Paralytic Twitch Sensor

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***Abstract* — The Paralytic Twitch Sensor is a device to monitor the level of muscle paralysis in patients from the neuromuscular blocking agents (NMBAs) used during general anesthesia. It's designed with the intention of being the helping hands of the anesthesiologist in the operating room. The apparatus will stimulate a peripheral nerve with a constant current and measure the response by the corresponding muscle. By assessing the depth of neuromuscular blockade through nerve stimulation, the anesthesiologist can ensure proper medication dosing and minimize the existing issue of prolonged paralysis and muscle weakness after an operation.**

***Index Terms* — biomedical engineering, biomedical monitoring, electrical stimulation, medical control systems, neuromuscular stimulation, sensor systems and applications.**

I. Introduction

The Paralytic Twitch Sensor is a senior design project sponsored by the anesthesiologist Dr. Looke. Anesthesiologists' current method for monitoring patients while under general anesthesia relies on their hand being the sensor while they use a stimulator that sends a current to stimulate the muscles to try and obtain the response or like in most cases the anesthesiologist will just look for the resulting twitch. Dr. Looke with his background in electrical engineering knew there could be a better way so he approached the senior design class and asked for help in designing a better way to measure the patience response.

The Paralytic Twitch Sensor will apply a current through electrodes placed above the nerves that correspond to the muscle that will be stimulated. If the muscle responds there will be a resulting twitch that is then measured by the sensor so the anesthesiologist will know how much of an effect the paralytic drug has on the body. This device will utilize the Cockcroft-Walton voltage multiplier to create a current that is large enough for a shock to stimulate the muscles that are being blocked due to the general anesthesia, as well as a pressure sensor that will sense the resulting twitches and a LCD screen that will allow the user to choose between the different settings for the current pulses and view the responses of the twitches that is observed by the sensor. This design was implemented with the intention of the final project being able to set-up within the operating room. The high level block diagram can be seen in Fig. 1.

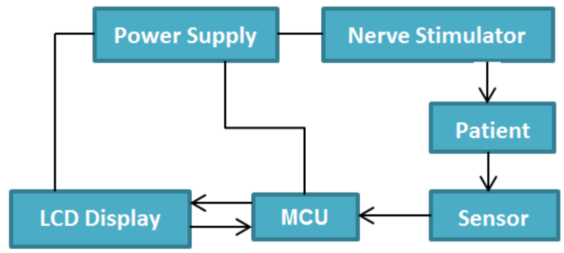

Fig. 1. High level block diagram of the Paralytic Twitch Sensor.

The overall goal for this device is to integrate a sensor that will be sensitive enough to not only show the twitches that are occurring on a LCD screen but will also be able to show the strength of the resulting twitches so the anesthesiologist can see how close the patient is to giving the full strength twitch. This way they know if more general anesthesia needs to be given during the surgery or how close the patient is to waking up in the recovery room.

II. Paralytic Twitch Sensor Overview

The nerve stimulator, with the electrodes, should be attached to the patient before the induction of anesthesia is administered, but should not be started until after the patient is unconscious. While the patient is unconscious, he or she is given a tetanic stimulation using the maximum current in order to obtain a baseline measurement. Once the response to this stimulation has been recorded, the anesthesiologist then injects the muscle relaxant into the patient and will change the stimulation to single-twitch. When the administered drugs have worn off enough to receive a feedback, the stimulation pattern will change to Train-of-Four (TOF). With this stimulation, the anesthesiologist can decide whether or not to administer additional drugs to the patient as well as monitor neuromuscular recovery.

A. Stimulation Patterns

The three main stimulation patterns that need to be included in the design are tetanic, single-twitch, and Train-of-Four (TOF). The tetanic stimulation is the concept of using a very rapid delivery of electrical stimuli at maximum current. The frequency impulse is most commonly between 50 to 200 Hz for the maximum duration of 5 seconds, due to the intensity of this type of stimulation. The single-twitch is the simplest form of nerve stimulation and is applied using a maximum current at frequencies ranging from 1 Hz to 0.1 Hz. This stimulation is mostly used to view the onset of the neuromuscular block up until muscle response is first detected. The most popular mode of stimulation for monitoring neuromuscular blockade is the Train-of-Four (TOF). This mode involves four successive stimuli that stimulate the target motor nerve every 0.5 seconds, which results in a frequency of 2 Hz, as seen in Fig. 2. During this phase, progressive fade occurs with each pulse in the TOF series. The extent of this fade serves as a basis for assessing the degree of neuromuscular recovery. This is done by comparing the amplitude of the muscle response of the fourth twitch to that of the first (T_4/T_1), which gives the TOF ratio.

