Paralytic Twitch Sensor

Senior Design 2

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Chapter 1 Introduction

1.1.A Executive Summary

In an increasingly technological world, the method for monitoring patients while under general anesthesia is becoming dated. The inspiration for this project began when Dr. Looke approached the senior design class with his proposal for integrating a sensor to measure the force of the patient's finger, toe, or eyelid instead of having him either hold his hand up to the twitching body part or just merely watching to see if a twitch resulted from the electrical current pulsing through the nerves. His idea got our group thinking and thus came the initial brain waves that started the building of the Paralytic Twitch Sensor.

Naturally using a sensor to monitor this paralytic twitch makes sense because it frees up space around the operating table for the surgeon and his staff to work, but this will also make checking while the patient is waking from his/her paralytic state somewhat easier and would allow for more anesthesiologists to check before removing the breathing tubes or other devices that were needed to support the life of the patient while they underwent surgery. The Paralytic Twitch Sensor is designed with the intention of being able to set-up within the operating room and be the helping hands of the anesthesiologist. The device will apply a current source through electrodes placed above the nerves that correspond to the muscle that we are trying to stimulate. If the muscle responds then the part of the body that it controls will twitch. The sensor will measure the force exerted by the resulting twitch to see how much the paralytic drug has an effect on the body.

The sensor will be integrated with a circuit that is attached to an LCD screen. The screen will display the results of the twitches so the anesthesiologist will know whether or not more medication is needed or that the body is responding just as it needs to for that point of the surgery process. A wireless option will also be integrated to allow for the transmission of the data to a computer or a tablet for the anesthesiologist to use for future studies. It will also allow them to keep an accurate history of past performances.

The end product will be a lightweight, portable device that is able to run on battery for shorter surgeries but also capable of being plugged into an outlet when a longer surgery is needed. Low cost is also an ideal for the sensor, as the hospital is leaning towards disposable instruments that come in contact with the body. The Paralytic Twitch Sensor will be useful in operating rooms where the anesthesia is being administered as well as in the recovery rooms so that the doctors do not pull out essential tubes too early to keep the risk of complications from the anesthesia to a minimum.

1.1.B Motivation

The motivation for this project lies mostly with the medical part of the Paralytic Twitch Sensor itself. Two members within the group have personal ties to this project, although for very different reasons. The first, Ryan, is fascinated by this project because of chronic medical conditions that have already required major surgeries and will require them again. Since his diagnosis Ryan has been considering a career in the medical field, and this project presents the perfect opportunity to test those inclinations. The other member of the group is Kelly, who grew up with both of her parents in the medical field. In addition to its current function, and although this part of the project does not focus on it, she hopes this project will continue and lead to research that will one day find a monitor for conscious activity even under sedation. Currently, anesthesiologists use bi-spectral indexing (BIS) to see the brain activity of a patient who has been given general anesthesia; however, with a patient such as Kelly, who has epilepsy, she has become interested in what they can possibly do to measure brain activity while there are constant abnormal electrical discharges in the brain. Her interest stems from the infrequent but possible occurrence of an anesthesiologist forgetting to administer or administering too few pain-blocking agents. If this project were to continue, she would like to find a way for the patient to communicate pain without being able to move or speak.

1.2 Project Specifications

The main goal, and only real specification, for this project is to find a way to quantify the twitches that occur as a result of the supplied current. From that requirement the group was lead to a couple different goals. First, the Train-of-Four device that sends the pulses must be recreated. This device will be able to create a constant current anywhere from 2mA to 30mA, which given its name will be able to sustain that current given the variations in human skin resistance. Once this is managed, the group will need to design or find a sensor that is capable of measuring the force that was created once the twitch occurs. The sensor will need to be low power to accommodate our limited power supply and be sensitive enough to respond to the lesser strengths of the exceptionally young and elderly. The sensor will also need to be cheap enough to dispose of at the end of use or capable of being cleaned as to avoid cross contamination as the device is used on multiple patients. Having these qualities the group will then be able to incorporate them into a controller that will trigger the current pulse and check the response.

It will need to be able to read very quickly so that the group gets reasonably accurate data from the short pulses that will be delivered. This is necessary so that the sensor doesn't give a false negative for the remaining twitches that are needed to be measured. The group also will need the data to be displayed on a screen that is easily accessible and readable by the anesthesiologists that are

using the device. It should also be safe to use in the operating room as that is where it will be implemented in most cases.

Upon the finishing the above requirements that the group feels are necessary, there are additional specifications that would be nice to add to the project but are not imperative to the device to make it work that the group decided would be nice to add if the time was there. These specifications are completely optional, and will not be worked on until the necessary specifications and requirements are met. If there is time at the end the group will try to implement as many of these additional requirements in an effort to create the ideal project within the allotted timeframe of senior design II.

First, the group would like the final project to be rather inexpensive as the goal is to mass produce the device and use it in the hospital operating rooms. Also, if possible the group would like to make the device capable of wirelessly transmitting data so that the display does not need to be directly connected to the device and can be placed anywhere within the operating room. It would also be a great feature to have if the anesthesiologist were to be working on a research study for new advancements in medicine and needed to have the data from multiple cases on their personal device so they can look over them during and after the study. It would also be nice if the group was able to make the device run on battery to keep the number of wires in the operating room to a minimum but, also this would allow the device to be used during the test of local anesthetics as well. These local anesthetics are administered to the patients in the areas outside of the operating room where there are not outlets readily available so a battery operated device would be able to serve multiple functions.

1.3 Sponsor/Group

The sponsor and mastermind behind this project idea is Dr. Looke. Without his presentation to the senior design class at the beginning of the semester this project would have never taken form. This was not an idea that was in any of the group member's initial designs. Dr. Looke is an anesthesiologist in the Orlando area. The reason that he came to the class to present this idea is because his undergraduate study was in the field of electrical engineering so he knew that this was a device that would be able to be created based on his past experiences in the engineering industry.

Dr. Looke helped guide the group with the medical research and answered any of the lingering questions that individual group members had when trying to relate the medical and the engineering worlds. He also, sponsored each member of the group to allow for the visit of the operating room in the hospital in Winter Park. This experience helped the group see where the major problems were with the old design of the current source and why the monitoring by the senses of sight and touch were not always an accurate way of obtaining information. Not only that but they were not completely reliable to give a reading at all.

The group's other sponsor is Dr. Zhihua Qu. His background in robotics will help the group in senior design II when questions arise as to how to integrate the circuits into the design. He also gave the group some ideas as to how to approach the devices design which helped give the group a shove in the right direction when it came to brainstorming and researching ideas for the sensor.

Chapter 2 Research

2.1 Required Medical Knowledge

When a patient is going into surgery there has to be an anesthetic administered in order for the surgery to be performed. This medicine blocks the receptors for pain and memory in the human body. It also stops the movement of involuntary muscles. With this the doctor would have to place a breathing tube in the patient in order for the patient to be able to breathe while the operation is being performed. This breathing tube is also needed in the recovery room because the neuro-muscular blockade does not wear off quickly so as it is wearing off so it is necessary to have a device that can help measure how much of the medicine has worn off in order to figure out if it is okay to take the breathing tube out at the present time. If the breathing tube is taken out too soon because the device that was measuring the response was wrong or not used then there could be complications where the patient is unable to breathe on their own so the tube has to be reinserted. These complications could be avoided with the help of a device that measures the muscle response to see how awake the muscles are in the patient.

In order to build or create this device some medical knowledge is imperative to know in order to make sure that the device will work properly without causing the patient any harm.

2.1.A Types of Anesthesia

In the medical world, there are four types of anesthetics: Topical, Local, Regional, and General. Although they all temporarily cause an absence of pain to the patient, they vary in degree of their resulting effect on the patient, depending on what type of procedure the medical staff has to perform. Topical anesthetics are the least abrasive and are administered on the skin by a spray, cream, gel, etc. They temporarily block nerve endings in skin and mucous membranes. They do not produce unconsciousness to the patient. Local anesthetics are given intravenously and temporarily block transmission of nerve impulses and motor functions in a specific area. They also do not cause unconsciousness to a patient. Regional anesthetics are administered and used for more severe surgeries. They temporarily interrupt transmission of nerve impulses, such as temperature, touch, or pain, and motor functions in a large area to be treated. However, they do not produce unconsciousness to the patient. General anesthetics, which are the most powerful of the four types, produce total unconsciousness, affecting the entire body. They are administered intravenously or through inhalation. Agents used for the latter of the two may either be gases or volatile liquids that are vaporized and inhaled with oxygen.

2.1.B General Anesthesia

The definition of General anesthesia is "the induction of a balanced state of unconsciousness, accompanied by the absence of pain sensation and the paralysis of skeletal muscle over the entire body. It is used during major surgery and other invasive surgical procedures" (http://www.surgeryencyclopedia.com/A-Ce/Anesthesia-General.html#b). The five distinct reasons for electing to use general anesthesia are to produce unconsciousness, to relax the muscles of the body, to block memory of the procedure (amnesia), to inhibit normal body reflexes to make surgery safe and easier to perform, and to give pain relief (analgesia) to the patient. General anesthesia occurs in four stages which can occur very rapidly. During the first stage, the patient is conscious, although mental and physical capabilities become progressively sluggish as the deeper part of the stage is approached. The sense of pain is dulled until it becomes abolished, often just before consciousness is lost. The second stage, or the excitement stage, includes uninhibited and sometimes dangerous responses to stimuli, resulting in the patient possibly becoming violent. Blood pressure rises and becomes irregular and breathing rate increases. However, this stage is usually shortened or even bypassed by administering a barbiturate, a drug with hypnotic and sedative effects. During the third stage, or the surgical stage, the skeletal muscles relax, the patient's breathing becomes regular, and eye movements stop. Additionally, the patient's pupillary gaze is central and the pupils are constricted. This is the target depth of surgical anesthesia. The fourth stage, or medullary paralysis, occurs if the respiratory centers in the medulla oblongata of the brain that control breathing and other vital functions cease to function. Death can result if the patient cannot be revived quickly. This stage should never be reached. Because it can happen from an overdose of anesthetics, careful control of the amounts administered to a patient prevents this occurrence.

It is common today to use a combination of intravenous drugs and inhaled anesthetic gases during general anesthesia, a practice called balanced anesthesia. This method is used because it takes advantage of the beneficial effects of each anesthetic agent to reach surgical anesthesia (stage three). The biggest benefit of general anesthetic inhalants is that it allows an anesthesiologist to quickly modify the amount of the anesthesia given to a patient by simply adjusting the concentration of the anesthetic in the oxygen. Intravenously injected anesthetic produces a fixed degree of anesthesia and cannot be changed as quickly and must be reversed by administration of another drug. However, intravenous anesthetics still remain popular because it controls the blood pressure better and it protects the brain. Inhalation anesthetics are rarely used alone in recent clinical practice. As a result, in most surgeries today, intravenous anesthetic agents are used for induction of anesthesia and then followed by inhaled anesthetic agents.

2.1.C Inhalation Anesthetics

There are several inhalation anesthetics today; but with each, there are both positives and negatives. Halothane has a pleasant smell and causes patients to lose consciousness, but provides little pain relief and can be easily over administered. Very rarely, it can be toxic to the liver in adults. Because of its good odor, it was a top choice when giving general anesthetics to children until the introduction of sevofluorane in the 1990s, which has caused its use to decline. Enflurane is known for producing a rapid onset of anesthesia and a faster recovery. It is less potent than some of the others, and acts as an enhancer of paralyzing agents. On the other hand, it is not used in patients with kidney failure and has been found to increase intracranial pressure and the risk of seizures. Isoflurane can induce irregular heart rhythms, but is good because it is not toxic to the liver. It is often used in combination with intravenous anesthetics for anesthesia induction. Nitrous oxide, also known as laughing gas, is used with other drugs such as thiopental to produce surgical anesthesia. It is regarded as the safest inhalation anesthetic because it does not slow respiration or blood flow to the brain. It also has the fastest induction and recovery time. However, it can diffuse into air-containing cavities and can result in a collapsed lung or lower the oxygen content of tissues. Because it is a relatively weak anesthetic, it is not suitable for being the primary agent in any type of major surgery. Sevoflurane works quickly and offers rapid awakening. Additionally, because it does not irritate the airway, it can be administered through a mask, and as a result, it is quickly becoming the first choice of use for pediatric patients. Its downside it that it may cause increased heart rate and should not be used in patients with a narrowed aortic valve. Also, one of the breakdown products can cause renal damage. Finally, there is desfluorane, a second-generation version of isoflurane. Its advantage is that is offers rapid awakening with few adverse effects. However, it seems to have several disadvantages. It is irritating to the airway and therefore cannot be used for mask inductions, especially not in children. It may increase the heart rate and should not be used in patients with heart problems. It also may cause coughing and excitation during induction.

2.1.D Intravenous Anesthetics

Just like inhalation anesthetics, there are several types of intravenous anesthetics that each offer their own individual advantages and disadvantages of use. Ketamine produces a different set of reactions from other intravenous anesthetics. It affects the senses and produces a dissociative anesthesia. This is where patients cannot respond to sensory stimuli even though they may appear awake and reactive. This anesthetic is not usually given to adult patients because it often makes them have sensory illusions and vivid dreams during post-operative recovery. This anesthetic is useful for use in developing countries and trauma casualties in war zones where anesthesia equipment may be difficult to obtain. It is also frequently used in pediatric patients because it causes unconsciousness and a loss of sensation with an intramuscular injection.

Ketamine is also popular for patients in shock because it also provides cardiac stimulation. Thiopental is a barbiturate that induces a rapid hypnotic state for a short duration of time. It should not be continuously infused, though, because toxic accumulation can occur since it is slowly metabolized by the liver. Additionally, patients may experience side effects that include nausea and vomiting when awakening. Opioids are frequently used prior to anesthesia and surgery as a sedative and analgesic. Opioids are extremely useful for cardiac surgery and other high-risk cases because they rarely affect the cardiovascular system. Opioids are the most common agent used in epidurals for spinal anesthesia because they act directly on the spinal cord receptors. Side effects for a patient may include nausea, vomiting, itching, and respiratory depression. Propofol is the most recently developed intravenous anesthetic to the medical world. It offers a rapid induction and short duration of action just like the thiopental, but recovery occurs more quickly and with much fewer side effects. The biggest advantage of propofol is that it is metabolized in the liver and excreted in the urine, which allows it to be used for long duration of anesthesia. As a result, it is rapidly replacing thiopental as an intravenous induction agent.

