Power Measurement for Performance Bicycles
IPRO 324 – Final Project Report

iitorque

Integrated Intelligent Torque Measurement System

“No Strain, No Gain”

Executive Summary

Over the course of the fall 2010 semester, IPRO 324 worked towards the production of a working prototype of a bicycle power meter. The power meter would need to be more accurate and more affordable than what is currently available in the market. In addition, the circuit responsible for communication between the power meter and the bike computer needed to be reworked and improved to allow for easier wireless communication. Included within this report are the methods and results of the fall semester IPRO along with final recommendations for next semester's IPRO.

Purpose and Objectives

The IPRO 324 team worked to develop a system that utilizes strain gauges to measure the applied torque on the crankset of a bicycle. The overall goal was 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 in which the cyclist has invested significant money, and can still be relatively inaccurate.

Therefore, our task was to find optimal configuration settings of strain gauges that could 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 would 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 required extensive testing with regards to accuracy and environmental stability, as well as mechanical and electromagnetic effects. A reduction in power consumption of the current electronic processing unit was also desired. Ideally, a standard CR2032 lithium battery cell would be able to power the unit over an acceptable operating time on the order of a few hundred hours.

An improved encasement also needed to be developed for the complete system that allowed functioning in a realistic environment (i.e. susceptible to dust and water). In addition, 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 desired 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.

To this end, our major objectives were as follows:

- 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.

Organization and Approach

Mechanical Team

As a small group, organization consisted of a division of tasks as opposed to a division of roles. Tasks such as making and maintaining contacts in the Idea Shop and with outside sponsors was one necessary role, with others consisting of case design and much of the analytical peripherals associated with the device while in a non-wireless configuration. These roles were not strict in their definition as many times tasks were assigned based on time constraints rather than perceived roles. The approach used was one of continuing the previous process while attempting to incorporate facilitation of future goals as well.

Electrical Team

The electrical and programming team decided to try and pick up where last semester left off. The previous semester had a circuit and a complementary program for it. The team decided to extensively comment the program and study the ANT+ protocol. The electrical team then took the time to take the circuit from the previous semester and improve and redesign it to work more efficiently. By redesigning the circuit, the electrical team managed to get wireless communication to work to a degree.

Research Team

The research team decided to stay current on the progress of the lab work taking place, documenting the progress of both the electrical and mechanical teams. Also, the research team studied the target market for the product the IPRO team has been working on. Moreover, a website was developed to publish the progress of the project and also in an aim to advertise the product. In addition, the research team worked on setting up and filming our IPRO video.

Analysis and Findings

Mechanical Team

The mechanical team continued where last semester left off as we had a continuing member. As some new members had backgrounds in cycling an amount of insight was available as to how our project compared to other products currently on the market. This allowed further understanding of the value of power data and to what extent of accuracy was necessary. A new casing design was constructed, and eventually integrated with the reed switch arrangement from the previous semester.

It was decided halfway through the semester that the mechanical team must have the ability to concurrently work on their dynamic testing while the electrical team designed a new circuit. This required the use of a slip-ring which was the same setup as last semester. To overcome the limitations of the previous slip-ring however, a new 10-connection slip-ring was acquired free-of-charge from Michigan Scientific. This allowed all the required data to be collected through the slip-ring to effectively calculate power through the use of LabView software.

Initially, power calculations appeared quite inaccurate, and it was discovered that a time averaging scheme was required to have decent values. Further use of exponential smoothing was used to create a steady power reading without various spiking that appeared similar to that observed on the Garmin.

Electrical Team

The electrical and programming team found after six weeks of learning the ANT+ protocol and attempting to understand the previous semester's code and circuit to start from scratch. With limited time remaining the team decided to attempt communication using sensRcore a special mode on the ANT+ wireless chip that allows easy to program communications. A test circuit for ANT+ communication was developed and our program using sensRcore was developed and debugged. Communicating with the Garmin was still not possible and the team was contacting support and requesting previous semester's assistance. Going back once more to the basics of sensRcore but using the guide left by the previous semester the team managed some form of contact with the Garmin device. After some difficulties and more research this communication was found to be a 'glitch' in the Garmin's programming. This discovery lead to the realization that sensRcore cannot communicate with a Garmin device.

With only one month left in the IPRO the electrical team decided that we could either have wireless communication by the end of the semester or start work on adapting what we had finished for the next semester. Continuing on the current path the electrical and programming team finished their circuit and programmed an interface for ANT+ communication to be received by a computer. The interface will allow for data to be collected and stored in an easy to use fashion for later evaluation.

Research Team

The research team conducted a survey that focused on exploiting the needs of the targeted market. The survey was sent to regional biking clubs around the Chicago Metro Area, and it confirmed the thoughts of the IPRO team about the priorities a biker looks for in buying a product, price, and measurement accuracy.

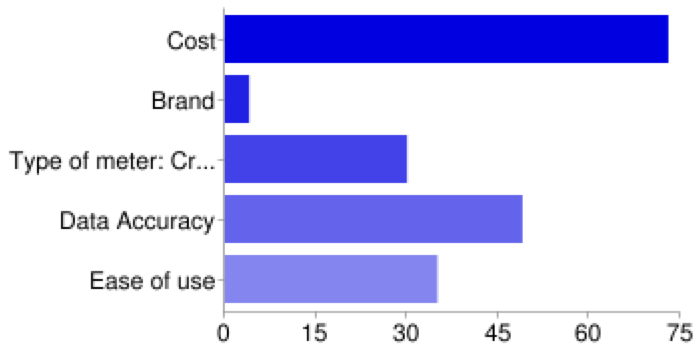


Figure 1: Factors in choosing a power meter

The survey also showed that bikers in this area, and due to the weather, are willing to send their crank sets in to get retrofitted during the months of the winter season.

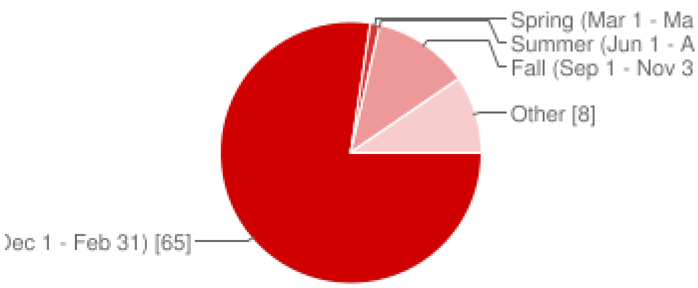


Figure 2: Times of year cyclists could be without their bikes

Conclusions and Recommendations

Mechanical Team

Conclusions

Progress consisted of further refining methods in which to gather data accurately while using the device in a slip-ring configuration. An interface developed using Lab View allowing acquisition and analysis of data was developed will be an asset to future teams.

Recommendations

Future tasks consist of further refining methods in which to determine coefficients used to determine power output as well as developing methods to securely seal and attach the casing to the crankset. In regards to determining coefficients possibly analyzing the style of the force imparted by a cyclist and mimicking it to an extent would allow for increased accuracy. Priorities should be placed upon developing a product that is capable to being user serviced after the initial installation of the strain gauges.

Electrical Team

Conclusions

The goal of having ANT+ communication between the Garmin and our device was not accomplished, but rather was defined and simplified. The new circuit allows for less logic to be programmed into the microprocessor and thus will allow the code used in the next semester to be legible. Wireless communication was achieved however between a computer and our device, allowing for a simpler data collection.

As the circuit was being tested we realized that the ANT+ communication was easily disrupted by distance and objects being between the transmitter and the receiver. Further the time between transmissions was found to be too small, this was partially fixed by adding a smoothing algorithm to the results on the ANT+ circuit. These fine tunings can easily be accomplished in the new program that will have to be written by next semester's members.

Recommendations

The electrical and programming team recommends that the next semester forges ahead with the simpler circuit and adds a microprocessor to it. The microprocessor will then allow a relatively simple program to output the data with the formatting needed by a Garmin device.

Research Team

Conclusions

Our most profound conclusion is that a market does exist for this product. It was encouraging to find that brand loyalty does not exist, thus we can be competitive on the attributes we desire most: accuracy and affordability.