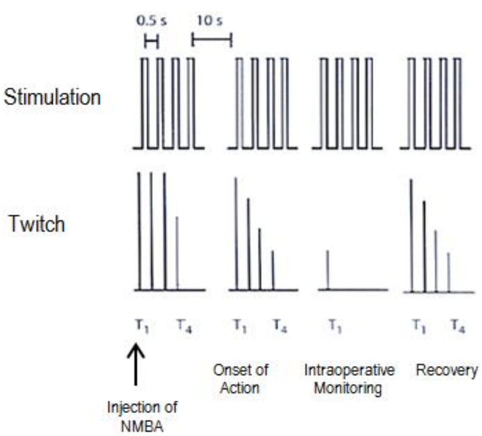

Fig. 2. Pattern of TOF electrical stimulation and evoked muscle response before and after injection of neuromuscular blocking agents (NMBA).

B. Monitoring Sites

The ulnar nerve is the most frequently used site for peripheral motor nerve stimulation because of its accurate and reliable feedback. It is easily accessible during an operation when the arm is outstretched. Also, because the ulnar nerve runs through the middle of the arm while the adductor pollicis muscle is located on the lateral side of the arm, the risk of direct muscle stimulation is diminished.

In previous designs, such as the TOF-Watch®, the recording method of choice was acceleromyography, which measures the acceleration of the muscle response and therefore requires the thumb to have full range of motion in order to get an accurate result. Because there are certain procedures in which the patient's arm is tucked to the patient's side of the body, a less reliable, alternative nerve must be chosen, such as the posterior tibial nerve, which measures flexion of the big toe, or the orbicularis oculi, which measures the wrinkling of the eyebrow.

III. Problem Formulation

The objective of this senior design project is to research and create an alternative sensor technology that can perform similarly to other neuromuscular monitoring systems but with greater reliability and that offers a more user-friendly and convenient way of measuring. After researching existing sensor systems, each had at least one of the following issues described below:

- The system provided false feedback because it stimulated the muscle instead of the nerve in the corresponding area.
- The system was not useful for everyday clinical use because of its lengthy setup time.
- The system measured muscle response of an area on the patient that was not easily accessible for the anesthesiologist.
- The system required a considerable amount of preparation time due to inaccurate reaction readings for the first 8 to 12 minutes of stimulation.
- The system produced erroneous measurements for the ulnar nerve with only slight changes in the patient's hand position due to its measuring technique.
- The system required the patient's hand and thumb be restrained, which resulted in possible nerve or tissue damage when not positioned properly.

A. Requirements of the New Sensor

Based on the research conducted and interactions with Dr. Looke, a list of requirements has been decided upon for the new sensor system.

- The sensor system should have the capability of measuring the ulnar nerve stimulation at all times, independent of the procedure type.
- The setup of the sensor system should be relatively quick and simple and show accurate readings at the start of stimulation.
- The sensor system should have the ability to be used on all patients, regardless of size, age, etc.
- The part of the sensor system that makes contact with the patient should be disposable for sanitary purposes.

- The measurement amplitude of the muscle response should be inversely proportional to the level of neuromuscular blockade in the patient.

IV. Sensor

Due to the sensor's main specification of being capable to work during procedures where the patient's arm is tucked to the side of the body, this limited the choices to a sensor that did not measure displacement or acceleration. After a great deal of research and testing, the group came up with the idea of using the technology of a pressure sensor as a new way to monitor nerve stimulation. The pressure sensor is connected to an inflatable pessary, a medical device known in the gynecological field of medicine. The pessary is round and made of soft rubber that is 2 inches in diameter. After layering the patient's hand with a disposable latex glove, the pessary will be placed in the palm of the patient's hand, as shown in Fig. 3. Stimulation to the ulnar nerve will initiate. The pressure sensor will then measure the strength of the muscle response of the hand twitch that results from the squeeze of the pessary.