2.1.E Precautions

There are many precautions that must be taken place when a patient is planning to receive general anesthesia. A complete medical history, including a history of allergies in family members, is very important to have. This is because patients may have a potentially fatal allergic response to anesthesia known as malignant hyperthermia, even if there is no previous personal history of reaction. General anesthesia is only given by board-certified professionals. These professionals, known as anesthesiologists, consider many factors when deciding what combination of anesthetic medication to use, such as a patient's age, weight, allergies to medications, medical history, and general health. General anesthetics cause hypotension, or lowering of the blood pressure, a response that has the ability to lead to death, and therefore requires close monitoring and special drugs to reverse it in emergency situations.

2.1.F Description of How It Works

Even in present day after all the years of research, the exact mechanism of general anesthesia is not yet fully understood. There are many hypotheses that have been made and studied to explain exactly why general anesthesia occurs. The first, known as the Meyer-Overton theory, suggests that anesthesia happens when enough molecules of an inhalation anesthetic dissolves in the lipid cell membrane, saying the higher the solubility of anesthetics is in oil, the greater its potency. Another hypothesis, called the Protein (Receptor) Theory, explains that the anesthetic strength is based on its capability to inhibit enzymes activity of proteins in the central nervous system. Another belief, brought about in 1961 by Linus Pauling, suggests that receptor function is inhibited when anesthetic molecules bind with water molecules, forming clathrates.

The interesting part about general anesthesia to this day is that no one is sure how it precisely works. Even with the abundant number of studies of patients' individual brain cells to try and better understand how general anesthesia works, they have only been able to observe and understand what anesthetics do. Exactly how the anesthetic does it is still not understood since the drug apparently does not bind to any receptor on the cell surface and does not affect the release of neurotransmitters, which are chemicals that transmit nerve impulses from the nerve cells. All that is known is that anesthetics appear to shut off the brain from external stimuli, nerve impulses are not generated; the brain becomes unconscious, does not store memories, does not register pain impulses from other areas of the body, and does not control involuntary reflexes. In recent studies, scientists have cloned forms of receptors to gain knowledge of the proteins involved in neuronal excitability. Despite decades of research however, the efforts to explain the mechanism of how general anesthetics produce a loss of consciousness still remains a mystery.

2.1.G Side Effects

In all patients, including the healthiest there can be large differences in the sensitivity that they have to the neuromuscular blocking drugs. This sensitivity can be increased by disease, hypothermia or a disturbed acid balance and altered liver and kidney functions. The patient's response to these drugs is unpredictable. The correct amount of the drug can be administered yet it can be an overdose or an under dose depending on the patient. The lack of predictability of the effectiveness of these anesthetics for the different patients is why the patients need to be monitored so closely. There can be large differences in the way the drug reacts even in the most ideal patients. This is why there is such a major necessity for a device of this nature.

The most common and worst side effect of an overdose of the muscle relaxant drugs is a post-operative respiratory failure. This is what happens when the anesthesia has ended and the patient is in the recovery room. The breathing tube is taken out and due to the fact that there is still some neuromuscular blocking drugs in the patients system the muscles within the respiratory system are still weak. This causes the patient to struggle with the task of taking normal breathes. In these cases doctors either have to reinsert the breathing tube to help assist with the breathing until the drugs have completely left the body or the anesthesiologist has to treat the patient with another drug that will either counter act the effects of the blocking drug or blocks the memory sensors in the brain so that the patient starts to breathe normal and does not have to remember the short breathes that they are taking, so that it will have less of a negative response in the patient. This is not something that doctors want to do to the patient.

The other major issue with these anesthetics lie with the fact that if too much of the drug is administered at one time there is no way to monitor the amount that is in a patient. The anesthesiologists rely on the patient being on the edge of alertness in order to make sure that when the surgery is over that there is not a major time difference between when the surgery is over and when the patient finally wakes up. This is also done to be sure that the patient is not being charged with additional medicine that is not truly needed. The operating room is occupied by the patient as long as the procedure takes as well as the time it takes for the patient to wake up when the anesthetic wears off. Therefore it is in the anesthesiologist's best interest to keep the patient as close to the edge of alertness as possible so they will be able to wake the patient up as soon as possible. If the patient is too far past that edge then there is no other option for the anesthesiologist but to wait for a twitch to become apparent again.

2.2 Biomedical Engineering Background

Neuromuscular blocking agents (NMBAs) are widely used in anesthesia practice. As a result, researchers created neuromuscular junction (NMJ) monitors to observe their effects in clinical anesthesiology practice. Traditionally, the degree of neuromuscular blockade during and after anesthesia is evaluated with clinical criteria alone. Recommendation has been made in recent years, however, for patients receiving NMBAs to have the application of neuromuscular monitoring throughout their medical procedure. One reason is because of the variable individual response and sensitivity to muscle relaxants. In patients that are awake, muscle power and feeling can be evaluated by voluntary tests, but during anesthesia and recovery from anesthesia this is not possible. To precisely test the degree of neuromuscular blockade during anesthesia, the response of muscle to nerve stimulation should be assessed. The other big reason for using neuromuscular junction monitors is because of the "narrow therapeutic window" (*Monitoring of Neuromuscular Junction*). There is no detectable block until 75% to 85% of receptors are occupied and paralysis is complete at 90% to 95% receptor occupancy. Adequate muscle relaxation therefore corresponds to a narrow range of 85% to 90% receptor occupancy. With neuromuscular monitoring, optimal surgical relaxation is able to be achieved by knowing how much NMBAs should be permitted to a patient. In addition, it provides a quicker and more reliable turn around when patients are given the medication to reverse the general anesthesia after the medical procedure. It has been shown that when monitoring of NMJ function is not performed and clinical criteria alone are used, up to 42% of the patients are inadequately reversed upon arrival to the recovery room. This residual neuromuscular block is a major risk factor for many critical postoperative events, such as ventilator insufficiency, hypoxemia, and pulmonary infections. However, the widespread use of perioperative NMJ monitoring has helped reduce these complications drastically.
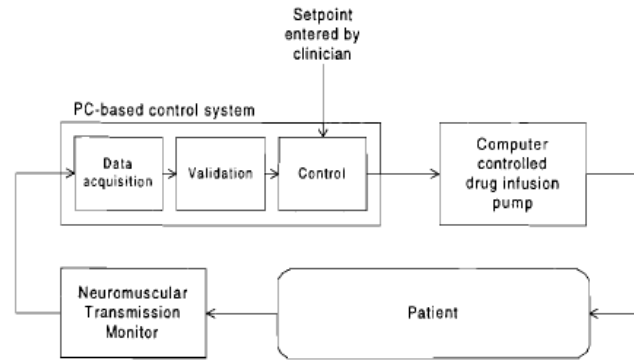
Figure 2.2-1 – Architecture of a control system for muscle relaxation (by *Validation of muscle relaxation measurements* PDF

2.2.A Nerve Stimulation

Peripheral nerve stimulation is caused by a battery powered device that delivers depolarizing current via the electrodes. When a single muscle fiber reacts to this stimulation, it follows an all-or-none pattern. In contrast, the response of the whole muscle depends on the number of muscle fibers activated. The muscle's strength progressively increases with increasing electrical current until it reaches its maximum response, or when the stimulation current is great enough to stimulate all of the muscle fibers. This response is called the threshold current; this baseline threshold should be found prior to initiating neuromuscular blockade. Once the muscle strength is at its peak, the stimulus must be truly maximal throughout the period of monitoring. Many factors can affect the intensity of the electrical stimulation and therefore the muscle response of a patient during surgery. For example, changes in skin temperature as well as anesthetic drug-induced changes in vessel tone can alter the skin's resistance. Resistance is the force opposing the flow of energy between the electrodes of the peripheral nerve stimulator. Therefore, an increase in tissue resistance must be compensated with a proportional increase in voltage in order to maintain a constant stimulating current.

CURRENT = VOLTAGE ÷ RESISTANCE

As a result, the muscle is stimulated with a current that is usually about 20% to 25% above that necessary for a maximal response. This electrical stimulus is said to be supramaximal and can be reached with a current of usually 50-60 mA in most patients during anesthesia. Since nerve stimulation can be painful, this technique should only be performed on the anesthetized patient. During recovery, on the other hand, the patient may be awake enough to experience the discomfort; therefore some researchers advocate stimulation with submaximal current during recovery. Submaximal stimulation is current between 10 mA and 30 mA, depending on the stimulated nerve. It is much less painful and better tolerated on a patient that is awake. However, testing has shown that submaximal current is much less accurate and gives a very widespread range.
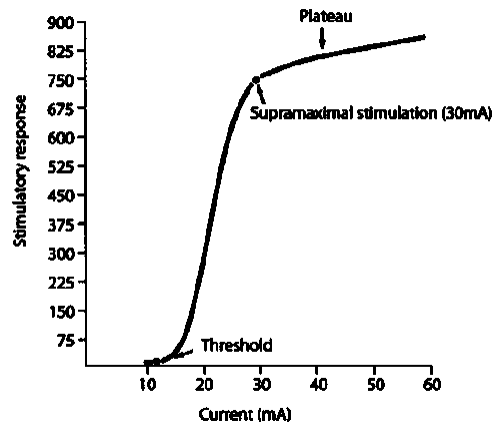
Figure 2.2-2 – Displays the plateau effect after supramaximal stimulation has been reached (usually at about 30 mA)   (picture from book)

2.2.B Monitoring Sites

An ideal stimulation site is one that is easily accessible in the operating room and where the corresponding neuromuscular response can be identified clearly and unmistakably. One caution is to avoid any direct muscle stimulation; positioning is a very important factor in proper stimulation of the respective motor nerve. To ensure that the selected stimulation current is conducted at full strength against the skin's resistance, it is important to make sure the electrodes have contact with the smallest possible area. Typically, the contact area of the stimulation electrodes should not exceed a diameter of 7-11 mm. Furthermore, the electrodes should be positioned somewhere between 3-6 cm apart on either side of the course of the nerve. Any significantly larger or small distance between the two electrodes should be avoided so it does not alter the penetration depth of the stimulation current. The three main sites of stimulation to monitor neuromuscular blockade are the ulnar nerve, the posterior tibial nerve, and the facial nerve.

Ulnar Nerve

The ulnar nerve is the most popular site for neuromuscular monitoring. For stimulation at this site, electrodes should be placed on the adductor pollicis muscle to measure thumb adduction. For correct stimulation, the positive electrode should be place approximately 2 to 4 centimeters proximal to the wrist crease, and the distal negative electrode should be placed at the ulnar head directly over the groove for ulnar nerve, which should be about 2 to 3 centimeters from the positive electrode.
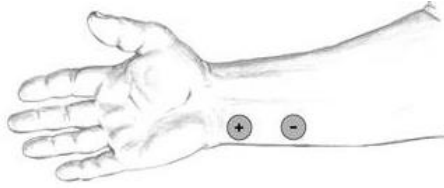
Figure 2.2-3– electrode placement for ulnar nerve stimulation

Picture from http://ionphysiology.com/ssep%20settings.htm

One reason the ulnar nerve is used so frequently is that neuromuscular monitoring of this nerve-muscle unit will not normally affect the surgical conditions. Additionally, it is easily accessible intraoperatively, as long as the arm is placed in an outstretched position. A big advantage is that the adductor pollicis muscle is located on the lateral side of the arm, while the ulnar nerve runs along the middle side, thus, there is little risk of any direct muscle stimulation, which can alter the results.

Posterior Tibial Nerve

If ulnar placement is not possible for the electrodes, neuromuscular monitoring can also be measured with the posterior tibial nerve. For stimulation, electrodes should be placed on the flexor hallucis brevis muscle to measure the flexion of the big toe. For correct stimulation, the positive electrode "should be placed between the medial malleolus of the ankle and the Achilles tendon just proximal to the malleolus" (http://ionphysiology.com/ssep%20settings.htm). The negative electrode should then be placed approximately 2 to 3 centimeters from the positive electrode. "This placement overlies the nerve as it follows a path around the malleolus. The ideal stimulation site is posterior to or slightly above the level of the malleolus, so as to stimulate both the medial and lateral plantar terminal nerve branches" (http://ionphysiology.com/ssep%20settings.htm).
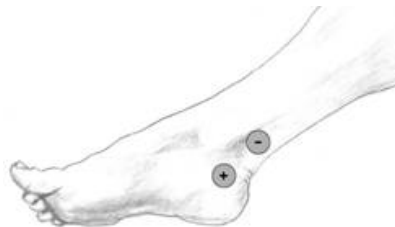
Figure 2.2-4 – electrode placement for posterior tibial nerve stimulation

Picture from http://ionphysiology.com/ssep%20settings.htm

Similar results have been found for the posterior tibial nerve as for the ulnar nerve. It is always a good choice for neuromuscular monitoring whenever the arms have to be immobilized or tucked in the body, or access to them proves to be too much of an inconvenience. One big disadvantage, however, is that the

stimulation site and response for that site are both localized on the median side of the foot, resulting in a higher risk of direct muscle stimulation compared to stimulation of the ulnar nerve. Moreover, monitoring the posterior tibial nerve is often challenging because in many cases, anesthesiologists remain near the head of the patient during surgery and have drapes separating them from the lower parts of the patient's body.

Facial Nerve

Lastly, for facial nerve stimulation, electrodes should be placed on the orbicularis oculi muscle to measure the twitch of the eyelid. Correct electrode placement for stimulation of the facial nerve will show, "as it [the facial nerve] leaves behind the stylomastoid foramen near the tragus 2-3 cm posterior to the lateral border of the orbit" (*Monitoring of Neuromuscular Junction* PDF).
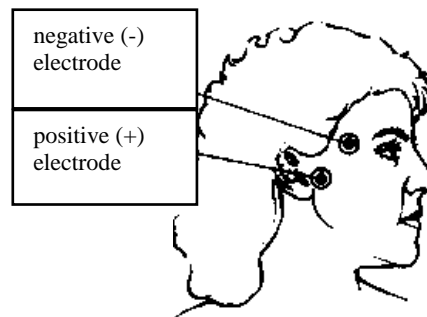

Figure 2.2-5 – electrode placement for facial nerve stimulation

(Picture from *Train of Four Monitoring* PDF)

Like previously mentioned, the anesthesiologist is mostly, if not always, at the head of the patient. Therefore, the main reason the facial nerve is favored as the stimulation site is that it usually gives the anesthesiologist a good and unimpaired access to the regions of the head throughout the entire surgery. Unfortunately, this stimulation site also offers the greatest risk of direct muscle stimulation compared to the ulnar and posterior tibial nerve. As a result, extra care must be taken so that the stimulation response is correct and not to falsely interpret the effect of neuromuscular blockade by another twitching muscle. Also, research has shown that lower currents, as little as 25-30 mA, are sufficient to elicit a response. Additionally, using higher currents for stimulation creates a greater risk of direct muscle stimulation due to the nerve's close proximity to the mimic muscles. To measure neuromuscular blockade at this site, an acceleration transducer should be used. However, stimulation at the orbicularis oculi muscle has proven to be difficult and frequently unsatisfactory in clinical practice.