Recommendations

Next semester's non-electrical and non-mechanical members will likely find themselves lacking in things to do. However, the most important contribution these members can make is in the realm of project management and preparation for a continuation of this IPRO as an EndPRO, the only logical next step. Suggested tasks and roles for these members are:

- Overall team leadership
    - Allocation of resources
    - Coordination and completion of project deliverables
- Conduct formal marketing analyses based on this semesters data
    - Bonus: Extend survey to regions outside of the Chicago area
    - EVC analysis
    - Conjoint analysis
    - Cost analysis
- Determine steps necessary for mass production of such a product

Appendices

Budget

Item	*Price*
Powertap	$750.00
Magnets	$11.40
Muxers	$18.80
	$780.20

Table 1: Budget for current semester

Team Members

- Boomgaard, Brian
- Buhay, Elena
- Carr, Ian
- Gaulin, Nick
- Gazda, Christopher
- Gowe, Arence
- Heo, Yun Seon
- McManus, Tom
- Mertens, Scott
- Onaissi, Samah
- Smith, Antoinette
- Wiese, Matthew

Survey Access

The survey was hosted as a Google doc. It can be found by logging into Google Docs with the IPRO 324 Gmail account. Login information can be found in iGroups files for fall 2010 under the website folder.

Mechanics

Strain Gauge Application

1. Surface Preparation
   1.1. Add a mild phosphoric acid (red bottle) to a small piece of 400-grit sandpaper. Shake off the excess acid and proceed to sand an area slightly larger than the strain gauge in a circular motion.
   1.2. Wipe the sanded area with a small piece of gauze. Be sure to wipe from the center of the sanded area outward. After each wipe, fold the gauze so a clean side is visible to prevent contamination. Once completed, throw the gauze away.

1.3. Add a mild phosphoric acid to a Q-tip. Shake off the excess acid and proceed to clean the surface in a circular motion. Start from the center and work your way outwards. If the Q-tip becomes excessively dirty, use a new one.

1.4. Repeat 1.2

1.5. Add a neutralizer such as ammonia water (blue bottle) to a Q-tip. Shake off the excess neutralizer and proceed to clean the surface in a circular motion. Start from the center and work your way outwards.

1.6. Repeat 1.2

2. Gauge Preparation

2.1. Add a neutralizer such as ammonia water to a piece of gauze. Shake off the excess neutralizer and proceed to clean the top surface of the plastic strain gauge casing.

2.2. Wipe the top surface of the plastic casing with another small piece of gauze. Be sure to wipe from the center of the plastic casing outward. After each wipe, fold the gauze so a clean side is visible to prevent contamination. Once completed, throw the gauze away.

2.3. Remove the gauge from the packaging with a small pair of tweezers. Be sure to grab the gauge from the soldering points, and carefully place it on the cleaned area on top of the plastic casing.

3. Gauge Application

3.1. Take a 2 inch piece of Mylar tape and apply one end to the plastic casing near the gauge. While holding the end, quickly slide your thumb across the tape and over the gauge to prevent static electricity.

3.2. Using a small angle of around 15 degrees to ensure the gauge remains firmly on the tape, slowly peel the tape off of the plastic casing.

3.3. Place the gauge in your desired location. Once properly positioned, slowly peel the tape back at a small angle of around 15 degrees to ensure the gauge remains firmly on the tape. Be sure not to fully remove the tape from the surface as this will change the orientation from your initial position.

3.4. Apply a very thin layer of drying catalyst such as xylene to the bottom surface of the gauge with a single pass. Before application, be sure to wipe the brush of the catalyst on the top of the jar at least ten times. Once applied, allow one minute for the catalyst to dry.

3.5. Apply one drop of super glue on the sanded surface where the strain gauge will be applied. Once completed, quickly place the gauge onto the super glue using a sliding motion with your thumb. Using a piece of gauze, press and hold the gauge in place for approximately one minute.

3.6. Using a large angle of around 170 degrees to ensure the gauge does not remain on the tape, slowly peel the tape off of the gauge. Be sure to completely cover the gauge with a new piece of tape until ready for soldering.

3.7. Once ready to solder, apply a new piece of tape to cover the gauge leaving the soldering tips exposed.

Strain Gauge Soldering

1. Prepare the wires.
   1.1. Cut sets of eight wires to the exact same length for each Wheatstone bridge.
   1.2. Strip both ends of each wire by placing each end between the soldering tip and the solder until the wire is in a drop of solder.
   1.3. Wait for the solder to melt the insulation and then trim the exposed wire to the length of the tab it shall be applied to.
2. Clean the surfaces to be soldered with an eraser to remove any oxide layers.
3. Apply a small amount of flux to the surface to be soldered.
4. Apply a bead of solder to the strain gauge tabs and to the wiring junction tabs.
5. Solder one end of each wire to the strain gauges and the other end to the wiring junction.
   5.1. Be sure to first solder either the tension or compression strain gauges.
   5.2. Ensure the resistances are correct.
      5.2.1. Two tabs connected to one strain gauge should give the resistance of that strain gauge.
      5.2.2. Two tabs connected to different strain gauges should give an infinite resistance.
6. Apply an epoxy to the first set of wires to ensure they stay in place while applying the second set.
   6.1. Ensure the resistances are correct. Either the resistance of the strain gauge should be observed, or a resistance given by the following equation:

$$\left(\frac{1}{R}+\frac{1}{3R}\right)^{-1} \tag{1}$$

7. Apply an epoxy to the second set of wires.
8. Solder the red, white, black, and green wire to the wiring junction. Be sure to secure it as well to prevent the wiring junction from being pulled off.

Coefficient Calculations

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 chainrings. 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:

$$C_1\varepsilon_{a_{large}} + C_2\varepsilon_{b_{large}} = T_{large} \tag{2}$$

$$C_1\varepsilon_{a_{small}} + C_2\varepsilon_{b_{small}} = T_{small} \tag{3}$$

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:

$$C = \frac{1}{T_E - T_S + 1} \sum_{n=T_S}^{T_E} \left(\begin{bmatrix} \varepsilon_{n,a_{large}} & \varepsilon_{n,b_{large}} \\ \varepsilon_{n,a_{small}} & \varepsilon_{n,b_{small}} \end{bmatrix}^{-1} \begin{bmatrix} T_{n_{large}} \\ T_{n_{small}} \end{bmatrix} \right) \tag{4}$$

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:

$$T_{calc} = C_1 \varepsilon_a + C_2 \varepsilon_b \tag{5}$$

This method is very efficient because the calculated coefficients apply to both the large and small chainring. 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 chainring by the slope of this graph to acquire the unknown torque, as seen in the following equation:

$$C_n = \frac{dT}{d\varepsilon_n} \tag{6}$$

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:

$$C = \frac{1}{\sum C_n^{-1}} \tag{7}$$

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

$$C = \left(\sum \frac{d\varepsilon_n}{dT} \right)^{-1} \tag{8}$$

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

$$T_{calc} = C \sum \varepsilon_n \tag{9}$$

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 chainring, 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:

$$\varepsilon_{max} = a_1\theta^6 + a_2\theta^5 + a_3\theta^4 + a_4\theta^3 + a_5\theta^2 + a_6\theta + a_7 \quad (10)$$

$$\varepsilon_{ref} = b_1\theta^6 + b_2\theta^5 + b_3\theta^4 + b_4\theta^3 + b_5\theta^2 + b_6\theta + b_7 \quad (11)$$

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:

$$W_{calc} = \frac{W_{max}-W_{ref}}{\varepsilon_{max}-\varepsilon_{ref}}\left(\varepsilon - \varepsilon_{ref}\right) + W_{ref} \quad (12)$$

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:

$$T_{calc} = grW_{calc}\sin\theta \quad (13)$$

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:

$$C = gr\sin\theta \begin{bmatrix} \frac{W_{max}-W_{ref}}{\varepsilon_{max}-\varepsilon_{ref}} \\ W_{ref} - \varepsilon_{ref}\frac{W_{max}-W_{ref}}{\varepsilon_{max}-\varepsilon_{ref}} \end{bmatrix} \quad (14)$$

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

$$T_{calc} = C_1\varepsilon + C_2 \quad (15)$$

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 chainring, and does not apply to both like the system of equations method.