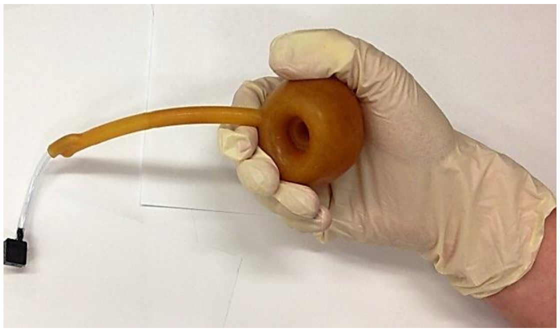

Fig. 3. Setup of the pressure sensor with the pessary.

The pressure sensor acts as a transducer as it detects force in the form of pressure, or gas flow, and converts the mechanical energy to an electrical output. The complete system of the transducer comprises of three parts: the pressure-sensing element, the transduction element, a device which converts the motion or force to another form of energy, and finally the recording instrument, where signal conditioning is done if needed. The measurements of a pressure sensor may be modeled as:

$$V_{out} = k_0 + k_1 P, \quad (1)$$

where k_0 is the negative offset to exclude air pressue and k_1 is the pressure sensitivity in V/pressure unit.

The project design requires the use of a gauge pressure sensor, which measures pressure relative to atmospheric pressure. Therefore, zero pressure means the pressure is the same as the ambient pressure.

A. Final Selection

The sensor that ended up being chosen for the project is the MPXV5050GP pressure sensor developed by Freescale. It is one of the only sensors that satisfies every requirement in this part of the project. Although the pressure sensor is the primary choice for this project, the design has been made with an additional optional sensing type using electromyography (EMG).

1. Specifications of MPXV5050GP

Some of the features of this pressure sensor are [1]:

- Supply voltage (V_s) of 5Vdc
- Offers only positive pressure outputs, ranging from 0 to 50 kPa
- Analog output for a more precise measurement
- Small accuracy error at ±2.5%
- Quick response time (t_R) of 1.0 ms

The benefit with the wide pressure range is that it is able to detect a very slight twitch with only minimal change in pressure while still being large enough to measure the baseline stimulation that is given to a patient before administering anesthesia. Having a sensor that has only a positive range rather than a ± system allows for the measurements to begin at zero with no force exerted, rather than beginning the measurements halfway of the maximum output value, which gives less of a range and therefore, becomes less precise. Because the project is measuring minor changes in pressure, the small percentage error is wanted. The quick response time is needed for the TOF stimulation where there is little time between each pulse in a set.

B. Electromyography (EMG)

The group has given the capability to use electromyography (EMG) as an optional way to monitor patient feedback if it is preferred by the anesthesiologist. However, the emphasis of this project is to use the pressure sensor system. An EMG measures the electrical activity of a muscle at rest and during contraction. This activity is proportional to its force development. As an alternative to the direct measurement of muscle force with the pressure sensor, evoked EMG can be used to record the electrical activity of the muscle. It indirectly measures neuromuscular blockades by recording the compound action potentials produced by stimulation of a peripheral nerve, more specifically the ulnar nerve for this design. The schematic of the EMG design can be seen in Fig. 4.

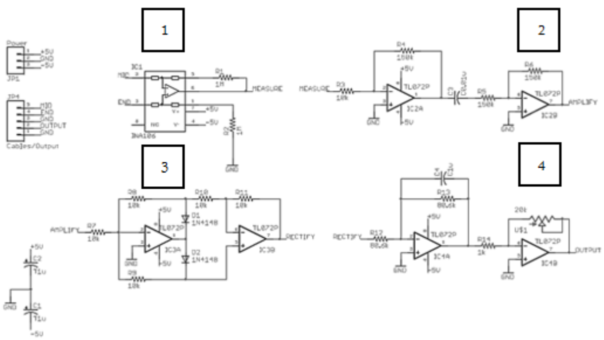

Fig. 4. Schematic of EMG sensor.