Patterns of Nerve Stimulation

For evaluation of neuromuscular function, the most commonly used patterns of peripheral nerve stimulation are single twitch, train-of-four (TOF), tetanic, post-tetanic count (PTC), and double-burst stimulation (DBS).

Single Twitch

Single-twitch monitoring is the simplest form of nerve stimulation and, for many years, also offered the only mechanical means of monitoring neuromuscular blockade. In the single-twitch mode of stimulation, single supramaximal electrical stimuli are applied to a peripheral motor nerve at frequencies ranging from 1.0 Hz (once every second) to 0.1 Hz (once every 10 seconds). It is important to note that the twitch can fade after high-frequency stimulation. As soon as a stimulation frequency of 0.15 Hz is exceeded, fade, or fatigue of the muscle response, can be observed. As a result, a frequency of 0.1 Hz is generally used. Because 1-Hz stimulation shortens the time necessary to determine supramaximal stimulation, this frequency has proven to be most useful to use at the onset of neuromuscular block. Using a single twitch at 1 Hz (1 twitch every second), it is possible to establish the level at which a supramaximal stimulus is obtained. The onset of neuromuscular block can then be observed, using a single twitch at 0.1Hz (1 twitch every 10s). The disadvantage to single-twitch stimulation is that it can only be used to measure the extent of muscle response when it is compared to a reference value; as a stand-alone stimulation pattern, it has no clinical relevance.
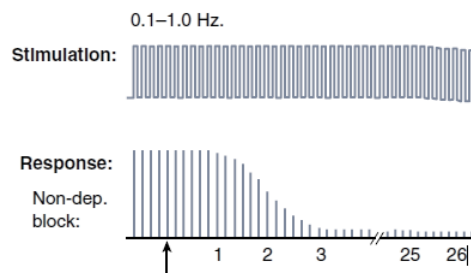
Figure 2.2-6 – Pattern of electrical stimulation and evoked muscle responses to single-twitch nerve stimulation at frequencies of 0.1 to 1.0 Hz after injection of non-depolarizing neuromuscular blocking drugs (*arrow*).

(Picture from *Ch 47. Neuromuscular Monitoring* PDF)

Train-of-Four (TOF)

This is the most popular mode of stimulation for clinical monitoring of neuromuscular blockades. The aim of this stimulation pattern was to deliver sound results even with a simple nerve stimulator and without the need for complicated objective monitoring. Its introduction made it possible for the first time to obtain essential information about the relevant phases of neuromuscular blockade, i.e., at the onset of action, during surgical blockade and neuromuscular recovery, in particular after administration of non-depolarizing relaxants. This

mode involves four successive stimuli that stimulate the target motor nerve every 0.5 seconds. The stimulation frequency here is thus 2/s, or the equivalent of 2 Hz. Just like any other stimulation, if it is applied too frequently, progressive fade of the motor response may indeed be observed. To prevent this from appearing and falsifying the interpretation of the neuromuscular blockade, a sufficiently large interval must be given between two TOF series to let the neuromuscular endplate regenerate. If a minimum interval of 10 seconds is maintained between two successive TOF series, this fading can be ruled out with certainty. The ratio of the amplitude of the fourth response by the amplitude of the first response provides the TOF ratio. Before the administration of muscle relaxants, all four responses are ideally the same; thus the TOF ratio should be 1.0. With increasing degrees of blockade, the twitches in the train of four slowly fade starting with the fourth twitch (T_4), and one by one eventually disappear. As muscle contractions reappear, they do so in the reverse order of their disappearance, i.e., the first response in the series of four is able to be detected first, then the second, third, and fourth.

There are several advantages with TOF stimulation which makes it a frequent choice in daily clinical use. It can be applied to a patient at any time during the neuromuscular block and can still provide quantification of depth of block without the need for control measurement, or a reference value, before relaxant administration. Due to the correlation between the depths of the block with the number of responses frees the clinician from having to use a recording device to calculate the TOF ratio. The relatively low frequency offers the capability to evaluate the response manually or visibly. It may be delivered at submaximal current. Also, TOF stimulation, unlike tetanic stimulation, does not generally affect the degree of neuromuscular blockade.
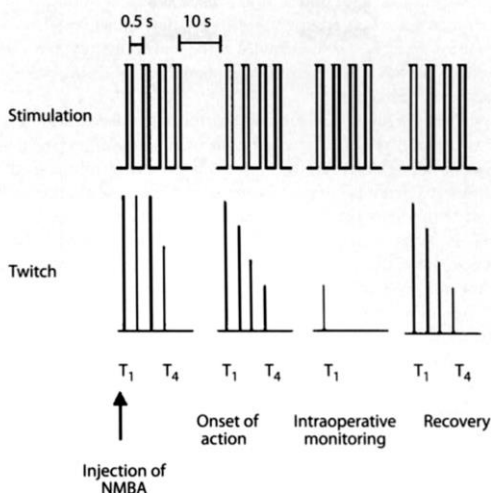

Figure 2.2-7 - Pattern of electrical stimulation and evoked muscle response to TOF nerve stimulation before and after injection of non-depolarizing neuromuscular blocking drugs (*arrow*).   (picture from book)

TOF Response	Approximate Percentage of Receptors Blocked by Agent	Clinical Significance
Four twitches	0 to 75%	Patient may be able to move but may experience weakness. Responsive to antagonist, or a reversal drug for the blockade.
Three twitches	75%	Administration of additional drug may be needed to prolong relaxation. Short or intermediate acting agents may be reversible.
Two twitches	80%	Suitable for both short term relaxation as well as long term mechanical ventilation.
One twitch	90%	Conditions suitable for short term procedures including intubation and long term mechanical ventilation.
No twitches	100%	Best conditions for intubation. Long term saturation may lead to prolonged effects.

Table 2.2-1 – Table displaying the approximate percentage of receptors blocked and the clinical significance based on number of twitches.

Tetanic

Tetanic stimulation is the concept of using a very rapid delivery of electrical stimuli. It was brought about to reveal more affectively the incomplete neuromuscular recovery of a patient. Tetanic stimulation is done with a high frequency impulse, between 50 to 200 Hz, for duration of usually 5 seconds, sometimes less when given a higher frequency. Due to the individual stimulatory responses blending together, the anesthesiologist can only detect one strong, continuous muscle contraction. If the recovery of the NMBAs is incomplete, it will be seen by an increase in muscle force when initially stimulated, followed by a viewable fade. Thus, the higher the frequency of tetanic stimulation to the patient, the more pronounced the fade.

Tetanic stimulation is not suitable for monitoring intraoperatively, but has proven useful for evaluating neuromuscular recovery. Additionally, tetanic stimulation is extremely painful because of its high frequency. For that reason, it is mostly only employed on anesthetized patients, and even further, only reserved for research studies when stimulating at the higher frequencies. Currently, it is mainly only used as a component in the post-tetanic count.
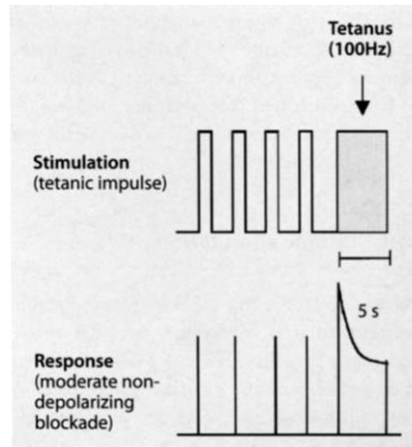
Figure 2.2-8– tetanic stimulation   (from book)

Post-Tetanic Count (PTC)

With making this stimulation pattern, the aim was to find a more powerful alternative to TOF when monitoring deep neuromuscular blockades. When initially being injected with neuromuscular blocking drugs, there is such a large dose to ensure smooth tracheal intubation. During this time, no response is shown to either TOF or single-twitch stimulation under these conditions. Therefore, these stimulations are not able to be used to determine the degree of the blockade of a patient at the onset of the drug being given. It has been made possible, however, to quantify intense neuromuscular blockade of the peripheral muscles by applying a tetanic stimulation. This will induce a transient exaggerated release of acetylcholine that is sent to the end motor nerve. Once this happens, even if there was no discernible twitch before, there will usually be a brief, but noticeable, muscle contraction afterwards. First, the anesthesiologist applies a tetanic stimulation of usually 50 Hz for 5 seconds, and then observes the post-tetanic response to single-twitch stimulation, which is given at 1 Hz starting 3 seconds after the end of the tetanic stimulation. During truly intense blockade, there will still be no response, however, when the intense neuromuscular blockade begins to wear off, but before response can be seen by the TOF, the first response to post-tetanic stimulation occurs. The PTC method is mainly used to assess the degree of neuromuscular blockade if no response is displayed to the TOF.
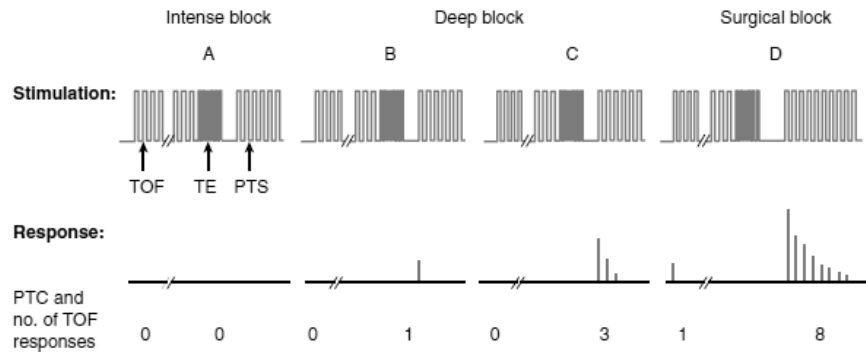
Figure 2.2-9– Stimulation and responses to TOF nerve stimulation, 50-Hz tetanic nerve stimulation for 5 sec (TE), and 1.0-Hz post tetanic twitch stimulation (PTS) during 4 levels of neuromuscular blockade

(Picture from *Ch 47. Neuromuscular Monitoring* PDF)

Double-Burst Stimulation (DBS)

The goal of double-burst stimulation was to establish a stimulation pattern that was even more sensitive than the TOF in the manual or visual assessment of residual blockade. DBS consists of two short bursts of 50-Hz tetanic stimulation pulses separated by a 750-msec interval. The duration of each individual square wave impulse in the burst is 0.2 msec. In the DBS3,3 mode, which is considered to be the most popular, there are three impulses in each of the two bursts. However, another choice is the DBS3,2 mode, which has three impulses in the first burst but only two individual impulses in the second burst. The response in the DBS3,3 mode in a non-paralyzed muscle is two short muscle contractions of equal strength. When the muscle has been partly paralyzed, the response of the second muscle contraction will be weaker than the first and will show fade. There is a close correlation between the TOF ratio and the DBS3,3 ratios, when measured mechanically.
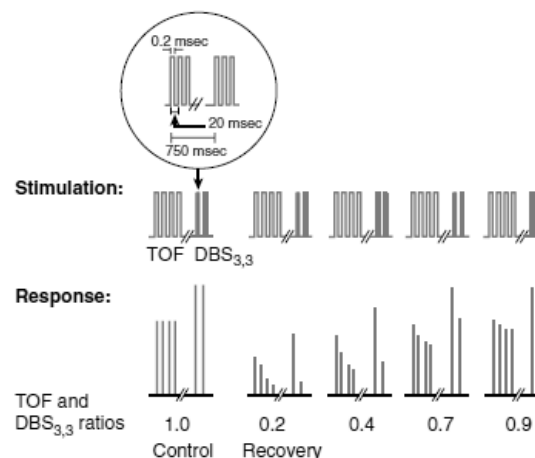

Figure 2.2-10 – comparing the stimulation and response of TOF and DBS3,3

2.2.C Measuring Methods

There are different methods that can be used to objectively measure the depth of neuromuscular blockade in a patient. The major ones include mechanomyography (MMG), electromyography (EMG), acceleromyography (AMG), kinemyography, and phonomyography (PMG). These methods measure either the compound muscle action potential or the evoked contractile response.

Mechanomyography (MMG)

Mechanomyography is the only approach that directly measures muscle force, which best reflects the degree of relaxation of a given muscle. For correct and reproducible data of the evoked tension, it is required that the muscle contraction be isometric. To do this, the palm of the hand is turned upward and restrained in this position. The thumb movement is then measured after the resting tension of 2-3 N to the thumb is applied. When the ulnar nerve is stimulated, the thumb acts on a force-displacement transducer. This transducer should be attached in such a way that the force development, or tension, of the thumb is applied exactly along the length axis of the transducer. The force of contraction is then converted into an electrical signal, which is amplified, displayed, and recorded.

Mechanomyography requires the most stringent preparation and precautions, making it far from ideal for routine clinical use. The preload and abduction of the thumb are critical to the measurement's accuracy. Just a slight adjustment in the position of the hand can change the preload and/or the degree of abduction, and thus disproportionately affecting the results of the force development. Therefore, the arm and hand should be rigidly fixed. This method must also be taken with caution so as to prevent overloading of the transducer. Moreover, reaction to the supramaximal stimulation increases during the first 15 minutes. Thus, recording of the control response (before injection of the muscle relaxant) should not be made until an appropriately long stabilization phase has passed as to avoid falsification of the measurement. At this point, the reference value is determined by the device; then the NMBA can be injected and the actual measurement started.

This measuring method is very time-consuming and prone to malfunction, and the MMG devices are awkward and bulky to prepare, making it an unsuitable choice for this project.

Electromyography (EMG)

The electrical activity of a muscle is proportional to its force development. As an alternative to the direct measurement of muscle force, electromyography can be used to record the electrical activity of the muscle and thus to indirectly quantify neuromuscular blockades. Evoked EMG records the compound action potentials produced by stimulation of a peripheral nerve. In addition to the two stimulation electrodes, this method requires another three surface electrodes applied over

the belly of the test muscle to record the action potentials. Most often, the evoked EMG is done to the ulnar nerve, and the EMG response is obtained from the thenar or hypothenar eminence of the hand, preferably with the active electrode over the motor point of the muscle. Typically, electromyographical stimulation is applied in the TOF mode. After stimulation, the signal is picked up by the analyzer and is processed by an amplifier, a rectifier, and an electronic integrator, and results display as the TOF ratio.