Power Calculations

Using the previous coefficients to calculate torque, power can be calculated as the product of torque and angular velocity as seen in the following equation:

$$P_{calc} = T_{calc}\omega_{calc} \quad (16)$$

To calculate this angular velocity, the time interval between two reed switches is required, and then used in the following equation:

$$\omega_{calc} = \frac{\pi}{4t} \quad (17)$$

When recording these power values during testing, a graph similar to the following will be observed:

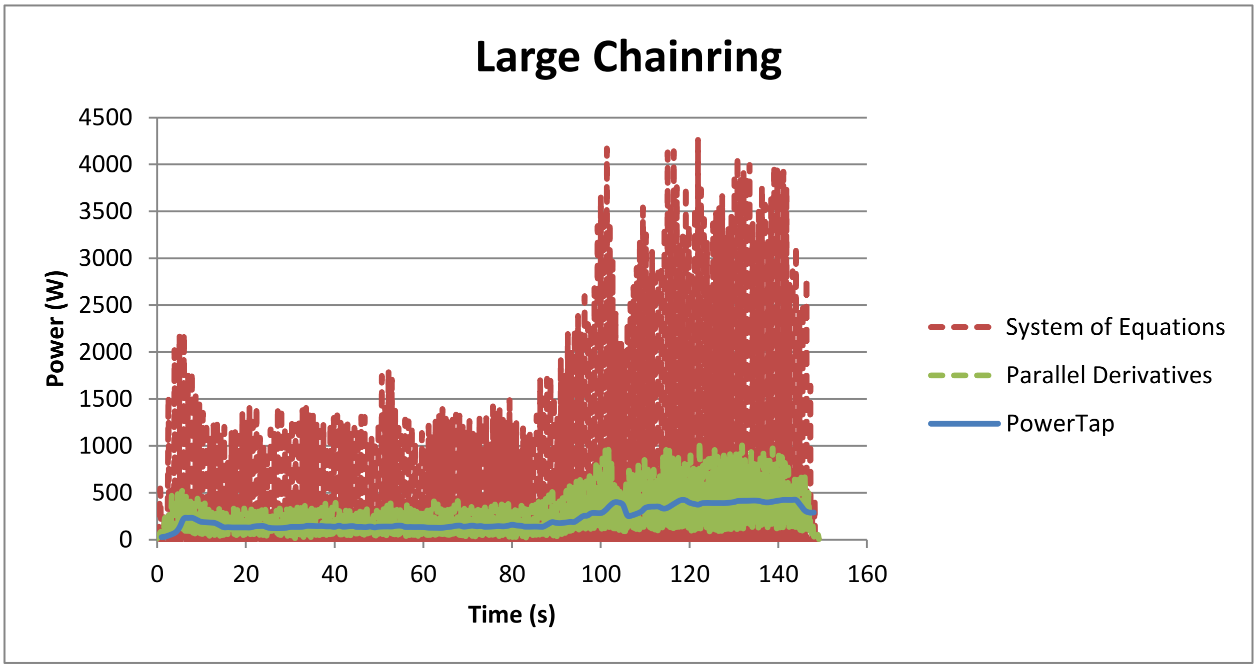


Chart 1: Raw power data

These oscillating power values are due to the fact that a high value of power is calculated at angles parallel to the ground level, while relatively small or sometimes negative power values are obtained at angles that are perpendicular to ground level. To obtain values that are within a relative range of what a commercial product would produce, they must be time averaged using the following equation:

$$P_{calc,avg} = \frac{\sum_{j=i-n}^{i} P_{calc,j}}{n} \quad (18)$$

In this equation, n corresponds to the interval of time averaging, and i is the current power value. An interval value in the range of 10 – 30 is acceptable, however selecting a multiple of 8 seems to make the most sense since this is the number of values collected per revolution. After applying a time averaging scheme with an interval of 24 to the data in chart (1), the following graph is obtained:

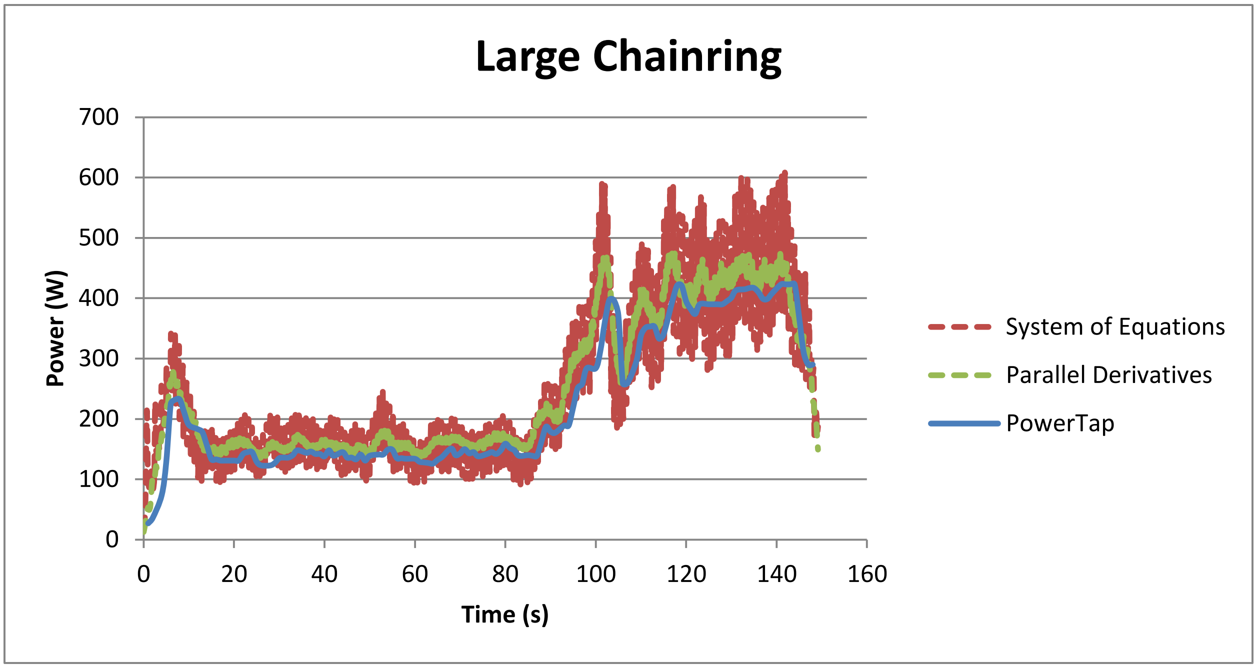


Chart 2: Power data after application of time averaging

These values are now within an acceptable range of what a commercial product would produce, but oscillations would still exist for even long durations of refreshing when displayed on a head-unit. To create a steady value that does not jump around, exponential smoothing can be applied to the data using the following equation:

$$P_{calc,smooth} = \alpha P_{calc,smooth_{i-1}} + (1-\alpha)P_{calc,avg} \tag{19}$$

In this equation, α is defined as the dampening factor, which is always within the range of 0 – 1. A separate dampening factor must be applied to the system of equations method and the parallel derivatives method. By inspection, this is due to the fact that even after a time averaging scheme, the system of equations method inherently produces a much larger oscillation than the parallel derivatives method, and therefore requires more smoothing. Relatively high dampening factors are required to produce commercial values, generally above 0.9, which corresponds to a factor of 90%. After the application of this exponential smoothing, the final power calculations will appear similar to that in the following graph:

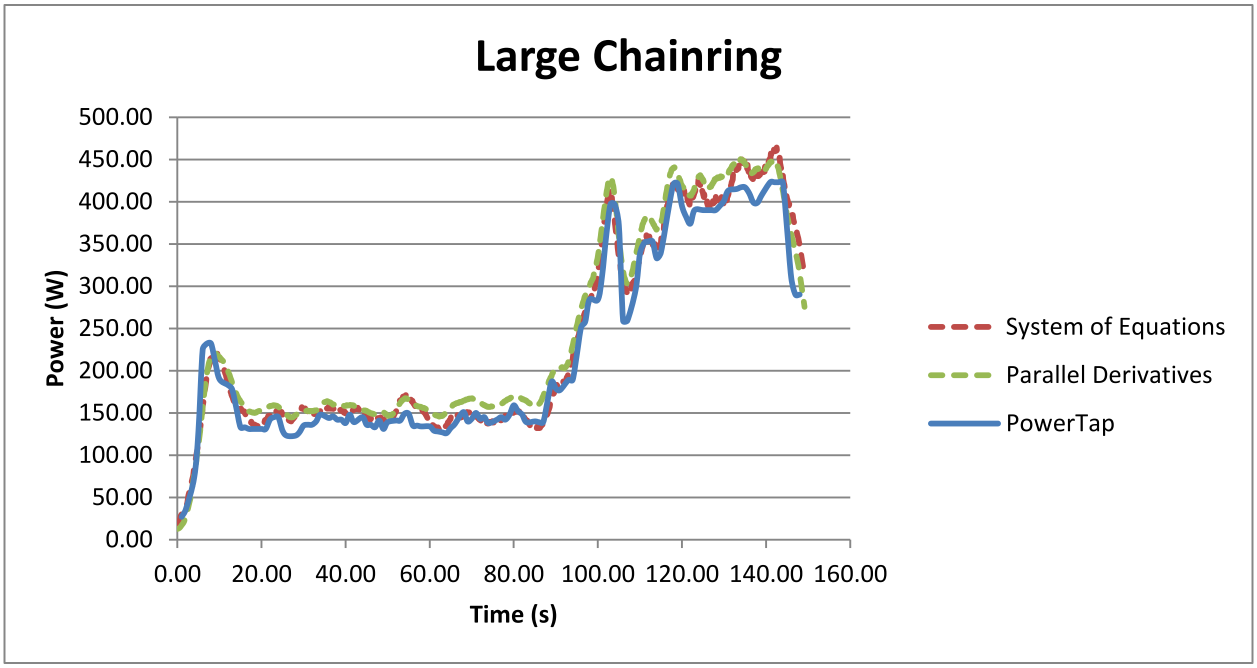


Chart 3: Power data after application of exponential smoothing

Utilizing these methods to calculate power, along with precise and accurate measurements during coefficient calculations will produce values that are generally within 5% of those obtained using a commercial product. The inclusion of more strain bridges can then produce an increasingly higher accuracy. It should be noted that from initial observations, the parallel derivatives method consistently produced viable power values due to the equations utilized in the method. The slope correlating strain to torque will always produce a positive value, which will consequently provide positive calculations for power. The system of equations method on the other hand, seems to produce extremely random results, which greatly depend on the initial measurements. Generally speaking, one coefficient will be positive, while the other will be negative in order to compensate. This is due to the inherent nature of Gaussian elimination when solving systems of linear equations, and must be revised into a new method that produces only positive coefficients. When linearizing the data before calculating coefficients using the system of equations method, extremely large coefficients were encountered, which ended up producing only negative values of power. This was due to the encounter of large negative coefficients at angles that produced a majority of the torque. It is suggested that the best direction to take would be further use of the parallel derivatives method. Coefficients calculated between the large and small chainrings are relatively close to each other, and could simply be averaged to produce accurate power readings that are applicable to both chainrings. Another possible method that should be investigated would be the use of the equation fitting method, along with an averaging scheme between various bridges that produces accurate values.

Circuitry

Overview

The circuit functions by taking inputs from two strain gauge bridges and eight reed switches. An analog torque signal is generated from the strain bridge signals. An analog speed (cadence) signal is generated from the eight reed switches. An analog power signal is then generated by using the torque and speed signals as inputs. The power signal then becomes the input to the ANT+ microprocessor which outputs it wirelessly.

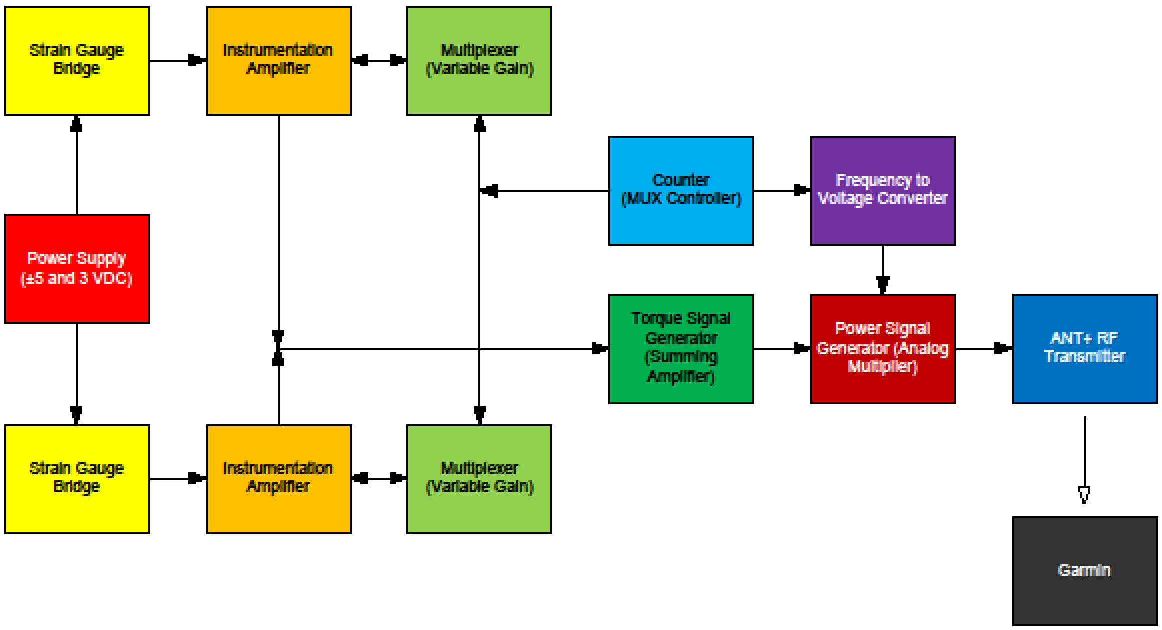


Figure 3: Circuit diagram

Reed Switch Signal Conditioning

The switches are used for two separate functions. The first is to be an input for the speed signal generator. The second is to determine the position of the crankset relative to the zero position (first switch triggered). The position is important because the gain of the strain gauge amplifiers is dependent on position. A multiplexer is used for each strain bridge to provide gain selection. As a result, a counter is needed to control the multiplexers. The switches are the inputs to this counter.

The eight reed switches are connected to the counter used for multiplexer control such that seven are wired in parallel and are active low (they pull up when open) while the remaining one switch is active high (pulls down when open). The single switch generates a RESET signal. The seven parallel switches cause the count to advance once per switch closure. A chart of the control signals is shown below for reference:

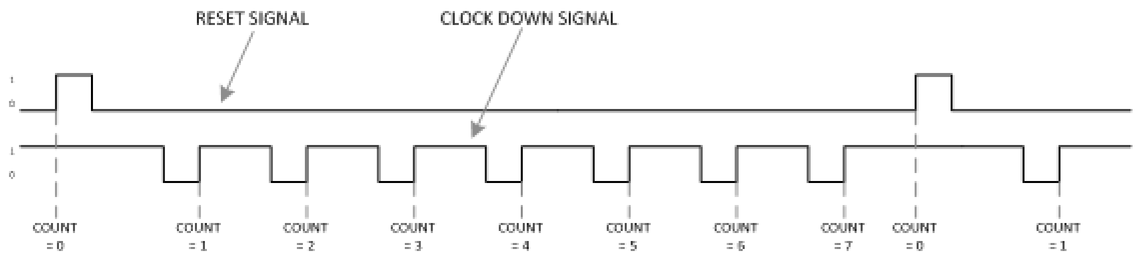


Figure 4: Control signals

It should be noted that the count is advanced and reset using positive edge triggering. Thus the counter is reset when the single switch makes closure. Conversely the count is advanced when one of the seven parallel-wired switches breaks closure.

The three least significant bits of a four-bit binary counter are then used as control (select) signals for the multiplexers. The least significant bit of the counter is used as the input to the speed signal generator as it incorporates all eight switches. It should be noted that the frequency of the least significant bit is half that of all eight switches. This is not significant because the speed signal must be scaled appropriately anyway.