Section 1 of Fig. 4 uses an INA106 IC chip. This difference amplifier measures and amplifies the voltage difference across the muscle by ten and outputs the signal. Section 2 through 4 of the circuit uses a TL072 chip, which offers two op amps in each section. The first op amp of section 2 is an inverting amplifier with a gain of -15. The second op amp of this section uses a capacitor to AC couple the signal, which will get rid of the DC offset. This stage is a unity gain inverter which turns the signal positive again. The first op amp in the next TL072 chip, which is seen in section 3, rectifies the signal using an active full-wave rectifier. The non-inverting input is grounded, while the inverting input is fed from the output of the previous op amp. The output is fed across two diodes to create the full wave rectification. The second op amp of this section inverts and amplifies the signal. The last TL072 chip in section 4 focuses primarily on smoothing and amplifying the signal one last time by using an active low-pass filter. The last op amp of this section also tunes the signal and offers a variable gain for different muscle groups.

V. Nerve Stimulator

The nerve stimulator, is a major part of the Paralytic Twitch Sensor because without the correct constant current the twitches would not be seen at the right times. The stimulator is created by using the Cockcroft-Walton Voltage multiplier. This is an electric circuit which generates a high DC voltage from a low AC voltage. It is made up of a voltage multiplier network of capacitors and diodes, these voltage multipliers can step up a relatively small voltage to extremely large ones.

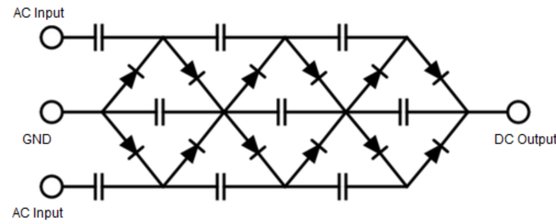

Fig. 5. The Cockcroft-Walton Voltage multiplier circuit.

The operation of the Cockcroft-Walton multiplier is fairly simple. When the input reaches the negative pole the leftmost diode is allowing current to flow from the ground to the first capacitor, then when the voltage is reversed in polarity the current will then flow through the second diode filling the second capacitor with both the current from the source and the first capacitor. As can be reasoned, this is accomplished my modifying the ground plain of the capacitor. This allows for the second capacitor to have doubled the amount of charge of the first one. With each change in the polarity from the input, the capacitors add to the charge of the next one in line towards the output on the other end of the circuit. The output voltage can be calculated, including capacitive impedance, by using the following equation:

$$V_{out} = 2 \times V_{in} \times 1.414 \times (\# \text{ of stages}). \qquad (2)$$

Based on (2), it is assumed that the more stages that the circuit has the higher the voltage. This is still the case but as more and more stages are added there starts to be a ‘sag’ in the increase because of the impedance of the capacitors in the lower stages. In order to compensate for this voltage fall out the plan was to create two circuits, one with a positive voltage gain and the other with a negative gain. This allows the multiplier to increase the voltage very quickly while eliminating the majority of the fall out that occurs in the higher stages of the Cockcroft-Walton multiplier.

One of the features about this multiplier which makes it so useful for this project is that one can easily tap the output from any stage of the multiplier to obtain a range of voltages. This is needed in the device so that the anesthesiologist can choose different current levels depending on what is needed. With that in mind MOSFETs were added as shown in Fig. 6 which allows the programmer to gain access to the multiplier at different stages in order to create the choice of different current levels.

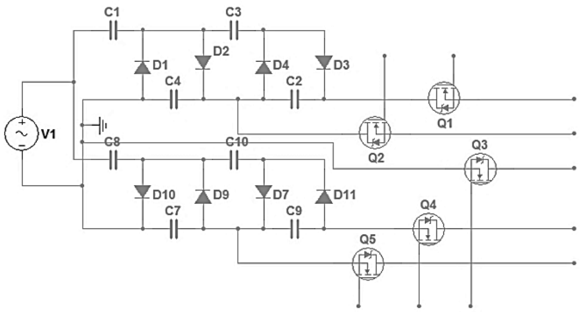

Fig. 6. Cockcroft-Walton Voltage multiplier in which the positive bias is on the top and the negative bias is on the bottom and there are MOSFETs connected to different stages.

MICROCONTROLLER

The microcontroller used in the Paralytic Twitch Sensor is the ATmega328P by Atmel. This microcontroller is a low-power 8-bit processer in a 28 pin PDIP chip. By being able to execute powerful instructions in a single clock cycle, the ATmega328P achieves throughputs at about 1 MIPS per MHz which allows the designer to optimize the power consumption versus the processing speed.

