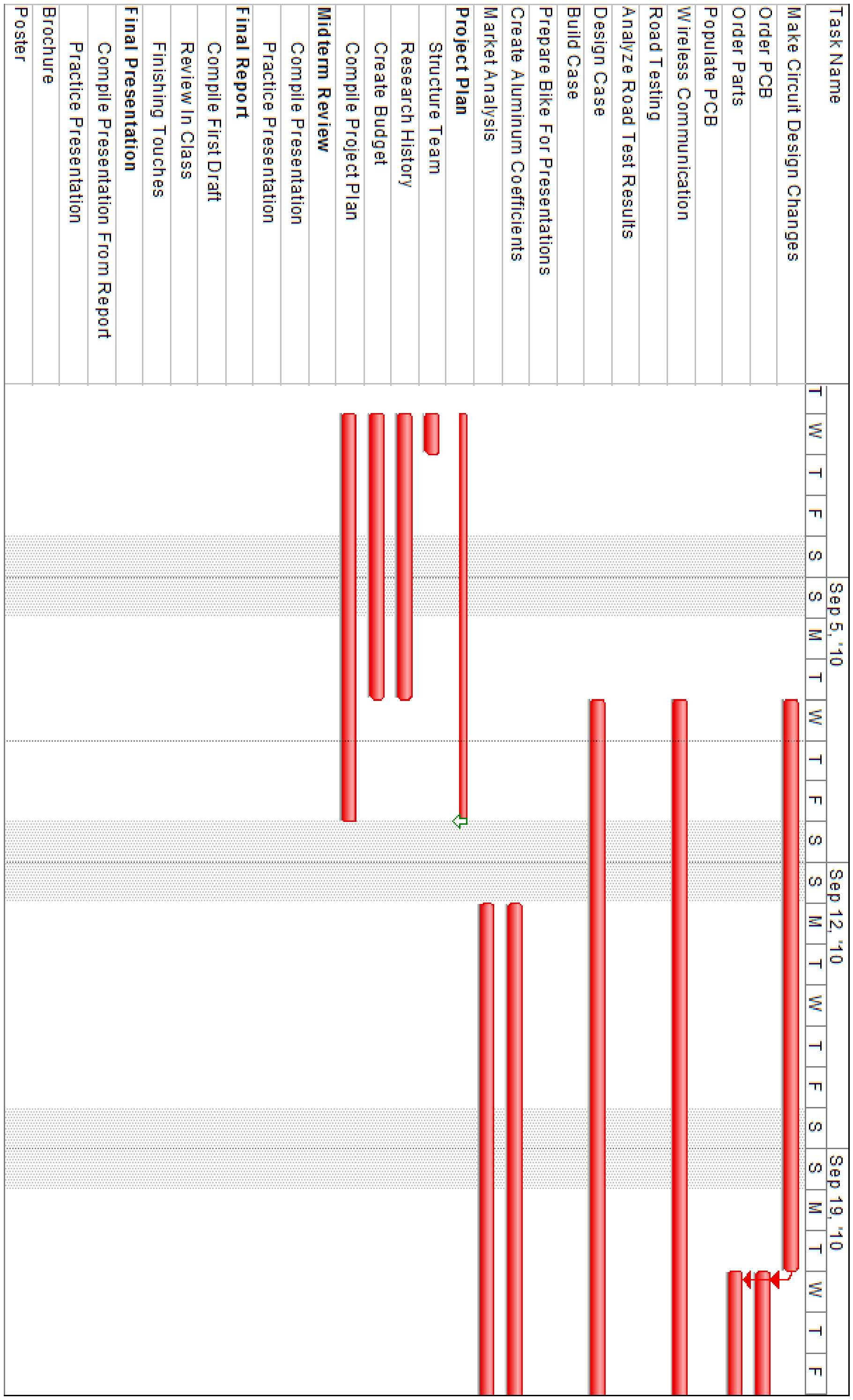
Practice Presentation - The entire team will practice presenting and answering questions for the Final Presentation.

Brochure *- Due 11/29/10* The Research team and possibly the other sub teams will help take the final presentation and make a brochure.

Poster *- Due 11/29/10* The Research team and possibly the other sub teams will help take the final presentation and make a poster.