Data captured by electromyography show very good agreement with those obtained by mechanomyographic methods for assessing the neuromuscular blockade. EMG proves beneficial for practical application because it does not require complete immobilization or a constant preload of the selected test muscle; instead, measurements can be taken with the hand in any position. This feature makes it extremely useful for everyday clinical use where operating rooms are small and crowded with medical staff and equipment. In addition, an evoked electromyogram can also be recorded on muscles, like the diaphragm, that are not monitorable by mechanomography. Overall, electromyography is far less complicated to perform as well. However, evoked EMG does entail some difficulties. The results of recordings are not always reliable. One reason is because inadequate pick of the compound EMG signal may result if there is improper placement of the electrodes. In addition, recording electrodes may pick up an electrical signal even though neuromuscular transmission is completely blocked as a result of direct muscle stimulation. Technical problems which can arise overtime with EMG include drift over time – the EMG potential does not return to control levels, failure to descent completely in fully relaxed muscles, and interference with other electronic devices.

Acceleromyography (AMG)

Acceleromyography measures acceleration of a given end-organ, such as the thumb. It is a technique based on Newton's second law:

FORCE = MASS X ACCELERATION

If mass is constant, acceleration is therefore directly proportional to force. Thus, after nerve stimulation, one can measure not only the evoked force but also acceleration. Acceleromyography is based on the piezoelectric effect, which derives from the phenomenon that electrical charges can be present on the surface of certain materials, mostly crystals. Their electrical current is induced by acceleration of the piezoelectric element, or the acceleration transducer. Once acceleration is measured, deductions are made to provide information about the force of the stimulated muscle.

Thus, acceleromyography can be performed on muscles that can be easily measured after stimulation. Evoked stimulation is usually performed on the ulnar nerve and the acceleration is then measured with a piezo electrode that is fixed to the thumb. Alternatively, it can also be applied to the nerve-muscle unit of the posterior tibial nerve or the facial nerve with the orbicularis oculi muscle.

Acceleromyography uses a piezoelectric ceramic wafer with electrodes on both sides. This signal can then be analyzed and displayed on a recording system. For accurate and reliable measurements, the thumb may only move in a strictly horizontal direction if measuring with a single-axis accelerometer. Acceleromyography is frequently used today because it is easy to apply, can be used with data processing devices and is relatively inexpensive.

The TOF-Watch is one detached monitor based on measurement of acceleration that is commercially available today. One feature that the TOF-Watch has made available is the hand adapter to keep the thumb in place. It still allows the entire arm to be restricted in place like other recording devices do, but it allows for more reliable measurements. Originally, accelerometers required that the thumb move freely, but to measure a preload, at least in research studies. However, it was realized that accurate readings were not being measured because the thumb did not return exactly to its starting position during a TOF sequence, and as a result, its resting extension changed before the next TOF stimulation. This preload has proven to be very beneficial because it allows the thumb to always return back to its exact starting position. Thus, measurements are less prone to error. Another main reason to add this feature to neuromuscular monitoring is because repositioning of the patient during operation is actually quite a common practice, such as lowering their head or turning them on their side. With these shifts, it can alter the patient's thumb position, making the measurements useless at that point.

With this project, the goal will be not to have anything that is restricting to the patient, but something that allows for more stabilization and accuracy to the positioning of the stimulated nerve. Therefore, it is a possibility that testing it with a support, similar to the TOF-Watch hand adapter, is very possible.

Kinemyography

Kinemyography, like acceleromyography, is also based on the piezoelectric effect. However, the electrical current is generated by deformation of a mechanosensor integrated in the piezoelectric element, unlike acceleromyography, where the current is induced by acceleration of the piezoelectric element. It has been proven useful for research studies, but has not yet had accurate or reliable results for everyday clinical use.

Phonomyography (PMG)

Phonomyography records the sounds emitted by a muscle contraction through a condenser microphone applied to the skin's surface. This method is a relative new method of monitoring neuromuscular function. The contracted muscles generate intrinsic low-frequency sounds, which can then be recorded by the microphone. These signals are measured peak to peak between 4 and 6 Hz and are proportional to the force developed. Although good feedback has been seen from this method, it is unsure whether it will ever be used in daily use. One of the biggest advantages with PMG is that in theory, it has the ability to monitor the

different muscle groups that have been unable to be previously measured, such as the diaphragm, larynx, and eye muscles.

Stimulation Electrodes

The stimulus electrodes conduct the current selected on the nerve stimulator against the skin resistance to the underlying tissue structures. They are crucially important in the quality of neuromuscular monitoring because they help ensure that the target motor nerve is actually stimulated. The electrode type can play an important factor in proper stimulation of the respective motor nerve.

Electrodes come in a few different varieties, but the basis is the same. An ECG electrode is usually composed of a small metal plate surrounded by an adhesive pad, which is coated with conducting gel to help transmit the electrical signal. The wire that connects the ECG electrode to the current source is clipped to the back of the electrode. Some electrodes are reusable, and other types are intended to be disposable after a single use. For our project, we will use ECG-type electrodes of the silver/silver chloride variety, or Ag/AgCl.

Reusable Ag/AgCl Electrodes

Pros:

- Permanently connected to leads which offer quick ease of access
- Reusable electrodes offer no waste and less expense to the consumers who are using them

Cons:

- They do not have adhesive disks included, which are required before use. Therefore anesthetists have to take the time to add these on each time before use.
- They do not come with recording gel, which is needed before each use.
- It takes time to clean them each time.
- Possible chance of electrodes not being cleaned thoroughly, which can affect results of next use.
- They have several warnings for handling that can be easily forgotten. These include: not cleaning them in hot water, making sure they are completely dry before returning to storage, and not allowing the electrodes to come into contact with each other during storage because it may cause an adverse reaction to take place.

Disposable Ag/AgCl Electrodes

Pros:

- Always sanitary, which is extremely important for hospital use
- Convenient and easy to use because they are pre-gelled and have peel-and-stick backing that already have the adhesive disk

- Saves time
- Don't have to handle them with caution like one would with reusable electrodes
- Some have been specially developed for neuromuscular monitoring

Cons:

- Although individually cheaper, they cost more overall because they are disposable and therefore must constantly be purchased
- Not eco-friendly
- Does not come with an electrode lead

Because of all the major benefits of using disposable electrodes, unlike the reusable electrodes with their numerous disadvantages, this project will be using the disposable type of electrodes. Dr. Looke also says disposable items are the way of the future for hospitals, which allow them to keep things as sanitary and efficient as possible.
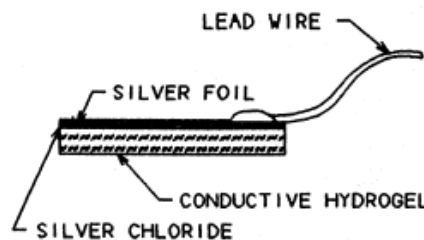

Figure 2.2-1– cross section of disposable hydrogel electrode

(picture from http://www.fis.uc.pt/data/20062007/apontamentos/apnt_134_5.pdf)

There are two general types of disposable electrodes that can be used for the stimulation in neuromuscular monitoring. There is the basic, single Ag/AgCl adhesive electrode that is pre-gelled and is high chloride for quick, accurate readings. The other type of electrode is the paired Ag/AgCl electrodes. These electrodes have been specially made for neuromuscular monitoring. As stated previously, electrode placement is vital to the accuracy of the monitoring results. It was stated that electrodes should be between 3 to 6 centimeters apart. Therefore, paired electrodes (one positive and one negative) have been made commercially available that offer a fixed distance for quicker setup.

One option that could be used for the single, Ag/AgCl disposable electrodes is the EL503 series by BIOPAC Systems, Inc. These snap electrodes do not contain any latex. They are easy and convenient because they are adhesive, pre-gelled, and designed for one use only.

Figure 2.2-2 – EL503 single surface electrodes

(picture from http://www.biopac.com/disposable-electrode-100)

For a pack of 100 individual electrodes, the BIOPAC Systems, Inc. website lists the price to be $38 without tax. When realizing that each patient needs two electrodes, the pack is able to be used on 50 patients. Therefore, the price for two electrodes, or for one person, is $0.76.

Because disposable electrodes do not come with leads, one must include the added expense for those as well. With the EL500 series, the BIOPAC Systems, Inc. website recommends the LEAD110 series electrode leads. For best results, use shielded leads with recording electrodes for minimal noise interference. On the other hand, the unshielded leads work best with ground or reference electrodes. As listed, one of each lead in the series is needed for each Biopotential amplifier module. These lead types are: LEAD110S-W, LEAD110S-R, and LEAD110.

Budget			
Item	**Shielded/Unshielded**	**Color**	**Price**
LEAD110S-W	Shielded	White	$39
LEAD110S-R	Shielded	Red	$39
LEAD110	Unshielded	Black	$15
Total Price of Leads:			$93

Another example that could be used is the EL500 series by BIOPAC Systems, Inc. They have been specially developed for peripheral nerve stimulation and recording for nerve conduction measurements. The EL500 is an electrode pair that has a 4.1 cm spacing (from center to center). They are advantageous because not having the correct distance might alter the penetration depth of the stimulation current, thus potentially preventing optimal stimulation of the target nerve. The EL500 electrodes have foam backing of size 42mm x 82mm x 1.5mm.

Figure 2.2-3 – The EL500 paired electrodes

(Picture from http://www.biopac.com/disposable-paired-electrode-foam-25pairs)

These types of electrodes can prove to be quite costly, however, when bought in large quantities. For 25 pairs of electrodes, the BIOPAC Systems, Inc. website lists the price to be $42 without tax. That is $1.68 per electrode pair, or the price per patient. For the EL500 series, one would also use the LEAD110 series electrode leads as well.

Although for testing, many electrodes will not be used, in the larger aspect for hospitals with thousands of patients, it is important to be efficient while also not wasting money. As seen, however, the price of two electrodes more than doubles for each patient when using the paired electrodes. Therefore, testing will be done with the individual electrodes.

2.3 Related Projects & Shortcomings

In coming up with this design time was spent browsing through other designs that have worked in the past to see what can be improved on as well as what technology can still be used in the new design. Problems that were found by the group and by others who have researched these devices were not overlooked but were taken into consideration so that as a group these problems could be solved and the end product would be better than the previous ones and cause less fear in the ability of them to harm the patients.

2.3.A The Anesthesiologist as the Sensor

In the operating rooms today Dr. Looke and many other anesthesiologists like him use a simple device that provides current in one of three ways: a twitch (one pulse of current per second), a steady current flow based off of how long the button is pressed, and the train-of-four (four pulses over a period of two seconds.) While the patient is awake the anesthesiologist applies two electrodes to the nerves that control the body part (the eye, thumb, or the toe) that they have access to and are able to monitor. While the current is pulsing through the nerve the anesthesiologist has two choices, they can either watch to see if there is a twitch or they can place their pointer and middle finger underneath the corresponding body part and see if they can feel the twitches that are being produced by the lack of anesthesia in the patient's body and they can decide from there whether or not to administer more.

2.3.B Force Transducer

In certain designs such as in US Patent No. 4,848,359 "New Developments in Clinical Monitoring of Neuromuscular Transmission: Measuring the Mechanical response" by J. Viby-Mogensen the muscle response is measured using a force transducer. This response is created by the stimulation of the muscle by an electrical current that is applied through the nerve in a similar way to the current that is applied in the above example. However instead of the anesthesiologist monitoring the force with their hands or just visually, a force transducer is used in their place. The force transducers in these designs require the patient's arm to be

restrained in order for the reading to be accurate. The transducer will register the force when the twitch is present and records the data for the anesthesiologist to see the strength of the twitches.

2.3.C Accelerometers

The use of accelerometers being used to measure the force of the twitches is one of the more common methods being implemented today. This method uses either a biaxial or a triaxial accelerometer that is placed on the thumb of the patient being monitored. When the nerve is stimulated the twitch is created which is monitored by the accelerometer and using the well-known force equation you can relate the acceleration to the force of the actual twitch. This method has also been used on the face in order to monitor the eye when the thumb or the foot is covered and are unable to be monitored.

2.3.D Piezoelectric Sensor

The flexible piezoelectric sensors that are produced in sheets also were one of the sensors that were used in previous designs. This sensor is used in U.S. Patent No. 5,131,401 "Method and Apparatus for Monitoring Neuromuscular blockage" where the sensor is placed on the palm of the patient's hand. This method does not require the arm to be restrained in order for the measurement to be accurate. This design monitors the smaller movement used in the contraction of the muscles that lie underneath the skin instead of the larger movement of the thumb in order to get its reading. It also stimulates the peripheral motor nerve instead of the ulna nerve that the more common sensors like the accelerometer or the anesthesiologists hand needs. This also has a processer within the device that is capable of making a visual representation of the response of the neuromuscular block caused by the anesthesia.

2.3.E Electromyography

Electromyography (EMG) evaluates the electrical activity or potential of the skeletal muscles. Using the surface electrodes the anesthesiologist can obtain the results needed through non-invasive means. While stimulating the nerves that control the muscles that need to be measured, the devices can measure the activity of these nerves without having to see or feel the force of the twitch.

2.3.F Shortcomings

After looking at all of the different methods that have been implemented in the past few years it became apparent that each one of them has their own shortcoming. The first method with the visual and the actual use of the anesthesiologist's finger has quite a few issues. The device that supplies the current to the nerve only runs on a nine volt battery meaning that the anesthesiologist would need to bring in extra batteries to make sure the device

will last through the entire surgery. There also is not an indicator as to whether or not there is juice in the battery so they could assume that they are applying 30 mA of current through the nerves when in fact they are not sending anything which would result in a false negative. Also, the only way to choose how much current is being supplied would have to be a guess because there is only a dial on the side of the device that allows you to choose the current that is being supplied. There is no indication as to how much current is being supplied so it really could be supplying 30 mA or 25 mA of current. There is no way of being completely positive that you are using the same amount of current every time the device is applied. The anesthesiologist may miss the actual twitch and assume that the neuromuscular blockage medicine is still working properly.

This method requires the anesthesiologist to be confident with his knowledge of the medicine and the patient's charts. They have to keep track of the time since they have administered the anesthesia in order to know when they need to give more. If they are too late in checking to see if they are waking up then the surgeon is going to let the anesthesiologist that the patient is moving under their knives.