This model provides 32K bytes of in-system programmable flash with reading and writing capabilities, and 23 programmable I/O lines, which is more than enough to control the sensor, the nerve stimulator, and the screen.

The microcontroller is in charge of talking to all of the devices in the Paralytic Twitch Sensor. It is programmed in a constant loop where it checks for user input from LCD screen. The main things that the microcontroller checks for is the choice of the current level, the amount of time that is between each twitch or set of twitches, and the mode of stimulation.

Based on the selection of current level and the stimulation mode the Atmega328P then executes the related function within the code. The section of code that is executed at this point will then help choose which of the MOSFETs that are attached to the Cockcroft-Walton voltage multiplier will be used in order to obtain the current that the anesthesiologist would like to use in his test. From the calibration that is done at the beginning of every surgery, a rough guess of the appropriate MOSFET settings can be made. This will give an initially higher current than selected to the patient. To modify for this and give a much more accurate current, the MOSFETs will then be pulse width modified until the appropriate current levels are reached. By using a variable duty cycle the circuit should be able to supply any required current within our reasonable, and safe, limits. The ATmega328P is also in charge of getting the twitch data from the sensor and then displaying it on the screen.

DISPLAY

The display subsystem considers all of the components as well as the software to produce the touch panel display with custom user menus. The requirements for the display are that the user can choose their preferred stimulation mode as well as display the resulting twitches after the stimulation has been applied. The Paralytic Twitch Sensor used the µLCD43PT by 4D-Systems, which is a slim 4.3 inch resistive touch panel display shown in Fig. 7.

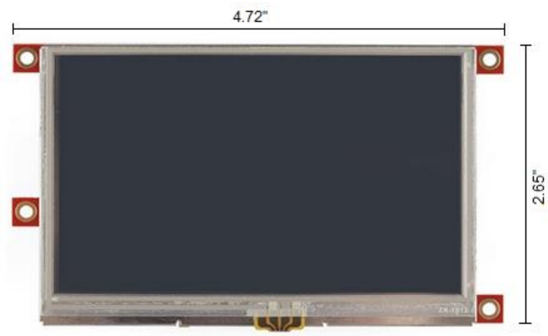

Fig. 7. The µLCD43PT display by 4D Systems.

A. Display Features

The µLCD43PT has a resolution of 480x272 and has physical dimensions of 4.72x2.65 inches which allows the display to be easily read by the anesthesiologist even with all of the information displayed on the screen. There is also 14K bytes of flash memory for user code storage and 14K bytes of SRAM for any user variables. There is also an on-board micro-SD memory card adaptor which allows graphics, video, and sound to be stored and used to output the display. To program this device, the µLCD43PT has an easy 5 pin interface which includes VCC, TX, RX, GND, and RESET.

The fact that this screen only needs 5 pins to program significantly simplifies the design of this project. Another nice feature of this screen is the built in PICASO-GFX2 Processor which functions as a graphics controller. This processor includes all of the data and control signals, including the high level commands needed to communicate directly to the display. Since this chip is already built into the µLCD43PT there is no need for an external graphics controller which allows the design to be simplified.

B. Display Software

The software tools included with the purchase of the display includes the 4S-Workshop4 IDE, PmmC loader, graphics composer and front tool. The PmmC loader allows the PICASO-GF2 processor to load the latest PmmC file into the chip imbedded in the µLCD43PT module [1]. The graphics composer is a tool that is used to compose images, animations, and movie-clips which can then be downloaded onto the micro-SD memory card. The font tool is used to generate the fonts shown in all of the menus throughout the display. It is compatible with all of the Windows font types and converts these fonts into bitmap fonts. The IDE also provides another valuable feature called 4D-ViSi which is a software tool that is used to see instant results of a desired graphical layout for the display. There are selections of premade buttons, dials, gauges, digits, etc. that can simply be dragged and dropped onto the simulated display. When using this feature it will generate a base code for everything that was put on this simulated display. This feature helps reduce some of the development time required for programming.