Torque Signal Generator

Torque is the sum of the individual bridge signals, and each bridge requires a different gain at each of the eight switch positions. An instrument amplifier is used for each strain bridge. Gain is set on the instrument amplifier by resistance across two of its pins. These two pins are wired to an analog multiplexer which allows one of eight potentiometers to be selected. Potentiometers are used for this development circuit because they allow for easy adjustment. The analog multiplexers are controlled by the counter described above.

Another instrument amplifier is used to perform the arithmetic operation of summation of the signals. This is done by connecting the excitation voltage opposite on the second bridge. This inverts the output signal. Since an instrument amplifier is differential, it takes the difference of the first signal and the inverted second signal, producing an output which is the sum of the two inputs. The gain of the summation amplifier is set to unity, and scaling is accomplished by limiting the gains selected by the multiplexer. The torque signal is limited in this manner to approximately 3 volts.

It should be noted that each bridge signal is bipolar, and thus the sum signal can be bipolar. In normal operation (pedaling forward) the torque signal is not anticipated to be negative. Operation in reverse may produce a negative signal, which is not compatible with the power signal generator as it utilizes one-quadrant multiplication. This has not been investigated, as reverse pedaling is not considered to be important.

Speed Signal Generator

The speed (cadence) of the bicycle is measured by using the input of the reed switches after it has been properly conditioned. This produces a signal whose frequency is proportional to bicycle speed. A circuit has been created which first measures half of the period (switch on-time). This section generates a signal proportional to the period of the input signal. That signal is inversely proportional to frequency and thus must be linearized. A graph of the intermediate (half of the period) signal and the linearized output signal is shown below for reference:

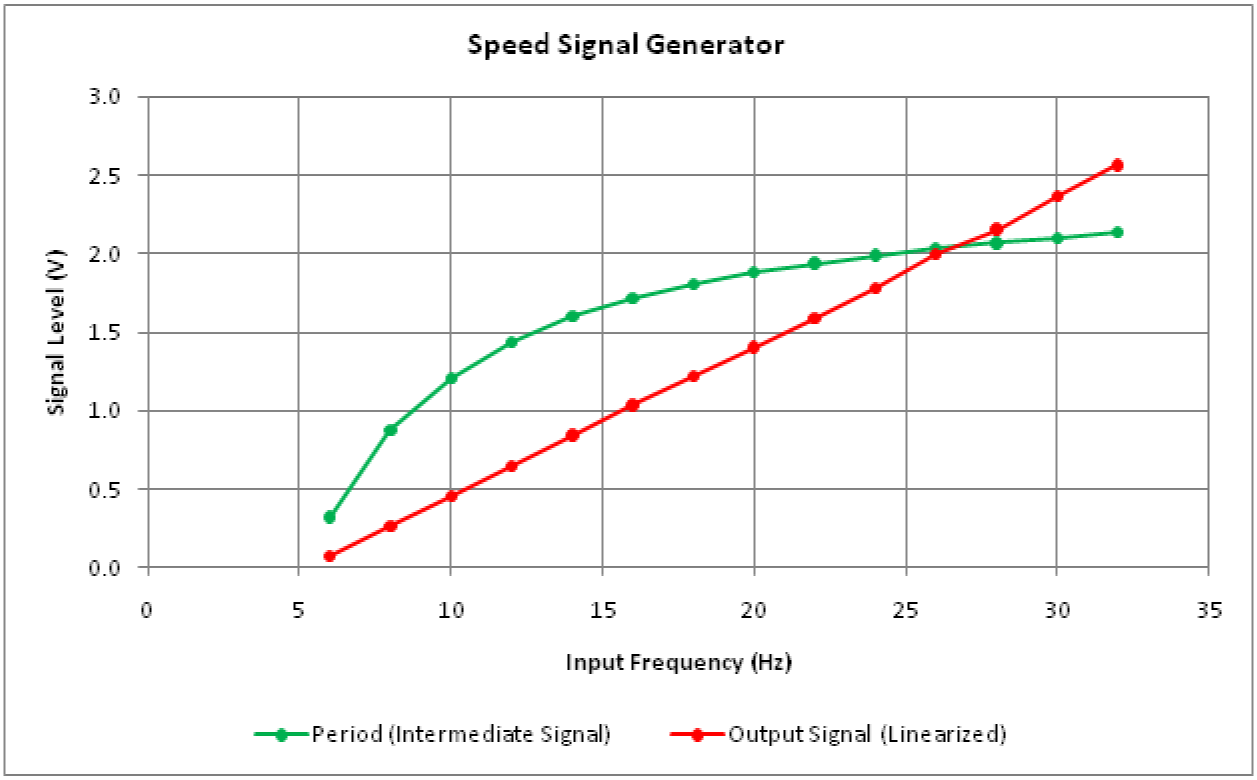


Chart 4: Speed Signal Generator

Measuring the period is accomplished by assuming the duty cycle of the input to be constant. Thus measuring the on-time of the signal is equivalent to measuring the entire period of the signal as long as scaling is considered. A base clock has been created by using a binary ripple counter with built-in oscillator. Selecting the proper output of the ripple counter determines the frequency of the base clock, and thus the measuring range of the input signal is adjustable. The base clock is run against the input signal and the number of base clock counts during the on-time of the input is measured. Two four-bit binary counters are cascaded to give eight-bit resolution of the input signal. The counter is designed to count down, since fewer counts correspond to a smaller period, and thus a higher frequency. Also, when 'reset' the counters actually reset to all 1's by loading the binary value of 1 to each bit.

Since the intermediate period signal appears as a binary word across the outputs of the cascaded counters, a digital-to-analog converter (D/A) is employed to produce an analog signal. The count on the counters is only accurate after a full on-time. As a result, the D/A must be disabled during counting so that it never outputs an inaccurate count. This is accomplished by a finite state machine.

A finite state machine (FSM) is employed to reset the counters and enable the D/A. The FSM has three states: count, sample and hold. During the count state, the counters are active and the count advances on each pulse of the base clock. The D/A is disabled during the count state. The FSM moves to the sample state after the count state. During the sample state the counters are inactive, but their output is accurate, and so the D/A is enabled and outputs an accurate voltage signal. Next the FSM moves to the load state. The D/A is disabled, and the counters are reset to all 1's by enabling their load pins. The FSM then moves back to the count state and repeats the process cyclically. The state diagram for the FSM is shown below for reference:

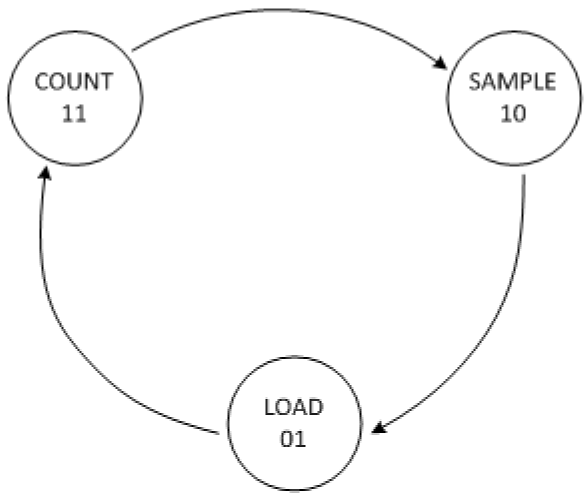


Figure 5: State diagram for the FSM

The FSM is implemented by using two JK flip-flops. The input frequency generated by the counter of the reed switch conditioner is used as the clock signal for the flip-flops. The states are chosen carefully such that no additional combinational logic is required to produce the output signals. The output of the first flip-flop is used as the load signal for the two counters and the output of the second flip-flop is used to enable the D/A.