Also, when our individual team members shadowed Dr. Looke in the operating room the conditions that the anesthesiologists work under became apparent. In the operating room a blue drape is put up to separate the sterile surgical field from the rest of the people in the room. So even if the hand is readily available they may have to go under the drape to check the patients thumb in order to see if there is a resulting twitch once they turn on the current device. This becomes rather inconvenient and this is under the best circumstances. One of the surgeries that Ryan watched they were unable to even get to the hand because it was tucked to the side of the patient and was covered by blankets, so only the eye was available to monitor.

When the arms are tucked to the sides of the patient this causes any of the sensors that require a restrained arm not to be allowed to be used. So the force transducer would not be a viable option for surgeries of this nature. Also, when the arm is restrained there is a chance of damaging the nerve or tissue if the arm is not position properly with respect to the transducer.

In hospitals cost is an issue because they try to keep everything that they use on the patients to be disposable in order to keep cross contamination to a minimum. With this in mind the devices that use the force transducer and the accelerometers that measure in more than just one direction are too costly in order to make them disposable so the hospital would need to put a protective barrier between the patient and the device or resort to washing it after each use. This becomes a bit of a pain and in most cases probably will not happen.

In the designs that use electromyography the problems lie with the difficulty of the actual application and the sophisticated equipment that is used. There is

also, the problem of excessive noise that creates a problem when the anesthesiologist is trying to decipher if there is activity that needs to be addressed or if it is just a false negative.

2.4 Controllers

This section of the document will look at different types of controllers that will be used in this project. The types of controllers that will be looked at are: microcontrollers, graphics display controllers, wireless transceivers and SoC chips for wireless transmission. In addition to various controllers, section 2.5 will look into wireless display modules for this project and compare two different display types, capacitive and resistive. Each part will be looked at in more depth and the pros and cons of each will be highlighted to help make a decision on the best suitable parts for the project design and how one device better fits the intended design and scope of this project.
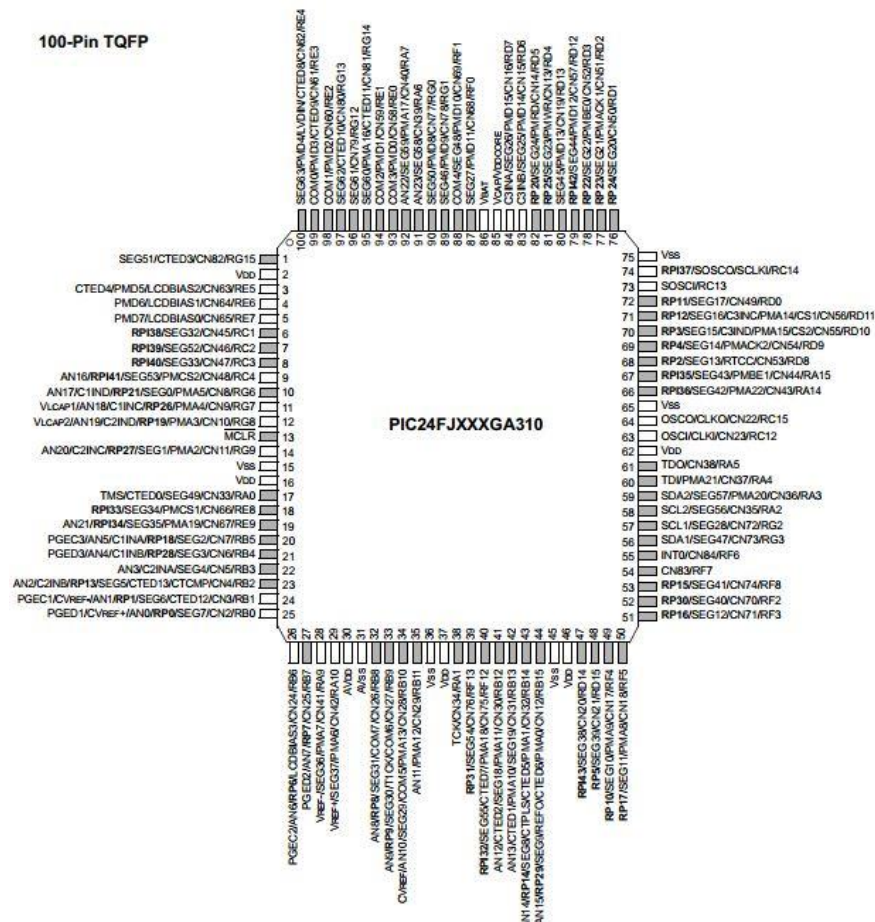
2.4.A Microcontrollers

A microcontroller is a dedicated chip in computer electronics that is used to perform very specific tasks/functions. For the purpose of this project a microcontroller will be used because of its small size, low cost and low-power consumption. A microcontroller takes input from the devices it controls and sends signals to different project components to achieve a specific task.

PIC24FJ64GA310 – This Microchip microcontroller is a very low powered chip that is designed for extremely low power consumption applications that run on battery power. This device has many low power features including a low voltage sleep mode, where the device state RAM is maintained by only using 340 nA of current and also a Vbat pin that allows the microcontroller to transition to battery power when Vdd is turned off or removed. In addition to all this the MCU has a 480 segment LCD Driver that can be very useful for this project when displaying sensor data from the patient.

This chip has a 16-bit MIPS CPU with 64KB Flash along with 8192 RAM bytes that operates at 32MHz. The chips' operating voltage is a typical 2V to 3.6V range that many of the competing chips have. This chip is fairly large with 100 pin count along with 85 I/O pins to interface the chip with your design. For digital communication, the chip has 4-UART, 2-SPI and 2-I2C peripherals. As for analog peripherals, this chip has a 12-bit A/D converter, 3 comparators and five 16-bit timers. There are a few variations of this chip within the chip family with fewer pin counts and different RAM size (32KB, 64KB and 128KB).

PROS	CONS
Samples Available	Relatively large in size (14 x 14 mm)
85 I/O Pins	No D/A converter built-in
Free IDE for students	No LCD Driver for TFT Displays
Very low power consumption	
Five 16-bit timers	
Sample code and libraries available	
C compiler optimized instruction set	
Fail-safe clock monitor	
JTAG programming interface	

Table 2.4-1: Pros and Cons for TI CF430F5137 Microcontroller

**Figure 2.4-1:** PIC24FJ64GA310 Pin Configuration - Courtesy of Microchip

MSP430F5438A – This Texas Instruments microcontroller is of ultralow-power family of chips that could be used for a variety of applications. The architecture of

this chip and its low-power mode is optimized to achieve great battery life in portable applications. This device has a 16-bit RISC CPU Architecture with 16-bit registers, up to 25MHz system clock, extended memory, wakes up from standby mode in less than 5us and three 16-bit timers.

When it comes to serial communication interfaces this device is similar to the PIC24F chip, it has up to four interfaces with each supporting UART, IrDA encoder and decoder, I2C and synchronous SPI. This device has a large flash memory size of 256KB, 16KB of SRAM along with 87 pins of I/O.

| PROS	CONS
Fairly fast 25MHz system clock	Not many open source libraries
16-bit registers	No LCD Driver for TFT Displays
Free IDE for MSP430 chips	Too large in size for this project
256KB of flash memory	Smaller SRAM than other MCUs
87 I/O pins	Relatively large in size (14 x 14 mm)
Compile code in C and Assembly	
Four USCI_A	
Low price and available samples	

Table 2.4-2: Pros and Cons for TI MSP430F5438A Microcontroller
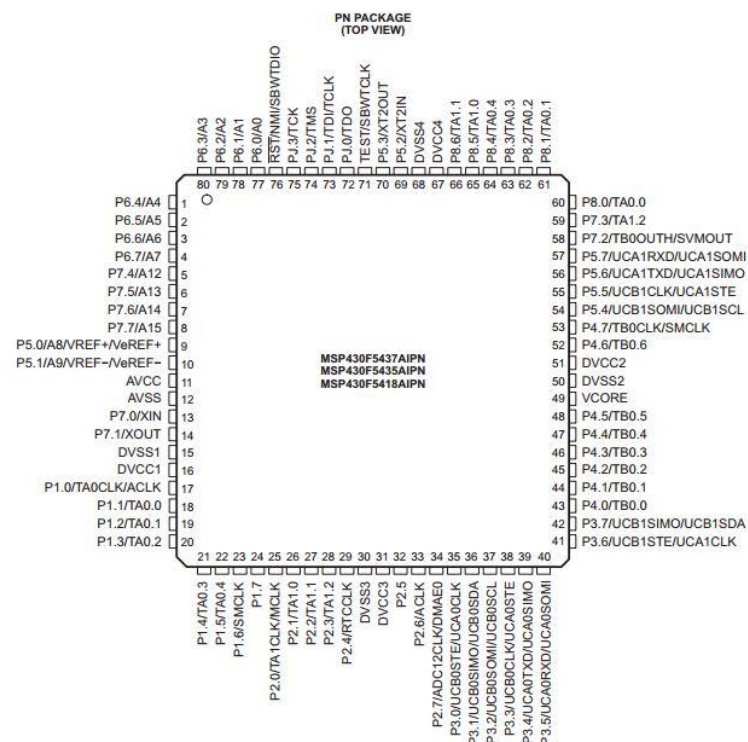
Figure 2.4-2: MSP430F5438A Pin Setup – Courtesy of Texas Instruments

MSP430F5329 – This Texas Instruments microcontroller is very similar to the above TI chip, but has its' subtle differences. This device runs on 1.8V to 3.6V and has a very fast wake-up from low-power mode of 3.5us. The device has a very powerful 16-bit RISC CPU with 16-bit registers and a system clock up to 25MHz. Among other features that are important to this project are: 12-bit AD converter, two universal serial communication interfaces, hardware multiplier, and real-time clock module. This chip is relatively small in size and has 63 I/O pins, which plenty enough for this type of project. This chip has 128KB of Flash memory, 10240 Bytes of SRAM and four 16-bit timers. This MCU would be a good choice for the finger sensor, since it has enough RAM and memory for the given application. Typically this device is used in applications like: analog and digital sensor systems, data loggers and other general purpose applications that require very low power usage.
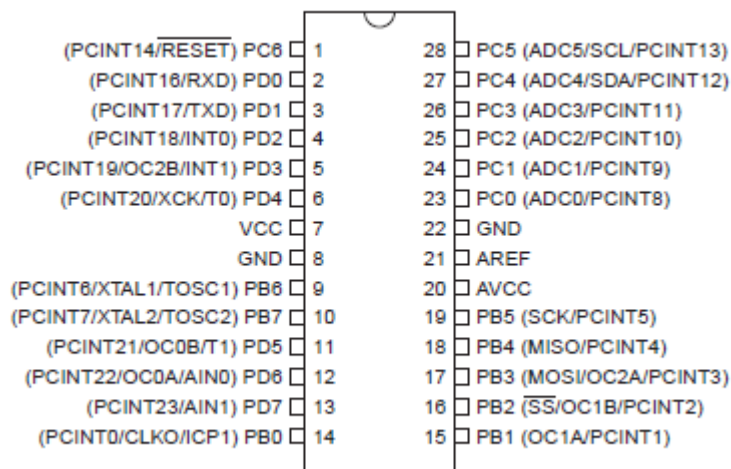
PROS	CONS
Relatively small in size	Higher power consumption than other chips
Samples available	Not enough internal ADC channels
Fast wake-up in 3.5us	Not many open source libraries
128KB of flash memory	
63 I/O pins	
10240 Bytes of SRAM	
Three channel DMA controller	
Temperature sensor	
Table 2.4-3: Pros and Cons for TI MSP430F5329 Microcontroller	
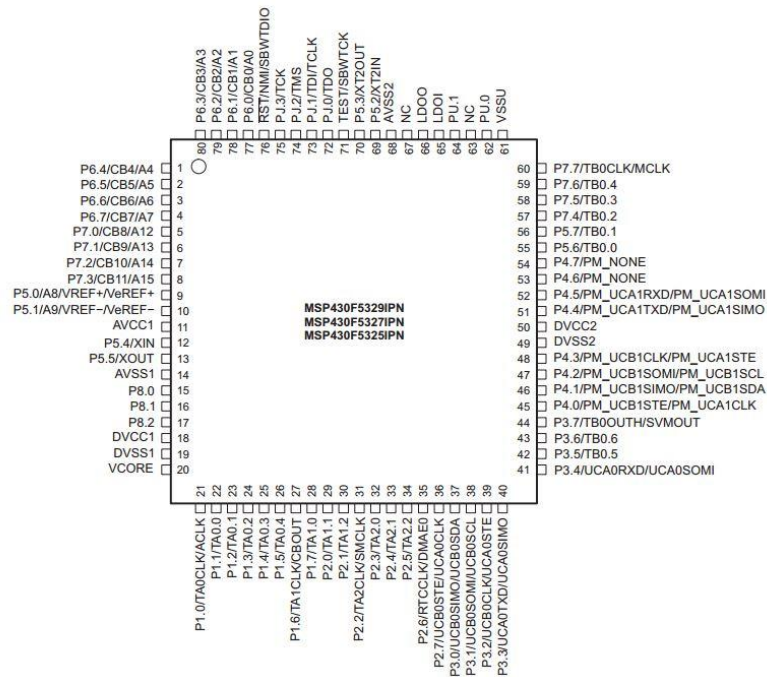
Figure 2.4-3: MSP430F5329 Pin Configuration – Courtesy of Texas Instruments

ATmega328P – This microcontroller is used on the arduino board that we are using to test out the sensors that we are using. This devices runs on a maximum of 6.0V and has 28 pins which is just enough for what we need and there are very few pins that would go unused. This controller also has 32K bytes of reprogrammable flash memory and 2048 bytes of SRAM. This microcontroller would be a good choice for our project because it gives us everything we need but at the same time it does not leave us with too many extra features that we do not really need. This means that if this is the chip that we choose we would not have wasted space. Plus we can easily obtain this chip as a sample so we would not need to purchase it keeping our final cost low.