D. User Menus

Shown in Figures 8 and 9 are the screen shots of two different user menus. Fig. 8 shows the screen for the settings where the anesthesiologist can choose the current level and the interval between the twitches or set of twitches.

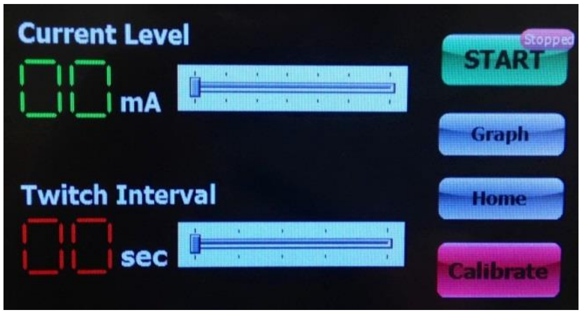

Fig. 8. Settings screen on the µLCD43PT screen.

Once the settings have been chosen the anesthesiologist can press the “Start” button and it will allow the user to continue to the screen shown in Fig. 8. On this screen the user can choose which stimulation mode should be used and they will push the corresponding button. Once the screen gets the feedback from the sensor it will display the values of the resulting twitches. Each twitch will be shown on the graph and for the TOF the ratio of the last twitch to the first twitch and will be displayed in the lower right hand corner, as shown in Fig. 9. When the user wants to stop the stimulation they will just need to press the “Stop” button. When everything is over to get back to the home screen they will just press the “Settings” button and that will bring up the settings screen in Fig. 8. and from there pushing the “Home” button the user will be brought to the main home screen and can safely turn the device off at that point.

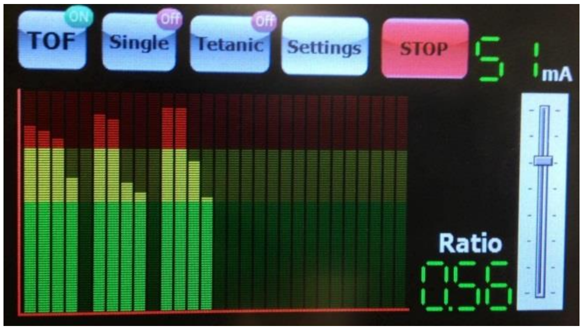

Fig. 9. Screenshot of the user screen that displays the graph and the TOF ratio.

POWER SUPPLY

The power for the Paralytic Twitch Sensor will come from a standard 110 VAC wall outlet. The first step in using an AC source for a DC project is to convert the first to the second. A standard extension cable will be used to go from wall plug to device. Once it reaches the device it will be connected using a standard screw terminal to guarantee a secure attachment but still maintain the ability to be replaced should the wire break or be damaged in the future.

The first piece of the power supply will be the actual manipulation of voltage that gives the circuit ability to create a constant DC signal. The hot wire will be connected to one end of a transformer while the neutral is connected to the other. This transformer performs two functions for the circuit; first it allows for an isolation of the circuit from the wall outlet and second it provides and initial voltage step down.

Isolation is critical when dealing with any kind of power grid because there is the potential that, if any piece of the grid fails to work properly, it will propagate a power surge down the line and through any device connected to it. Luckily most of the circuitry to be used will be robust enough that minor voltage spikes should not harm any of it, but that does not apply to the EMG sensor which will register a reading, falsely, if it experiences any minor electric field change. Also, while an internal power surge is unlikely in a hospital, it is better to be prepared for the situation then not; this leads to a second reason for power isolation, patient safety. In the unlikely event that something went wrong with the device (maybe a power surge fried something) a possibility exists that instead of frying in the off position the component will be permanently on. This can lead to major issues if, say, the component stuck in the on position happens to be the switch allowing current to flow through the patient. A continuous, unregulated current flowing through a human can do extensive damage in a short period of time, with a worst case scenario being the loss of use of the body part being electrocuted.

The transformer being used is center tapped which means that halfway along the secondary coil a lead is placed for various reasons; in this circuit it will be used as the common/negative output to the diode bridge while the outside two are used as positive lines. This can be done because the two outside lines are wired in series with their own diodes preventing current from leaking back when that lead is actually negative relative to the common. Using a center tapped transformer provides the circuit with its first voltage step down even if the transformer has the same number of turns on both coils; this is because the common is halfway through the secondary winding effectively creating a virtual ground. This leaves the outside two taps to be 180° out of phase with each other relative to the virtual ground. Thus using two diodes to prevent the outside taps from exerting their negative sweep on the diode bridge the AC signal is effectively completely rectified.