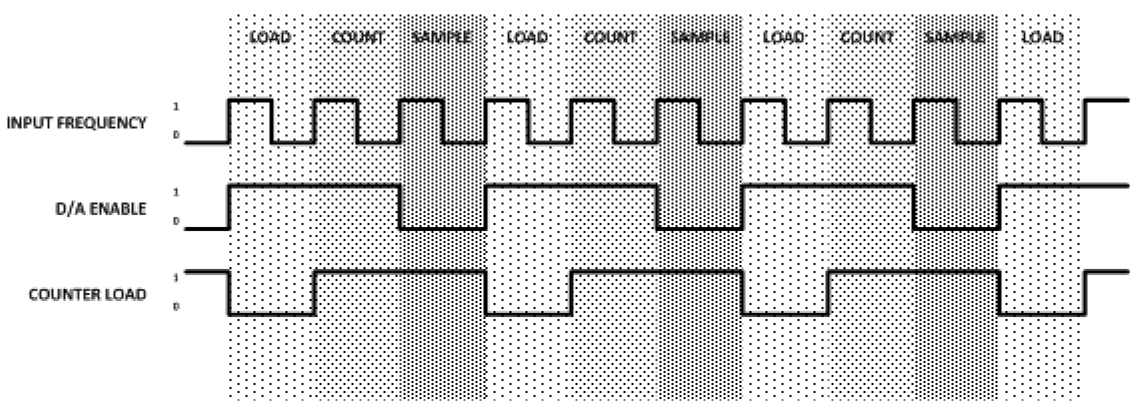


Figure 6: Speed signal

The scale of the D/A output is set to 2.55V. The period signal is converted to the speed signal by the following equation:

$$Speed\ Signal = \frac{Period\ Signal}{2.55 - Period\ Signal} \tag{20}$$

This is implemented by using an analog computational unit configured as a divider. The output of the divider is the speed signal, which is proportional to the input frequency.

Power Signal Generator

Since power is defined to be the product of speed and torque, the power signal is generated by multiplication of the torque signal and speed signal. This is implemented with another analog computational unit, this time configured as a multiplier. It should be noted that when configured as a multiplier only one quadrant multiplication is possible. This means that both input signals must be positive. The output of the speed signal generator can only be positive; however the torque signal can be negative. This would result in erroneous output of the power signal generator. It should also be noted that the power signal is scaled by half, since the input of the ANT+ module must be unipolar and limited to 3 volts.

Diagrams

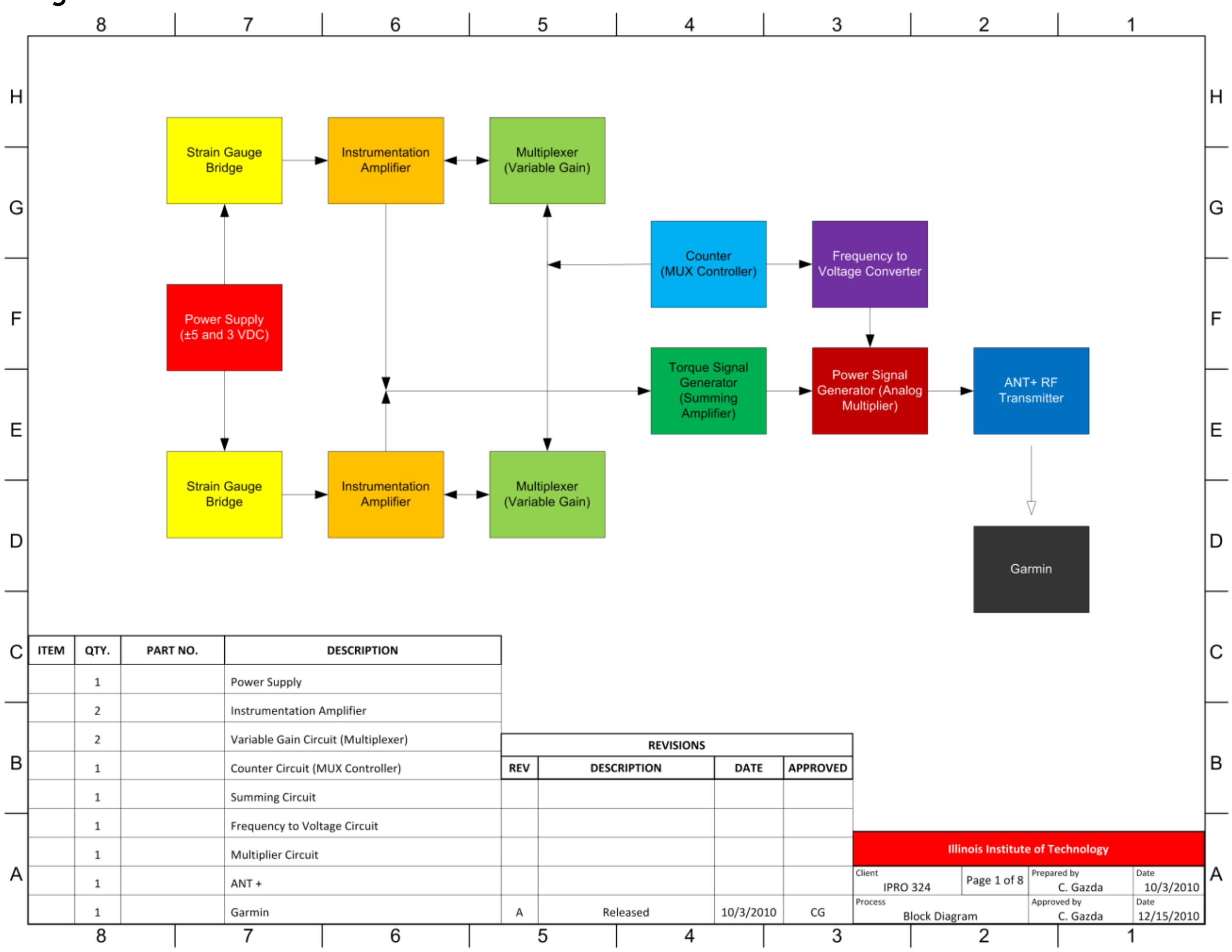
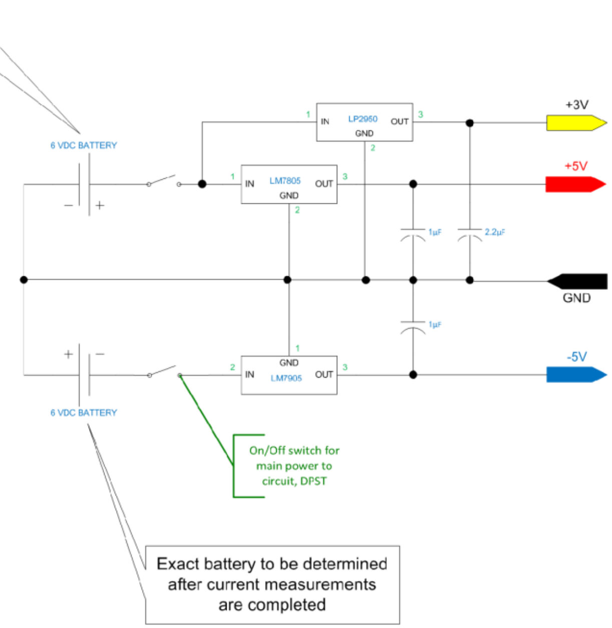


Figure 7: Circuit Diagrams



ITEM	QTY.	PART NO.	DESCRIPTION
	1	LM7805	5-Volt Positive Voltage Regualtor
	1	LM7905	5-Volt Negative Voltage Regulator
	1	LP2950CZ-3.0	3-Volt Positive Voltage Regulator
	2		1µF Ceramic Capacitor
	1		2.2µF Tantalum Capacitor
			Lithium Ion Battery
			Lithium Ion Battery
	1		DPST Switch

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
B	Added 3-Volt Regulator	11/4/2010	CG
A	Released	9/13/2010	CG

Illinois Institute of Technology

Client: IPRO 324	Page 2 of 8	Prepared by: C. Gazda	Date: 9/3/2010
Process: Power Supply (±5 and 3 Volt)		Approved by: C. Gazda	Date: 12/15/2010