PROS	CONS
Relatively small in size	Higher power consumption than other chips
Samples available	Not enough internal ADC channels
Tons of open source libraries	Only an 8-bit MCU
Programming lock	
23 I/O pins	
Low power consumption	
Used before	
Table 2.4-4: Pros and Cons for ATmega328P Microcontroller	


```
(PCINT14/RESET) PC6 ▯ 1          28 ▯ PC5 (ADC5/SCL/PCINT13)
(PCINT16/RXD) PD0 ▯ 2            27 ▯ PC4 (ADC4/SDA/PCINT12)
(PCINT17/TXD) PD1 ▯ 3            26 ▯ PC3 (ADC3/PCINT11)
(PCINT18/INT0) PD2 ▯ 4          25 ▯ PC2 (ADC2/PCINT10)
(PCINT19/OC2B/INT1) PD3 ▯ 5     24 ▯ PC1 (ADC1/PCINT9)
(PCINT20/XCK/T0) PD4 ▯ 6        23 ▯ PC0 (ADC0/PCINT8)
VCC ▯ 7                         22 ▯ GND
GND ▯ 8                         21 ▯ AREF
(PCINT6/XTAL1/TOSC1) PB6 ▯ 9    20 ▯ AVCC
(PCINT7/XTAL2/TOSC2) PB7 ▯ 10   19 ▯ PB5 (SCK/PCINT5)
(PCINT21/OC0B/T1) PD5 ▯ 11      18 ▯ PB4 (MISO/PCINT4)
(PCINT22/OC0A/AIN0) PD6 ▯ 12    17 ▯ PB3 (MOSI/OC2A/PCINT3)
(PCINT23/AIN1) PD7 ▯ 13         16 ▯ PB2 (SS/OC1B/PCINT2)
(PCINT0/CLKO/ICP1) PB0 ▯ 14     15 ▯ PB1 (OC1A/PCINT1)
```

Figure 2.4-4: ATmega328P Pin Configuration – Courtesy of Atmel

2.4.B Microcontroller w/Transceiver

ATmega128RFA1 – This Atmega chip offers a unique SoC(Single-on-Chip Solution) that combines both the microcontroller and a 2.4GHz RF wireless transceiver in one chip which makes it a very convenient and potentially implementable chip choice for this project. This chip has a 2.4GHz IEEE 802.15.4 compliant RF transceiver with a link of 103.5dBm, 32-bit MAC symbol counter, temperature sensor, 128-bit AES encryption and high data rates up to 2Mb/s.

The microcontroller included with this chip has 128KB of Flash memory, 16MHz operating frequency, 16KB SRAM, 4096 EEPROM Bytes, 38 I/O pins, and its operating voltage (Vcc) is from 1.8V to 3.6V. Although this chip is very convenient for use in this project and is very small in size it has its disadvantages in small I/O pin count and small number of analog peripherals and most likely

won't be used for this project due to these issues. Due to project's constantly changing design and requirements this SoC chip still remains our top backup choice.

With that said, this microcontroller could be a very good chip to use with the thumb sensor that needs to be as small as possible and the transceiver can be used to send the sensor data to the wireless LCD display for graphing. Although the wireless LCD display is a secondary option that will be exercised if time permits.

PROS	CONS
128-bit AES encryption	Only one USCI_A port
128KB of flash memory	Small number of I/O ports
Low operating voltage 1.8 to 3.6 Volts	Only an 8-bit MCU
2.4GHz transceiver	Small memory size
6 Timers	
Built-in A/D converter	
Wake-on-Radio communication	
Small in size (9 x 9 mm)	
Code examples in Assembly and C	
Table 2.4-5: Pros and Cons for Atmel ATmega128RFA1 MCU with Built-In RF	
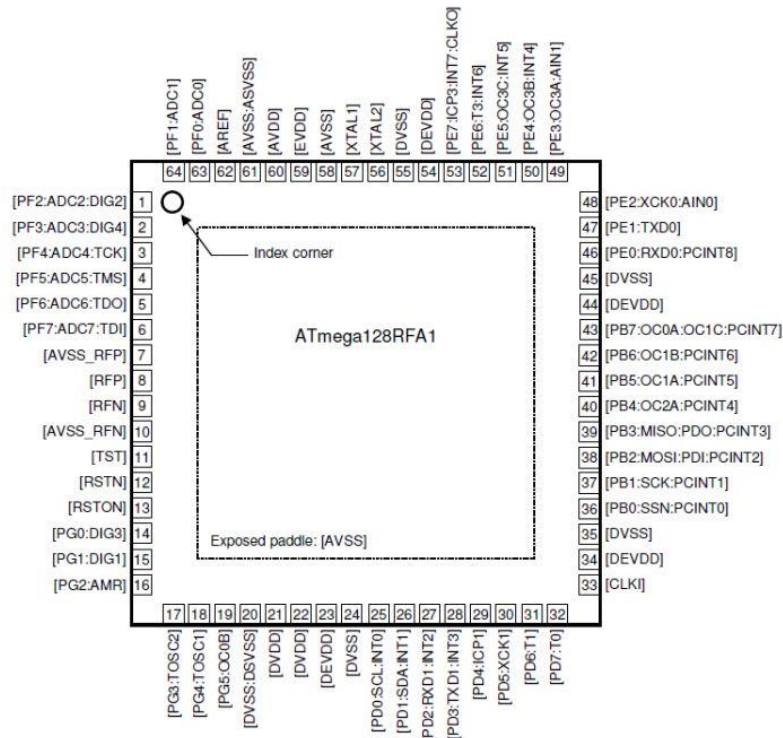
Figure 2.4-5: ATmega128RFA1 Pin Configuration – Courtesy of Atmel

_CC430F5137_ – This Texas Instruments device is a true System-on-Chip (SoC) that has a built-in wireless sub-1GHz RF transceiver built in. This part is a combination of two devices – the MSP430 microcontroller and the CC1101 RF transceiver. The MCU part of this chip is very similar to other TI microcontrollers described above, so the features of this specific MCU will not be discussed in detail. Some of the main features are: 32KB of flash memory, 4KB of RAM, two timers, A/D converter and 32 I/O pins.

The most important and catching part of this device is the combination of both the microcontroller and a transceiver. For this project, this chip is an ideal solution considering its' small size that will save space on the PCB board. This board can be programmed using C which is a widely used programming language and familiar to many students and beginner programmers. Because this board has a slower rate transceiver it is currently the second choice chip.

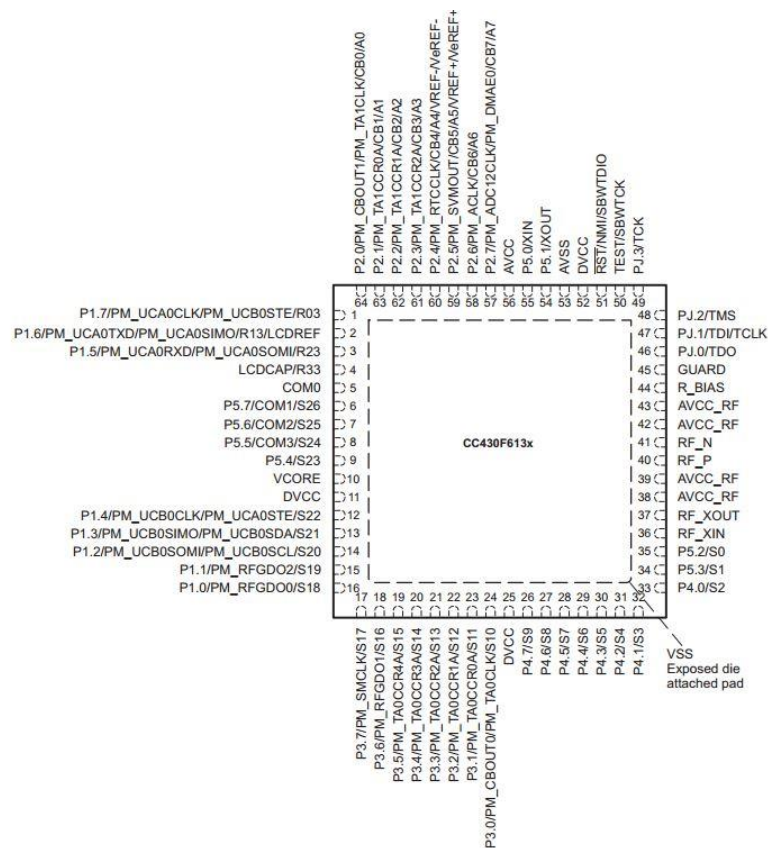| PROS	CONS
True SoC chip	32 I/O pins, might not be enough
Wake from stand-by in about 5us	Small number of A/D converters
Small in size (9 x 9 mm)	Slow data rates of the RF module
Real-time clock	
Free IDE	
Table 2.4-6: Pros and Cons for TI CF430F5137 Microcontroller	

Figure 2.4-6: CC430F5137 Pin Configuration – Courtesy of Texas Instruments

2.4.C FPGA

An FPGA board is an integrated logic circuit that is intended to be programmed by a customer just like a microcontroller, but where it differs is in variety of applications that it can be used for. FPGAs are often used to prototype integrated circuits and once the design of the circuit is set the design is then transferred to a hardware chip for faster performance and better power consumption. They are

simple an array of logic blocks connected together to perform a designated function. FPGAs can be used to design many different logic functions instead of a complete design.

When comparing it to microcontrollers and FPGA can be treated as part of a microcontroller. FPGAs allow you to perform many logic functions, but if you need to perform any arithmetic or mathematical calculation, communicate with other devices then you will need an MCU for that. For this project in particular an FPGA board would be insufficient and would require more knowledge to run a microcontroller in an FPGA board. Because FPGA boards are generally much slower and consume large amounts of power you would not use one for this kind of project. Below are some of the reasons why research of FPGA boards was not pursued in detail for this project (The Cons outweigh the Pros in this case).

PROS	CONS
Simple to use	Slower than other MCUs
Easy prototyping	High power consumption
Uses simple logic	Limited in its functionality
Can be used in many applications	Large in size
Table 2.4-7: Pros and Cons for an FPGA board	

2.5 Display

For this project we looked into a wireless display unit to graph the sensor data received from the thumb sensor. In order to use a wireless display it is required to know what kind of display you are going to use the size of the display that will be optimal for this application. At this time there two main types of displays right now, capacitive and resistive.

2.5.A Capacitive vs. Resistive

Capacitive touchscreen display is made up of a glass panel that is coated with a material that can store electrical charge, so when you touch the screen that charge that is on that surface gets transferred to your body and the location at which the touch occurred loses some charge and that location gets sent to the device and the touch is registered. That is the basic principle of how capacitive screens work.

Resistive touch screens on the other hand work a little different, the screen is made up of a normal glass panel and this panel is coated with three layers: a conductive and resistive layer and these two layers are covered by a third scratch resistant layer. When you press on the screen the conductive and

resistive layers touch each other and an electrical field is created giving out a charge. This charge is then registered and the point of contact is sent to the display driver for processing. Now that the basic operation principles are understood one can look at the pros and cons of each display technology to the related project and make proper decisions.

Capacitive

PROS	CONS
Very sensitive to touch	More expensive
Good visibility in sunlight	Only works with finger touches
Multi-finger-touch support	Very fragile
Not prone to dust particles	
Table 2.5-1: Pros and Cons for Capacitive LCD Displays	

Resistive

PROS	CONS
Mature and reliable technology	Not as accurate as capacitive
Easy to use (can use hard objects e.g. pen, nails)	Low brightness output
Very cheap at this point	No multi-touch support
Very durable and reliable	
Table 2.5-2: Pros and Cons for Capacitive LCD Displays	

Looking at the pros and cons above for each display technology it can be concluded that under the circumstances and the project specifications given the resistive touch screen would be a suitable choice. Being that this project has a very limited budget and the budget affects the selection of parts, the resistive screen makes most sense and will most likely be used in the project design. The TFT resistive screen is much easier to setup and drive using the graphics controller, so this is a major reason in choosing to go with resistive touch screen.

2.5.B Graphics Display Controllers

Each display needs a controller to drive the display and for each display type and size there is a variety of controllers. Let's look at some of the ones that are considered for this project.

NHD-4.3-480272MF-22 – This Newhaven TFT display controller evaluation board was specifically made for the 4.3 Inch Newhaven TFT touch screen display that is described in the next section of this design paper. This board can control a display of 480x272 RGB pixels and uses 22-POS FCC interface with 8-bit data input. The controller chip that is included with this evaluation board is Solomon's SSD1963, which is a very popular controller for this type and size of screen. This board provides very simple hardware interfacing with the TFT panel by just using the flat ribbon cable of the display. More detailed features and specifications of the Solomon SSD1963 controller that are relevant to this project will be discussed in the next section of this document.
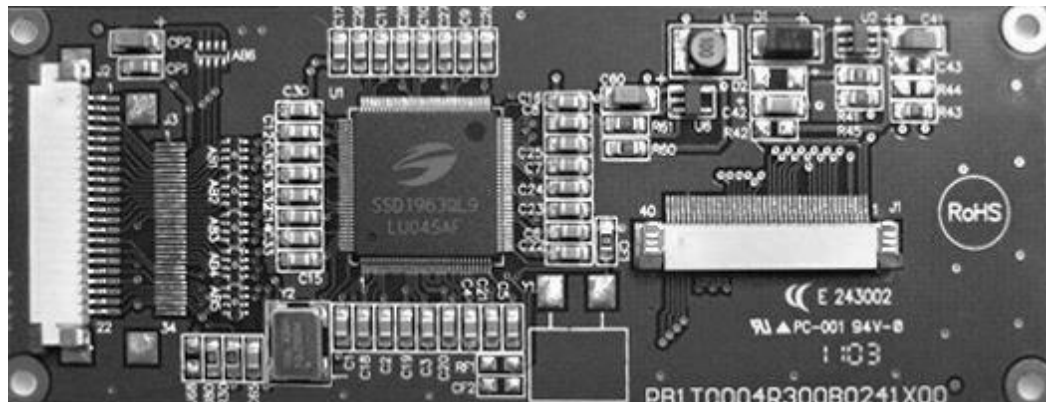
Figure 2.5-1: Newhaven TFT Controller board w/SSD1963 Graphics Controller – Courtesy of Newhaven Display International

SSD1963 – This Solomon display controller is a market leader in this display category and is widely used in many displays. It has 1215KB of embedded display SRAM and frame buffer. This particular display controller supports screens up to 864 x 480 pixels at 24bpp. Below are the important display features for the project listed by Solomon on their website:

- Support for TFT 18/24-bit generic RGB interface panels
- Support for 8-bit serial RGB interface
- 8/9/16/18/24-bit MCU interface
- Hardware display mirroring
- Hardware rotation of 0, 90, 180, 270 degree
- Programmable brightness, contrast and saturation control
- Dynamic Backlight Control (DBC)
- Deep sleep mode for power saving
- Built-in Clock Generator

The figure below shows a simple design overview of this graphics controller and shows the I/O pins that will be used to interface this controlled with a TFT display. Because this is a widely used controller for the type of display that will be

used in this project, a lot of resources and sample code is available online as open source.
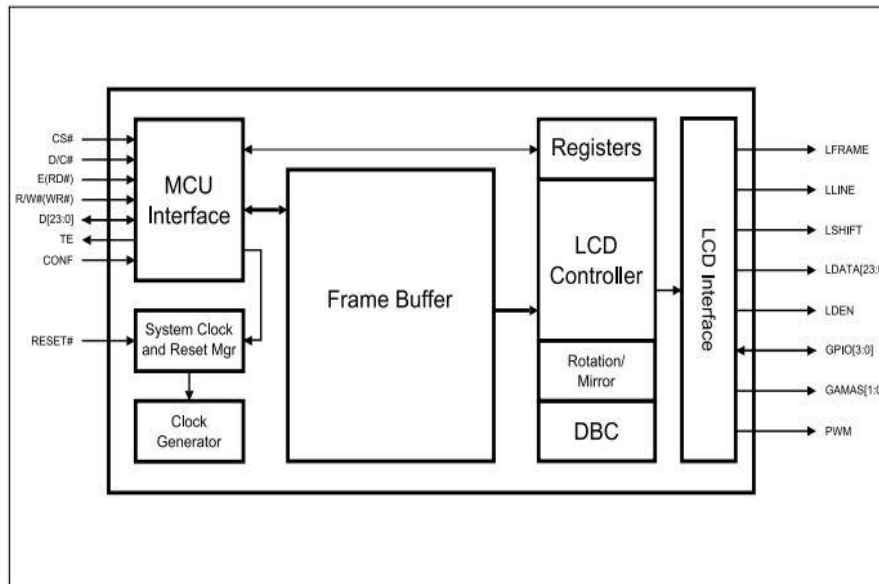
**Figure 2.5-2:** SSD1963 Block Diagram – Courtesy of Solomon

Since this project will require a lot of parts to be surface mounted and the cost of mounting can grow very quickly, this particular chip will we purchased as a built-in chip on the Newhaven controller board discussed above in section 3.4.b. This Solomon controlled comes mounted on this controller board and mounting is not required.