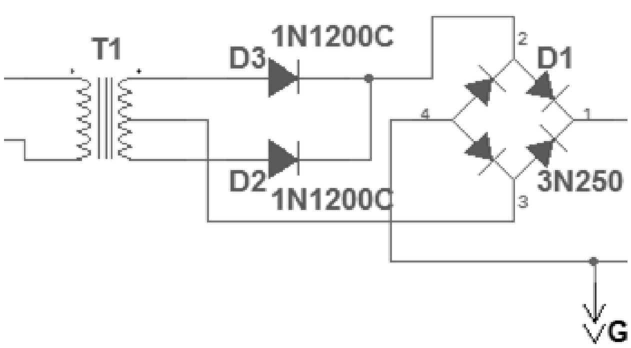

Fig. 10. The Power Circuit with the transformer connected to the diode bridge.

At this point the diode bridge comes in, as can be seen in Fig. 10 the bridge is wired in such as was as the diodes look like they're pointing in the direction of the positive current flow. This is how the bridge works, allowing current to flow in their forward active direction and preventing it from flowing in the opposite direction. The post-rectification part of the circuit, herein called the DC side, will be wired so that the current always flows out of its positive side and in to its negative. The rectified AC signal will be wired to the other two poles of the diode bridge; once the DC have been hooked up properly it is actually irrelevant which lead goes to which pole from the transformer, here it is chosen in the simplest manner with the common on the bottom.

The diode bridge will feed in to two positive five volt regulators and a single negative. One of the positives will go on to power our microcontroller, in-system programmer, and the 4D uLCD screen. The other two regulators will be paired and used of various operational amplifiers to smoothly power our EMG circuit and the current sensing unit.

Conclusion

This project helped each group member become more familiar with designing, implementing, and testing a real world engineering project. It also provided experience in working in a group setting to produce the final product. This experience will in turn help each member of the group when they go out into their respective jobs.

Throughout the work on the Paralytic Twitch Sensor, each member of the group got to experience circuitry, hardware, programming and communication between all of the different components in a hands-on approach. In addition to adding experience in these engineering areas it also allowed the members to get a look into the field of Biomedical Engineering. Not only that but it provided Dr. Thomas Looke, the sponsor, with an initial prototype in hopes to replace the outdated device that he currently uses in the operating rooms.

Acknowledgement

The authors would like to acknowledge the support and dedication of Dr. Thomas Looke for the lengths that he has gone to in educating and guiding our medical research for this project. Also, we would like to thank him for his help in funding the Paralytic Twitch Sensor.

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We also offer our thanks and gratitude to the men who have so kindly agreed to give us an hour of their time to review our project that we have worked so hard on.

Lastly, we would like to thank Dr. Samuel Richie for helping us through the many obstacles that we faced by giving us other solutions as well as the right guidance when needed.

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BIOGRAPHIES

Kelly Boone

Kelly is currently a senior at University of Central Florida and will receive her Bachelors of Science in Electrical Engineering in the spring of 2013. She has interned with NASA and is currently working as a service engineering intern at Siemens. She is also a current member of SWE and IEEE. Her primary interests, as a result of this project, lie in medical control systems and biomedical engineering.

Ryan Cannon

Ryan is currently an electrical engineering senior at University of Central Florida and will receive his B.S.E.E. in the spring of 2013. When he graduates he will continue to work at his current position as a systems engineer for the Center for Microgravity Research and Education.

Sergey Cheban

Sergey is currently a computer engineering senior at University of Central Florida and will be graduating in May of 2013. After graduation he plans are to find a position as a Software Developer and work for a few years before trying himself as an Entrepreneur in the Mobile Software industry. He also plans to get his master's degree in Computer Science after settling with his job.

Kristine Rudzik

Kristine is currently a senior at University of Central Florida and will receive her Bachelors of Science in Electrical Engineering in May of 2013. She will be attending Stetson University's College of Law beginning in the fall to peruse a career as a patent attorney.