Figure 8: Circuit Diagrams

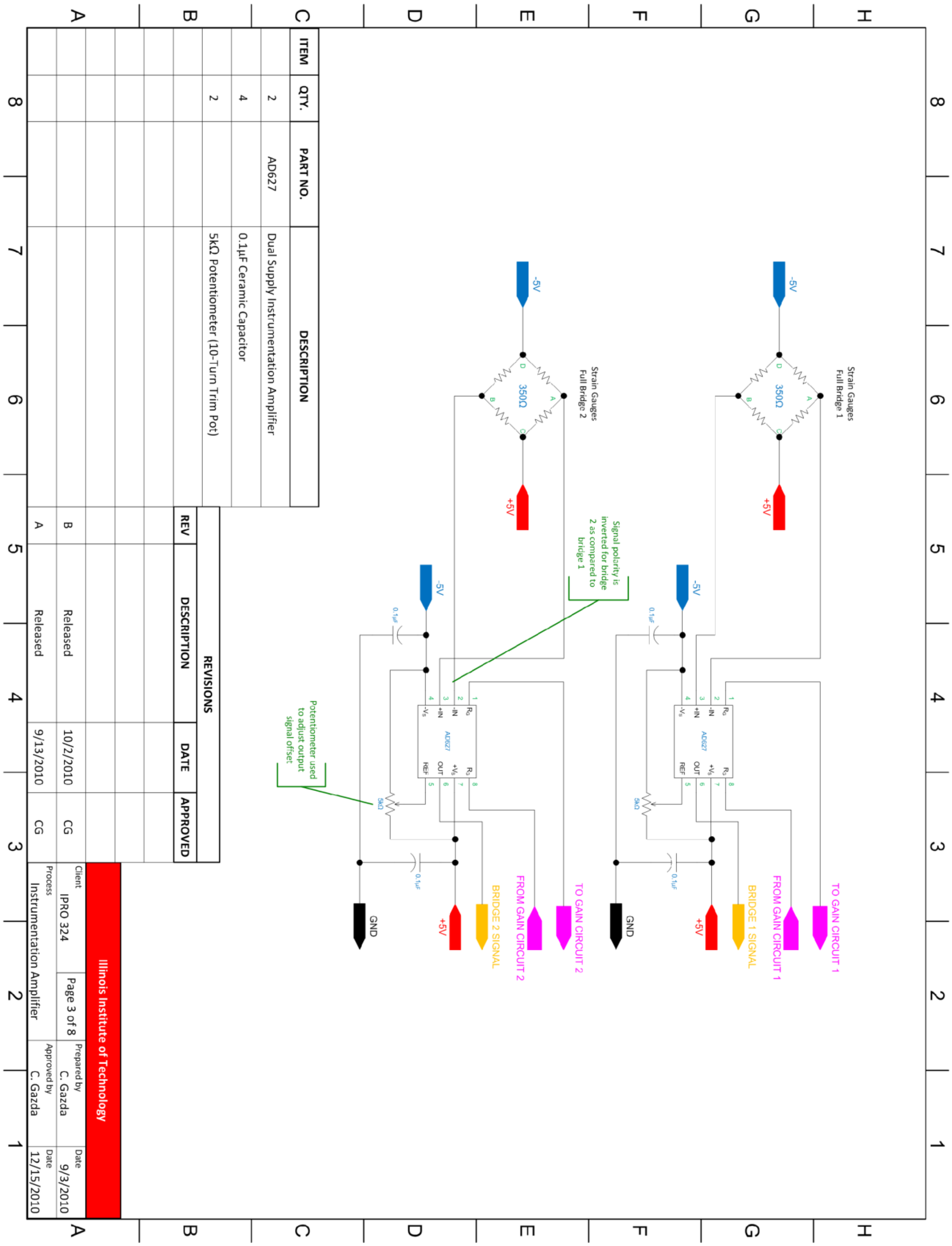


Figure 9: Circuit Diagrams

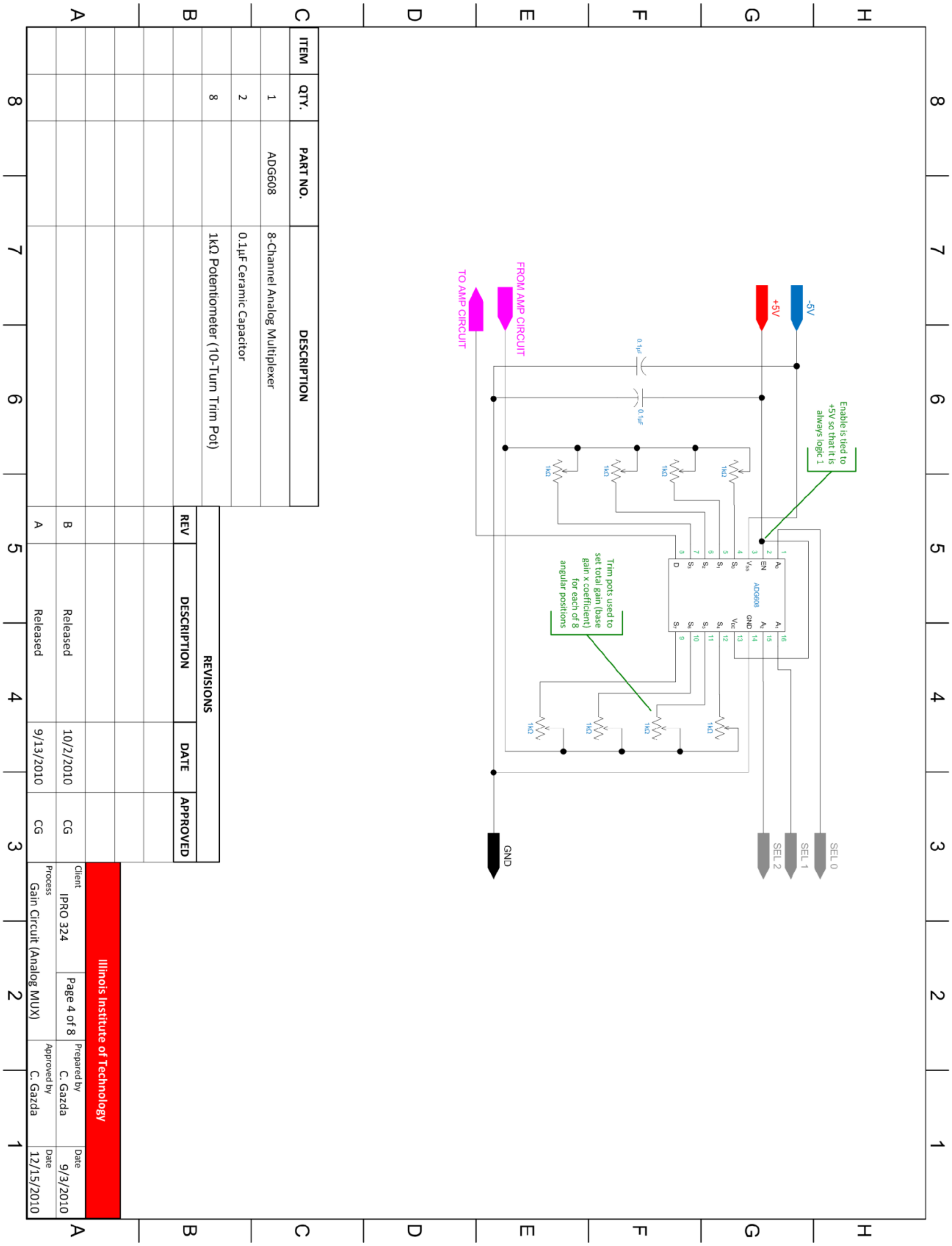
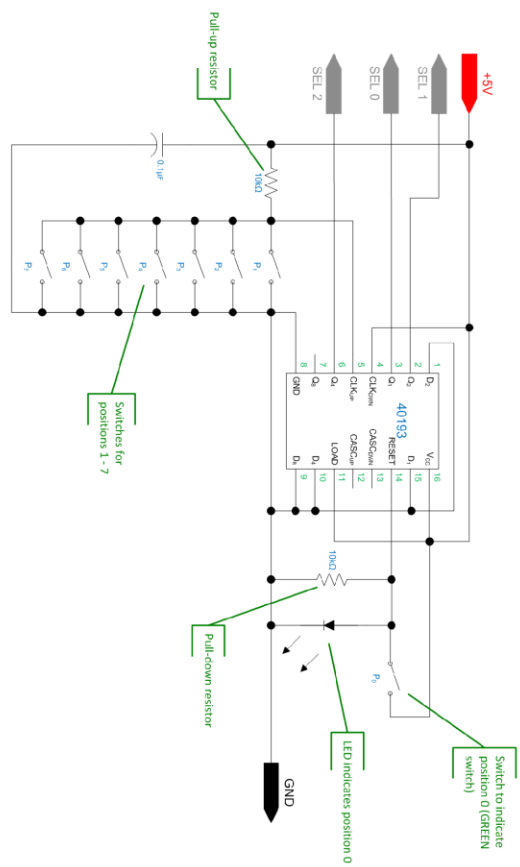