_AR1011_ – The Microchip mTouch AR1011 resistive touch screen controller is a complete, easy to integrate and cost-effective universal chip solution for applications that require a use of resistive touch screen panels.

This chip uses a very sophisticated touch decoding algorithm to process touch data that was received from the surface layer of the display. This chip is not to be confused with a display controller, because this chips' main function is to control the touch input of a display not the LCD itself.

Here are some of the features that are important to this project:

- Power-Saving Sleep Mode
- 128 Bytes of EEPROM
- 2.5 to 5.0V Operating Voltage
- 17mA Typical Operating Current
- Supports 4-Wire, 5-Wire and 8-Wire Analog Resistive Displays
- UART, 9600 Baud Rate Communication
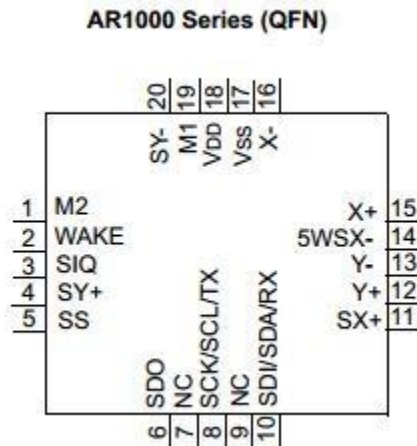
Figure 2.5-3: Microchip AR1011 Pin Configuration – Courtesy of Microchip

Although this touch screen controller can simplify the control of touch input from the display unit, this will raise the price of the project and potentially increase the overall size of the PCB board and the device as a whole. Considering these drawbacks, this controller will be used as the budget allows.

2.5.C TFT Displays

NHD-4.3-480272EF-ATXL#T – This Newhaven TFT color LCD with Touchscreen is a 4.3 inches in size measured diagonally. The touch panel of this display is a 4-wire resistive panel. The resolution of this display is 480 x 272 pixels with a parallel 24 bit RGB interface and supports up to 16.7 million colors.

This display comes with no built-in graphic controller, but it does come with a built-in driver. As far safety is concerned, this display is lead free and RoHS compliant. The supply voltage Vdd for this display ranges from 3.0V to 3.6V and typically runs at 3.3V. The backlight requires a maximum of 22V and a current of 20mA maximum, with typical current of 32mA.

PROS	CONS
SD Card Socket	24-bit Interface
Built-in Controller	Available Controller Board
Up to 16.5 Million Colors	Requires 5V of Supply Voltage
4-Wire Control Interface	
Table 2.5-3: Pros and Cons for TFT Display without Controller	

uLCD43(GFX)- This 4D-systems display module is 4.3 inches measured on the diagonal. This screen delivers multiple useful features in a compact and cost effective display. With this being said it can be programmed using the 4DGL language which is similar to that of C, with the help of the 4D programming cable and windows based PC. This LCD is also a touch screen and has a micro SD-card adaptor for programming. It uses between 4B and 5.5V to operate. It also has an easy 5 pin interface to make joining it with the rest of the project easier.

The nice thing about this screen is that it has a built in PICASO-GFX processor. This processor is a custom graphics controller with all of the functions built into the chip already. So this should make programming how we want the screen to look and the functions we want it to perform a little easier.
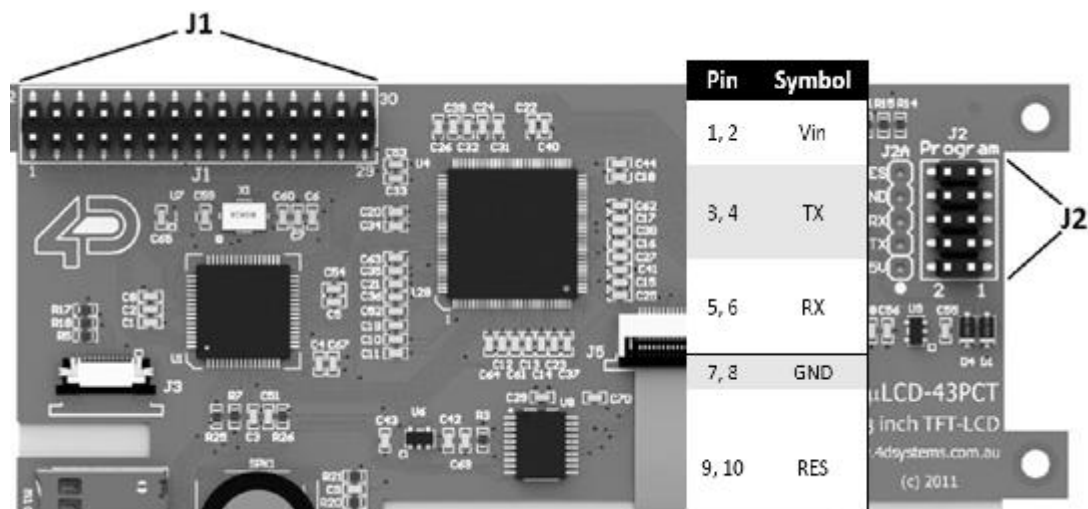
Figure 2.5-4: uLCD43 Pin Configuration – Courtesy of 4D-Systems

PROS	CONS
SD Card Socket	Cost ~$140
Built-in graphics processor	4.0V to 5.5V operation range
Easy 5 pin interface	
65K colors	
Table 2.5-4: Pros and Cons for uLCF43 Display w/Controller	

2.5.D Display w/built-in Controller

ITDB02-4.3 – This Itead Studio display module is 4.3 inches measured diagonally with 65K colors and is 272 x 480 pixels in resolution. This LCD is controlled by Solomon SSD1963 graphics controller. This display also includes a touch screen and an SD card socket for extended memory if needed. The connection is a parallel 16 bit data interface with 4-wire control interface.

This particular display is supported by the open source UTFT library that has many code examples and resources to interface and setup your display.

Below is the layout for the pin connection hardware interface:
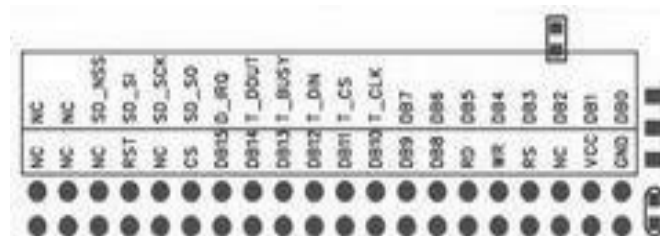
Figure 2.5-5: ITDB02-4.3 TFT Pin Configuration – Courtesy of Itead Studio

PROS	CONS
SD Card Socket	Only 65K Colors
Built-in Controller	Limited Documentation
Supported by UTFT Library	
4-Wire Control Interface	
Table 2.5-5: Pros and Cons for TFT Display w/Controller	

2.6 Wireless

Having a wireless display for this project would be an ideal solution. This lets the person view the data from wherever they, from different positions and much more frequently. The government of course has many regulations when it comes to wireless communication and data transmission. The organization that regulates all of this is FCC (Federal Communications Commission).

The following research section will look into some different types of wireless communication options available and compare them to see which is more suitable for this project. This includes, but is not limited to, Bluetooth, WiFi and ZigBee.

2.6.A WiFi

This is a very popular technology that is being used in almost every personal electronic device. WiFi uses high speed internet connection to exchange data wirelessly using radio waves over a computer network. WiFi is based on IEEE 802.11 standards. Some things to consider for WiFi are: WiFi is readily available in most locations, reliable error correction, and fast data transfer rates. There are disadvantages though, and some of them are: too much for the scale of this project design, need extra components for connection, interference in this RF band.

CC3000-TIWI-SL – This TiWi-SL module from LS Research utilizes Texas Instruments' SimpleLink WiFi CC3000 technology. To be clear this not a TI product, but simply uses Texas Instruments' SimpleLink technology. This kind of solution simplifies the design and implementation of a wireless internet connection. SafeLink minimizes microcontroller requirements on the software side, reduces development time, lowers cost, saves space on the PCB and requires less RF expertise knowledge.
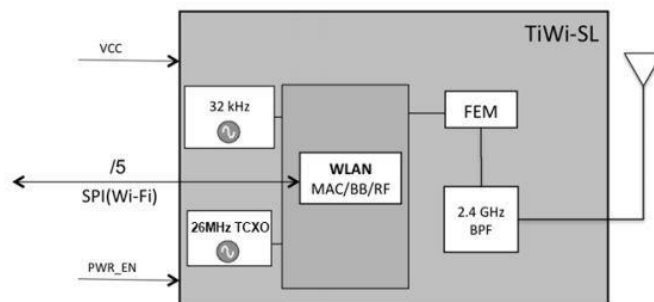
Figure 2.6-1: Block Diagram for TiWi-SL Module – Courtesy of LS Research

PROS	CONS
Embedded Software for Drivers	Chip is Large (21 x 14 mm)
FCC Certified	Complex Design
Sample Application Available	Cluttered 2.4GHz Band
SPI Host Interface	Fast Transfer Rate Not Needed
-89dBM Rx Sensitivity	
User API Guide	
Table 2.6-1: Pros and Cons for TiWi-SL 802.11 Module	

RN171 – This WiFi is built by Microchip, a very popular chip maker amongst hobbyists and even professional electronics manufacturers. This chip is a full-featured 802.11 b/g WiFi module for ultra-low powered embedded applications. This device like many other similar device supports TCP/IP protocol stack. The device is interfaced with UART and SPI slave and includes a real-time clock, auto-sleep, auto-wakeup modes and WEP/WPA/WPA2 authentication. Below is the block diagram for the device that highlights the important features of this module:
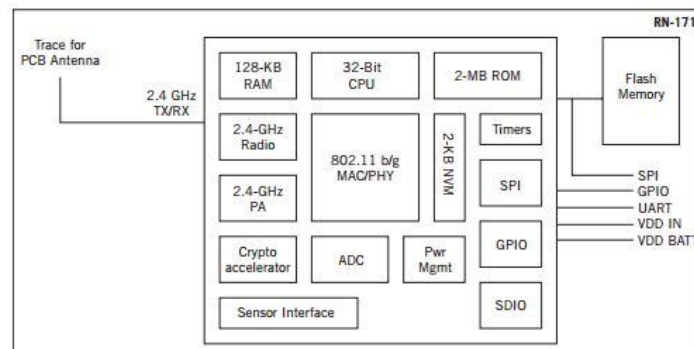
Figure 2.6-2: RN171 Block Diagram – Courtesy of Microchip

PROS	CONS
Preloaded Firmware	Chip is Large (27 x 18 x 3 mm)
FCC Certified	No Built-in Antenna
38 mA RX Power Usage	Cluttered 2.4GHz Band
8Mbit Flash and 128KB RAM	
Accepts 3.3V Regulated and 3V Battery Power Supplied	
Up to WPA2 Authentication	
Table 2.6-2: Pros and Cons for RN171 WiFi Module from Microchip	

2.6.B Bluetooth

Bluetooth is commonly used on small portable electronics. It is mostly used to exchange data over short distances. This wireless technology is fast and highly secure. The range of each device depends on the power-class of each device. Some devices are capable of transmitting data from up to 100 meters, but most operate at approximately 10 meters.

The devices that were looked at for this project are mostly similar but a few important features to the project make a difference in choosing or not choosing

the module for the design. Some advantages to consider are: low power requirement, many options for short range communication, simple connection. The following are some disadvantages of using Bluetooth: short transfer distance, need to pair the devices, weak wall penetration, and interference in the 2.4GHz band. Here are some of the devices that were researched as potential parts for the design.

RN42 – This Microchip Bluetooth module has a class 2 radio and therefore can deliver up to 3Mbps data rate for distances up to 20 meters which makes it a perfect solution for this project. This device support multiple interface protocols making it a complete embedded Bluetooth solution that is simple to design and in addition to all this it is fully certified. This device also supports EDR and has a high-performance PCB trace antenna type. As far the data connection interfaces, this chip supports UART and USB data connections. Some of the important features of this device will be listed below in a pros and cons table to highlight them.