*(**Italics** denote Milestones)*

Gantt Chart


Task Name
Make Circuit Design Changes
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Populate PCB
Wireless Communication
Road Testing
Analyze Road Test Results
Design Case
Build Case
Prepare Bike For Presentations
Create Aluminum Coefficients
Market Analysis
Project Plan
Structure Team
Research History
Create Budget
Compile Project Plan
Midterm Review
Compile Preview
Practice Presentation
Final Report
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Review In Class
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Compile Presentation From Report
Practice Presentation
Brochure
Poster
Sep 5, '10
Sep 12, '10
Sep 19, '10
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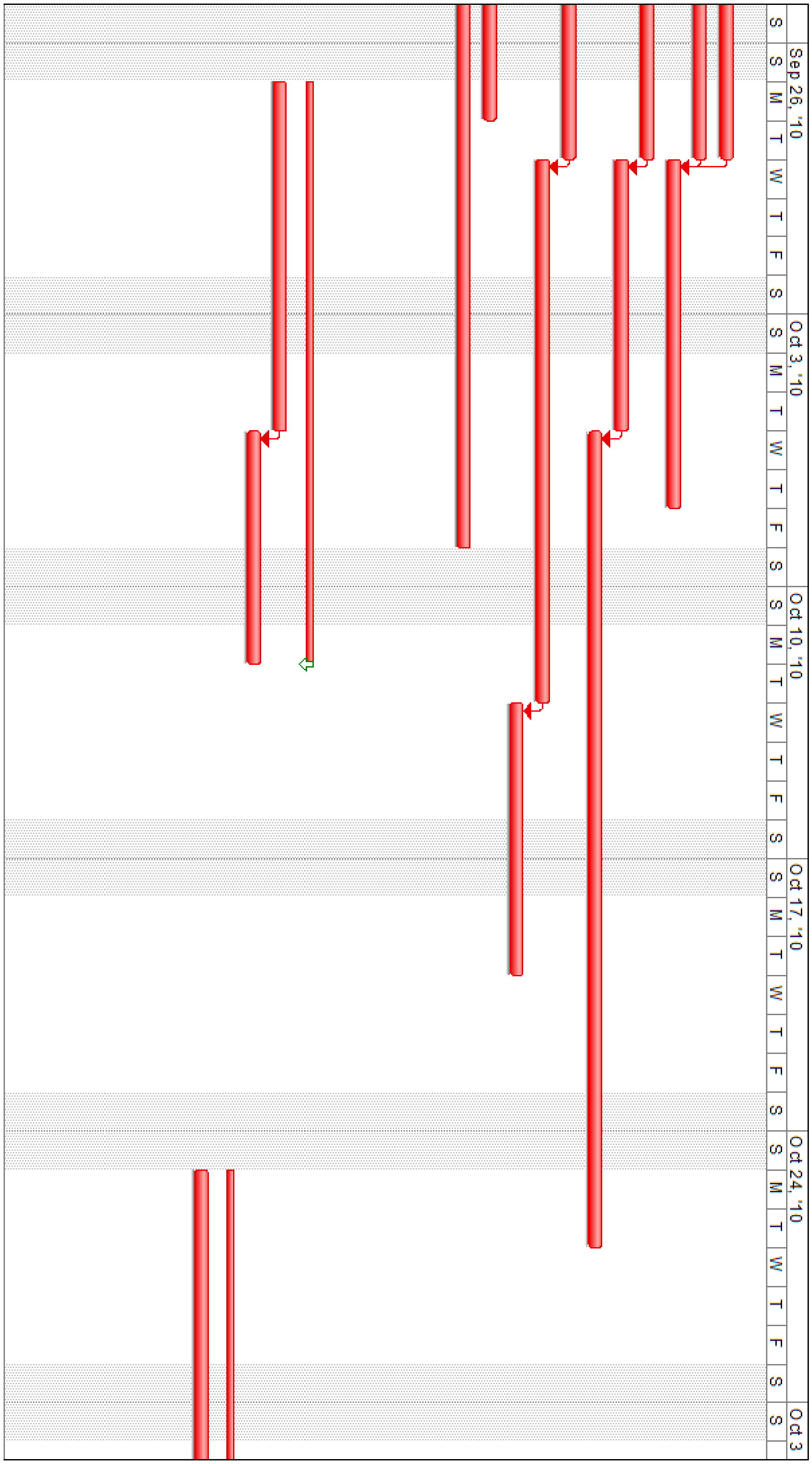
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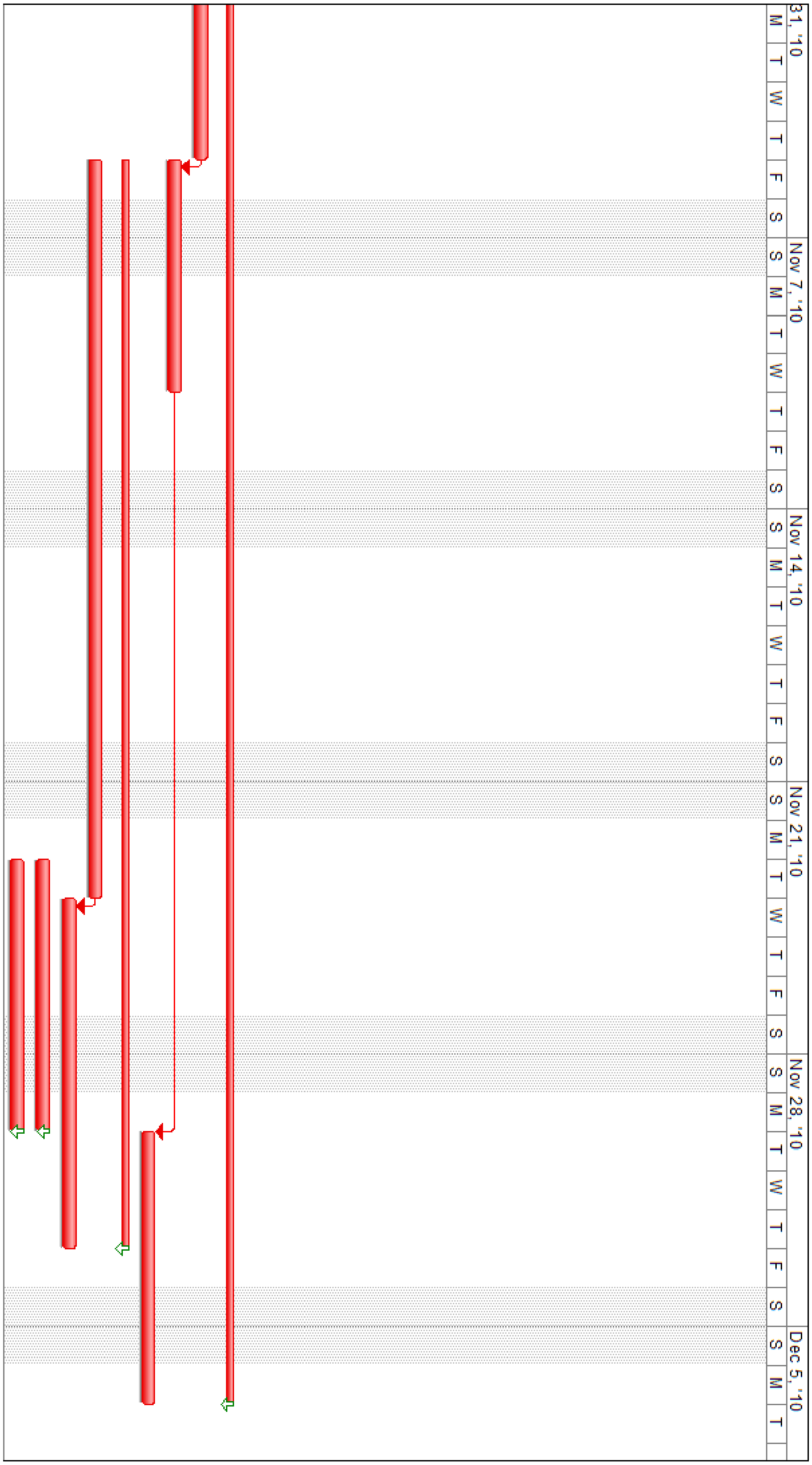
Oct 24, '10
Oct 3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X. Appendix C