Figure 10: Circuit Diagrams



ITEM	QTY.	PART NO.	DESCRIPTION
	1	40193	CMOS Binary Up/Down Counter
	1		0.1μF Ceramic Capacitor
	2		10kΩ Resistor
	8		SPST Switch (Reed)

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
A	Released	10/2/2010	CG

Illinois Institute of Technology

Client: IPRO 324	Page 5 of 8	Prepared by: C. Gazda	Date: 10/2/2010
Process: Counter Circuit (MUX Control)		Approved by: C. Gazda	Date: 12/15/2010

Figure 11: Circuit Diagrams

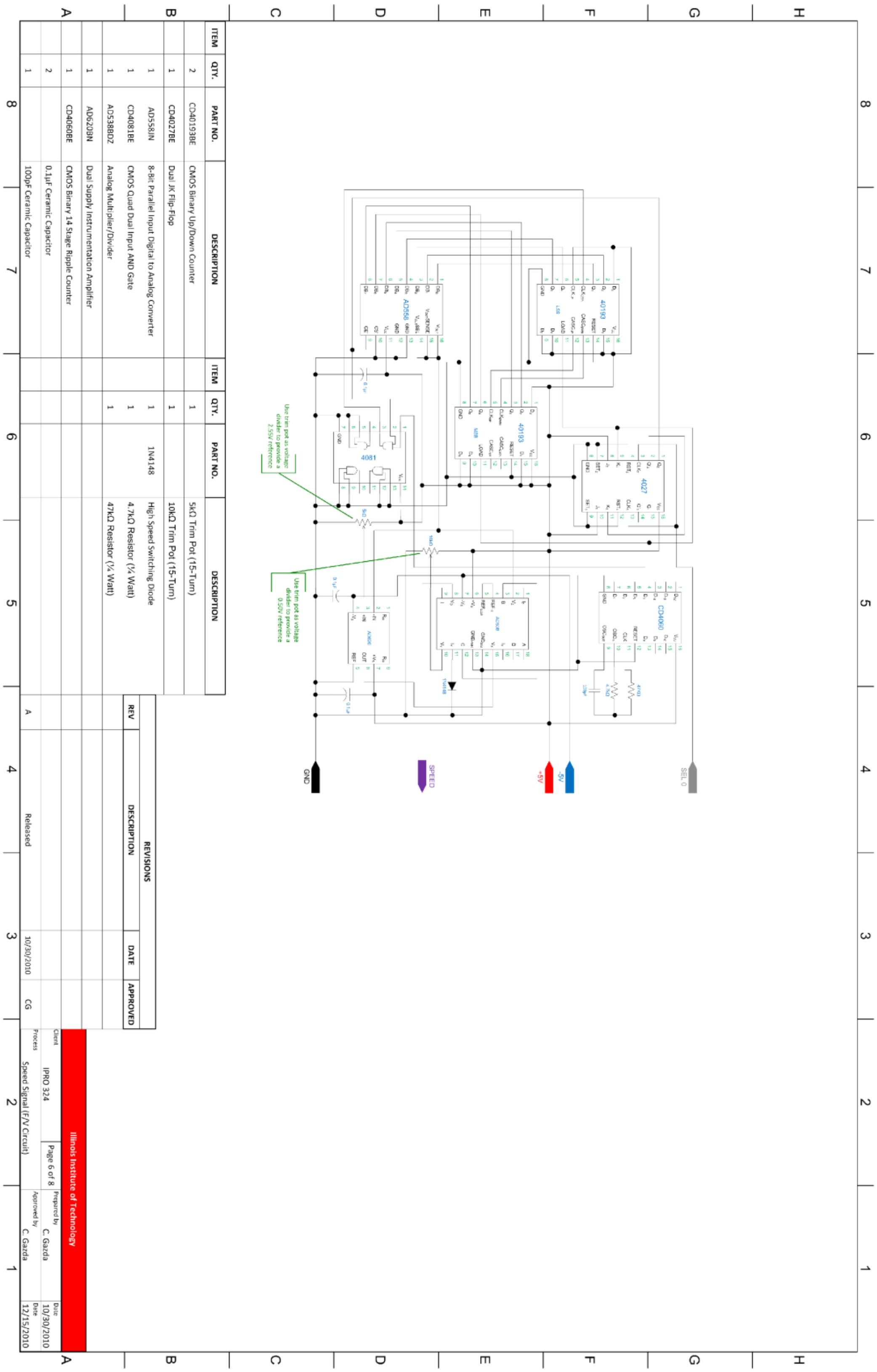
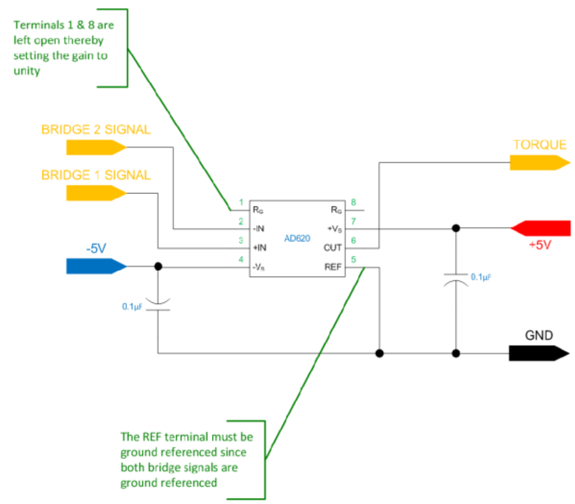


Figure 12: Circuit Diagrams



ITEM	QTY.	PART NO.	DESCRIPTION
	1	AD620	Instrumentation Amplifier
	2		0.1µF Ceramic Capacitor

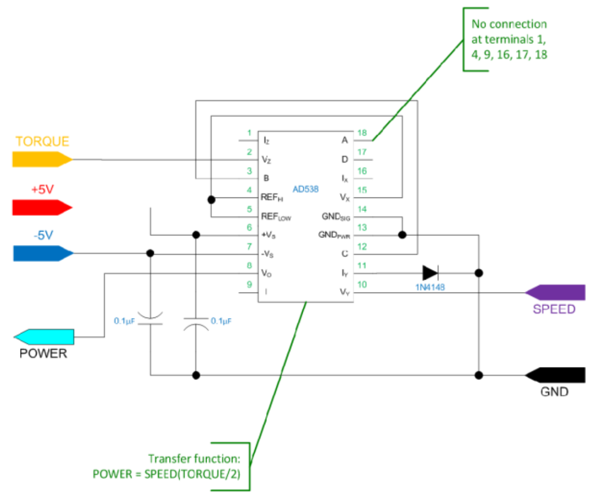
REVISIONS

REV	DESCRIPTION	DATE	APPROVED
A	Released	11/4/2010	CG

Illinois Institute of Technology

Client		Prepared by	Date
IPRO 324	Page 7 of 8	C. Gazda	11/3/2010
Process: Torque Signal (Summing Circuit)		Approved by: C. Gazda	Date: 12/15/2010

Figure 13: Circuit Diagrams



ITEM	QTY.	PART NO.	DESCRIPTION
	1	AD538	Analog Multiplier/Divider
	1	1N4148	Small Signal Diode
	2		0.1µF Ceramic Capacitor

REVISIONS

REV	DESCRIPTION	DATE	APPROVED
A	Released	11/11/2010	EB

Illinois Institute of Technology

Client: IPRO 324	Page 8 of 8	Prepared by: E. Buhay	Date: 11/11/2010
Process: Power Signal (Multiplier Circuit)		Approved by: E. Buhay	Date: 12/15/2010

Figure 14: Circuit Diagrams