Spring 2010 IPRO 324 Data Calculation Documentation

There are currently three independent methods to calculate various coefficients for our bicycle crankset:

System of Equations

When two independent channels are used in a system of equations, coefficients can be calculated to fit the data between the large and small chain rings. Using arbitrary channels a and b, two equations can be formulated which express the torques exerted on both the large and small chainrings. Since the strains on both channels a and b are unknown, two coefficients can be calculated to make the set of equations true. This system is given by the following equations:

$$C_1 \varepsilon_{a_{large}} + C_2 \varepsilon_{b_{large}} = T_{large}$$

$$C_1 \varepsilon_{a_{small}} + C_2 \varepsilon_{b_{small}} = T_{small}$$

The coefficients for this system of equations can easily be calculated using Cramer's rule. However, since data was collected at various torques, the coefficients for each set of data must be averaged in order to accurately calculate these values at arbitrary strains. Once a range of torques has been selected, the starting and ending torques can be defined as T_S and T_E respectively. The following equation is then used to calculate the two final coefficients at a defined angle:

$$C = \frac{1}{T_E - T_S + 1} \sum_{n=T_S}^{T_E} \left(\begin{bmatrix} \varepsilon_{n,a_{large}} & \varepsilon_{n,b_{large}} \\ \varepsilon_{n,a_{small}} & \varepsilon_{n,b_{small}} \end{bmatrix}^{-1} \begin{bmatrix} T_{n_{large}} \\ T_{n_{small}} \end{bmatrix} \right)$$

These coefficients are then used in the following equation to calculate the torque for arbitrary strains on defined channels a and b at a defined angle:

$$T_{calc} = C_1 \varepsilon_a + C_2 \varepsilon_b$$

This method is very efficient because the calculated coefficients apply to both the large and small chain ring. Averaging the coefficients over the variable torque range appears to produce minimal error as well. The only downfall of this system is that it does not utilize all of the available channels.

Parallel Derivatives

It is known that the relationship between the torque and strain at a defined angle is linear, and also that zero strain will result in zero torque, causing a plot of this data to intersect at the origin. Therefore, one can easily multiply an arbitrary strain for a defined chain ring by the slope of this graph to acquire the unknown torque, as seen in the following equation:

$$C_n = \frac{dT}{d\varepsilon_n}$$

Using this derivative, the slope of each channel can be calculated to achieve a set of n coefficients. To minimize error, a range of torques can also be selected with which to calculate this slope. If each channel is treated as a resistor in a parallel electrical circuit, an overall coefficient can be calculated using the following equation:

$$C = \frac{1}{\sum C_n^{-1}}$$

The final coefficient can then be simplified and expressed in terms of torque and strain as seen in the following equation:

$$C = \left(\sum \frac{d\varepsilon_n}{dT}\right)^{-1}$$

This coefficient is then used in the following equation to calculate the torque for arbitrary strains on each channel at a defined angle:

$$T_{calc} = C \sum \varepsilon_n$$

This method is very accurate because it factors in each available channel. Also, since all strains are added together, any channel that is more sensitive or produces higher values will have a greater effect on the final calculation. The only downfall of this method is that the coefficient is calculated for a known chain ring, and does not apply to both like the system of equations method.

Equation Fitting

When plotting the relationship between angle and strain for an arbitrary weight, a graph resembling two parabolic arches exists. These parabolas intersect at an angle equal to 180 degrees, and can be approximated by two polynomial equations. Staying within the reference frame of either above or below 180 degrees, two polynomial equations can approximate the maximum strain and a reference strain at an arbitrary angle in the reference range as seen in the following equations:

$$\varepsilon_{max} = a_1\theta^6 + a_2\theta^5 + a_3\theta^4 + a_4\theta^3 + a_5\theta^2 + a_6\theta + a_7$$

$$\varepsilon_{ref} = b_1\theta^6 + b_2\theta^5 + b_3\theta^4 + b_4\theta^3 + b_5\theta^2 + b_6\theta + b_7$$

This will provide two sets of two polynomial equations for the angles above 180 degrees and the angles below 180 degrees. Then, since the relationship between strain and weight is linear, these two polynomial equations within each set can be linearly interpolated for an arbitrary strain using an equation of the following format:

$$W_{calc} = \frac{W_{max} - W_{ref}}{\varepsilon_{max} - \varepsilon_{ref}}\left(\varepsilon - \varepsilon_{ref}\right) + W_{ref}$$

This weight can finally be used to calculate the torque for an arbitrary strain and arbitrary angle within the reference range as seen in the following equation:

$$T_{calc} = grW_{calc}\sin\theta$$

Two three-dimensional equations for angles above 180 degrees and below 180 degrees with two variables of angle and strain have now been formulated. However, these equations can be further simplified and combined by solving for a constant angle. This will provide two coefficients that can be calculated using the following format:

$$C = gr\sin\theta \begin{bmatrix} \dfrac{W_{max} - W_{ref}}{\varepsilon_{max} - \varepsilon_{ref}} \\ W_{ref} - \varepsilon_{ref}\dfrac{W_{max} - W_{ref}}{\varepsilon_{max} - \varepsilon_{ref}} \end{bmatrix}$$

These coefficients can then be used to calculate the torque for an arbitrary strain at a known angle using the following equation:

$$T_{calc} = C_1\varepsilon + C_2$$

This method is useful because it can be utilized to calculate a torque for an arbitrary angle and an arbitrary strain. Also, since a polynomial is being approximated for the strain at an arbitrary angle, small errors in measurements will be averaged out. One of the downfalls of this method is due to the fact that only a single channel is used for data. Another problem with this method is that the coefficient is calculated for a known chain ring, and does not apply to both like the system of equations method.

Strain Gage Application

1. Prepare the Surface
   a. Add mild acid (Phosphoric acid-red top bottle in student kit) to the end of 400-grit sandpaper. Shake of the excess acid on the sandpaper. Sand the surface. Sand an area slightly larger than the strain gage.
   b. Use gauze and wipe from the center, of the sanded surface, out to one side, then fold the gauze and wipe from the center to the other side of the sanded surface. Be sure to throw away the gauze.
   c. Add mild acid to a Q-tip. Shake of the excess acid. Clean the surface in a circular motion with the Q-tip. Start from the center and work way out. If the Q-tip gets too dirty, throw it away and continue process with new Q-tip.
   d. Repeat step b
   e. Add neutralizer (Ammonia water-blue top bottle in student kit) to a Q-tip. Shake of the excess. Clean the surface in a circular motion. Start from the center and work way out.
   f. Repeat step b
2. Gage Preparation
   a. Add neutralizer to a piece of gauze. Clean the surface of the plastic strain gage case with the gauze.
   b. Use gauze and wipe from the center out to one side, then fold the gauze and wipe from the center to the other side.
   c. Use tweezers to take gage out of its package. Grab near the soldering points. Carefully place on the top of the case. Do the same for the soldering tabs.
3. Gluing
   a. Take about a 2-inch piece of Mylar tape.
   b. Stick one end of the tape next to the gage.
   c. Slide thumb firmly and quickly along the tape over the gage. This is done to avoid static electricity.
   d. Peel the tape slowly, at a very low angle to the case, until it is past the gage. Then pull the rest of the tape off.
   e. Apply the strain gage to the sanded surface. Peel the tape back slowly similarly to step d. Peel just past the gage.
   f. Apply a very thin layer of drying catalyst (Xylene in student kit) to the bottom surface of the strain gage. Before applying to the strain gage wipe the brush of the catalyst on the top of the jar 10 times. Then apply the catalyst to the bottom of the strain gage. Let this dry for 1 minute on the strain gage.
   g. Place 1 drop of super glue on the sanded surface directly beneath the strain gage. Then quickly run thumb firmly over the tape and gage. Press and hold for approximately 1 minute. A piece of gauze should be used to do this so hands do not get super glue on them. (There is better glue that can be used for longer life)
   h. Peel off the tape back onto itself. Peel off at an angle of almost 180 degrees.
   i. Cover the gage completely with a piece of Mylar tape until ready for soldering.
   j. Once ready for soldering, peel off the tape and reapply so that one edge just overlaps the soldering points.