PROS	CONS
Embedded Bluetooth Stack	Relatively Large (20 x 13 mm)
Bluetooth 2.1 + EDR	No Built-in Antenna
Error Correction	Weak Wall Penetration
128-bit AES Encryption	Relatively Expensive @ $15 USD
Auto-discovery/pairing	
No Host Processor Required	
Backwards compatible with 2.0 and 1.1	
Simple Setup	
Table 2.6-3: Pros and Cons for RN42 Bluetooth Module from Microchip	

SPBT2632C2A – This STMicroelectronics Bluetooth module is from a class of micro-sized modules. This device support Bluetooth v3.0, 2.1 and EDR and is also backwards compatible with previous versions of Bluetooth. This is a class 2 module with a maximum data rate of 1.5Mbps which more than enough for the scope of this project. This device is FCC and Bluetooth qualified. This chip runs on ST micro Cortex-M3 microprocessor with a frequency of up to 72MHz. Below is a high level block diagram showing the major modules of this chip and highlighting some important features that make up this Bluetooth module.
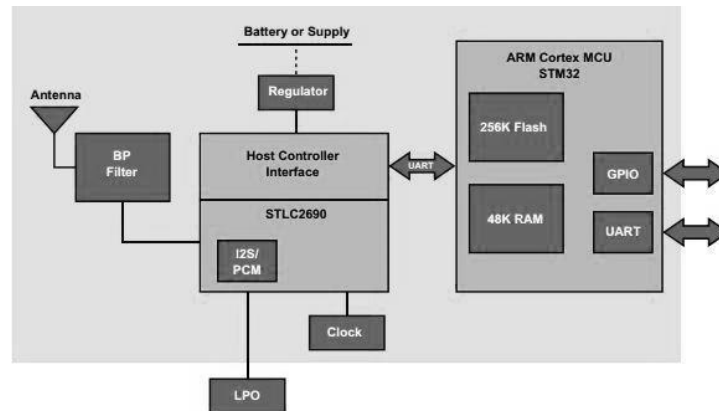
Figure 2.6-3: Block Diagram of STBT2632C2A – Courtesy of STMicroelectronics

Here is a look at some of the pros and cons that are important for the decision of this project.

PROS	CONS
Fully Embedded v3.0 Profiles	Expensive @ $32 USD
Bluetooth v3.0 + EDR	Small Flash Memory
Integrated Antenna	Weak Wall Penetration
128-bit AES Encryption	Cluttered 2.4GHz Band
48kb RAM	
FCC Certified	
Micro-sized (11.6mm x 13.5mm)	
Table 2.6-4: Pros and Cons for STBT2632C2A Bluetooth from Microchip	

2.6.C 802.15.4 – ZigBee

When it comes to low-powered wireless communication ZigBee is a smart choice because it was specifically designed as a low powered mesh networking protocol standard to monitor sensor data in buildings where the data might potentially traverse multiple hops before it reaches its destination. The advantages of using a ZigBee device is that it has a unified standard for data transfer, so you are assure to have compatibility amongst similar devices that use this protocol. ZigBee can be used for point-to-point communication, which is what this project will be focused on and also for point-to-multipoint communication. Below

_CC2531_ – This USB enable true SoC is made by Texas Instruments. This module is intended for IEEE802.15.4, ZigBee and RF4CE applications and is primarily used in personal area networks. This chip is a combination of an RF Transceiver with an enhanced 8051 microcontroller. This device has programmable flash memory, 8KB of RAM and has various operating modes that it supports. This device is well suited to be used in ultralow power requirement designs. The ZigBee protocol stack that this device supports simplifies the data transfer for any similar project design. Below are some of the features of this device that are relevant to this project (Provided by TI):

RF Chip:
- 2.4-GHz IEEE 802.15.4 Compliant RF Transceiver
- Excellent Receiver Sensitivity and Robustness to Interference
- Programmable Output Power Up to 4.5dBm
- Few External Components
- Only a Single Crystal Needed for Asynchronous Networks
- 6-mm × 6-mm Chip Size

Microcontroller:
- Low-Power 8051 MCU Core With Code Prefetching
- 256-KB or 128-KB In-System-Programmable Flash
- 8-KB RAM With Retention in All Power Modes
- Hardware Debug Support

PROS	CONS
Low Voltage 2V - 3.6V	External Components Needed
128KB Programmable Flash	Only Two UARTs
Integrated Antenna	Slower Data Rates than Bluetooth
128-bit AES Encryption	Cluttered 2.4GHz Band
Very Small (6mm x 6mm)	
FCC Certified	
ZigBee Protocol Standard	

Table 2.6-5: Pros and Cons for CC2531 from Texas Instruments

2.6.D HIPAA Regulations Intravenous Anesthetics

Now that the choices for a wireless device have been shown we have to take a step back and look at the regulations that the hospitals face due to The Health

Insurance Portability and Accountability Act that was passed in 1996 to protect the medical information for a patient. Even though the final HIPAA rules did not directly point out wireless tools the regulations cover many separate areas that have to deal with protected health information (PHI).

Just to briefly summarize the act the three major areas that are affected are the administrative safeguards, physical safeguards, and technical safeguards. These have standards that fall under them which will directly affect how secure our wireless needs to be in order to comply with HIPAA and be allowed to use in the hospital. We have to worry about the access control (164.312(a)(1)) which just means that the device has to be able to keep anyone out that should not have access to the information that is on it. There needs to be auditing (164.312(b)) which just means that the device should be able to tell an administrator who had access to the device and when they accessed and used it. The next standard would be integrity (164.312(c)(1)) that there is no way to modify the information that is tested with the machine between when the data is received and when it is stored in the ending spot. Lastly the transmission security (164.312(e)(1) which means that the transmissions are kept private so that nobody can obtain the information from an outside source.

So with that being said we have to make sure that if we decide to equip this device with wireless capability we need to follow these specific guidelines as closely as possible. We know that there is not a real way to make sure our device is one hundred percent secure but we must be able to make it secure enough so that we could see if someone was trying to hack into the data.

Chapter 3 Design

Section 3.1 Sensors

Because visual and tactile assessment of neuromuscular function is unreliable, there has been an emerging interest in the development devices that will offer quantitative measurements. These devices measure either the compound muscle action potential (MAP) or the evoked contractile response.

Today, there are several ways that stimulation during neuromuscular monitoring can be measured. However, because the project is based around certain parameters given by Dr. Looke, the focus will be finding a sensor that can accurately and reliably read the measurement results from the TOF stimulation.

3.1.A Accelerometers

Modern AMG-based nerve stimulators use a piezoelectric wafer made of ceramic as the acceleration transducer. Acceleration of the transducer produces an electrical charge. Piezoelectric accelerometers rely on the piezoelectric effect of quartz or ceramic crystals to generate an electrical output that is proportional to applied acceleration. The piezoelectric effect produces an opposed accumulation of charged particles on the crystal. This charge is proportional to applied force or stress. The technique of the piezoelectric monitor is based on the principle that stretching or bending a flexible piezoelectric film (e.g., one attached to the thumb) in response to nerve stimulation generates a voltage that is proportional to the amount of stretching or bending.

According to Newton's second law of motion, force equals mass times acceleration *(F=mxa).* At constant mass, the acceleration measured and the voltage thereby generated can be used to derive the force of the stimulated muscle. Thus, acceleromyography can be performed on all muscles whose movement or acceleration is easily measured after electrical stimulation of its innervating nerve.

There are two types of piezoelectric accelerometers – high impedance and low impedance. Low-impedance uses the same type of piezoelectric sensing element as the high-impedance units, but they also have a miniaturized built-in charge-to-voltage converter. Additionally, they require an external power supply coupler to energize the electronics and decouple the succeeding DC bias voltage from the output signal. Therefore, with these features, low-impedance piezoelectric accelerometers will be the choice of use for the project.

- For acceleromyography, accelerometers measure the rate of angular acceleration of a skeletal muscle enervated by electrical stimulation of a peripheral nerve and gives an output current
- Most commonly used are either single-axis or triaxial accelerometers
- Usually utilizes a disposable, adhesively affixed transducer

- Nonisometric measurement

Pros:

- less stringent requirements, i.e. does not require patient cooperation, rigid restraint of patient extremity, or an expensive sensor requiring precise orientation and/or rigid attachment to the patient
- Just as reliable and accurate as the quantitative measuring methods used in mechanomyography (MMG) and electromyography (EMG)
- Easier application; less hassle
- Convenient
- They offer good results if mounted correctly

Cons:

- device is both expensive and fragile
- the single-axis accelerometers measure movement in only one direction; thus, accelerometer mounting orientation is critical
- Triaxial accelerometers, preferred for their better accuracy, are too expensive with the added hardware and software
- Triaxial accelerometers are more accurate, but are not usually used on the ulnar nerve because other simpler ways are available
- Patent 4,817,628

A couple possible options for an accelerometer that has been researched are shown below.

ACH-01 Series
The use of piezoelectric polymer film in the ACH-01 by Measurement Specialties, Inc. provides many cost/performance advantages that allow it to be used in a wide range of applications where the use of traditional accelerometer technology is impractical.
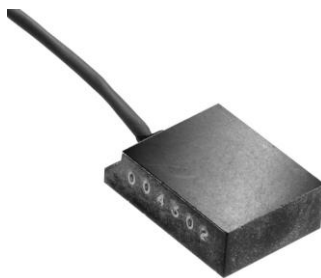
Figure 3.1-1– ACH-01 piezoelectric Accelerometer
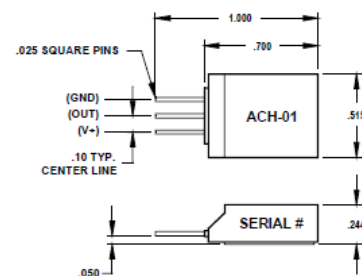
Figure 3.1-2– block diagram with pins of ACH-01 series
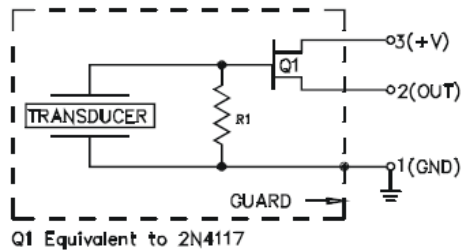
Figure 3.1-3 – schematic of ACH-01 series
(Pending approval by Measurement Specialties, Inc.)

ACH-01 Series Features	
wide frequency response	low transverse sensitivity
excellent phase response	3V to 40V supply
low noise	very high resonance frequency
low cost	excellent Linearity
ultra-low power	

Mounting method plays a critical role in the overall performance of any accelerometer. Erroneous results can be given if an accelerometer is improperly mounted. Therefore, Measurement Specialties, Inc. (MSI) recommends an adhesive mounting method for proper performance of the ACH-01. It calls for the surface to be flat and the area where the ACH-01 is to be mounted should be thoroughly cleaned; then, add the adhesive. To keep the product cost low, the project design will probably use a ceramic substrate as the mounting base.
 The table below is all the product qualifications for the ACH-01 series as listed on the Measurement Specialties, Inc. website.

		ACH-01-XX
Key Features		-Wide Frequency Range -Wide Dynamic Range -High Sensitivity -Low Noise -JFET Buffer
Sensitive Axes	X-Axis	---
	Y-Axis	---
	Z-Axis	X
Sensitivity (Nominal)		10 mV/g
Frequency Range (±3 dB)		1.0 Hz-20 kHz
Dynamic Range		±250 g
Resolution (@ 100 Hz)		$40\mu g/\sqrt{Hz}$
Resonant Frequency		>35 kHz
Resonant Q (Hz/Hz)		30
Transverse Sensitivity		5%
Linearity		0.1%
Operating Temperature		-40 °C to +85 °C
Storage Temperature		-40 °C to +85 °C
Maximum Shock		1000 g
Supply Voltage		3 V to 40 V
Supply Current		2μ A Typical
Weight		3 grams
Size (mm)		13 x 19 x 6
Mounting Method		Adhesive

Figure 3.1-5 – Table of the product qualifications of ACH-01 series as listed on the website (Pending approval by Measurement Specialties, Inc.)

A way to offer the most reliable results without having to restrict the patient's arm is using a hand adapter for the thumb. The makers of the TOF-Watch first implemented this idea to provide the most accurate and reliable data possible. This has been done because the thumb always returns to its original position after being stimulated. In past uses, it was common for monitoring results to be unusable because shifting of the original position for the thumb would change after each stimulation. As a result, the makers of the TOF-Watch came up with their own hand adapter. It proves to be beneficial for patients in the operating room, especially when patients must be repositioned, thus throwing off all the results. If the project is to use a hand adapter, the website of Mainline Medical offers a Bluestar Enterprises Hand Adapter.

Figure 3.1-6- Bluestar Enterprises Hand Adapter
(Pending approval by Mainline Medical)
Price (quantity: 1) = $43.95

Bluestar Enterprises hand adapter	
Pros	**Cons**
Positions hand and holds acceleration transducer in place over thumb, thus providing more reliable and accurate measurements	May require too much time to prepare on everyday clinical usage
	May not be applicable with designed stimulator

MMA8452Q
The other type of accelerometer we researched was the MMA8452Q, by Sparkfun. It is a 3-axis, capacitive accelerometer with 12 bits of resolution. It also offered user selectable full scales of ±2g, ±4g, ±8g. It offers I2C digital output interface which is what is needed for our project.

Figure 3.1-7 – MMA8452Q model

MMA8452 Features	
1.95V to 3.6V supply voltage	I2C digital output interface
12-bit and 8-bit digital output	2 programmable interrupt pins
low cost	Current consumption: 6uA-165 uA
ultra-low power	3-axis

Having an accelerometer with 3-axis measurement allows a much more accurate result. However, it also becomes much more expensive and more difficult to perform. For accelerometers, we decided to test this sensor because of its 3-axis

capability and because of its low error percentage to sensitivity, which was only ±2.5%.

3.1.B Pressure Sensors

Here are some examples that were researched and found as a possible uses for a pressure sensor that could be used.

The MPL115A, by Freescale, is a simple barometer with a digital SPI output for cost-effective applications. It has a MEMS pressure sensor with a conditioning integrated circuit to provide accurate pressure data from 50 to 115 kPa. It has low current consumption of 5 uA during Active mode and 1 uA during Sleep mode, which is beneficial when aiming for a low-power application. An integrated ADC converts pressure sensor readings and digitized temperature to digitized outputs through a SPI port. It also offers factory calibration data, which is stored internally in an on-board ROM. The host microcontroller is able to execute a compensation algorithm utilizing the raw sensor output and calibration data to find Compensated Absolute Pressure. The MPL115A are ideal with their small size at 5.0 mm x 3.0 mm x 1.2 mm.

Figure3.1-8 – MPL115A
pressure sensor
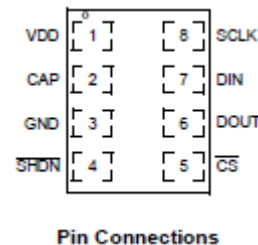
Figure3.1-9 – MPL115A
pin connections
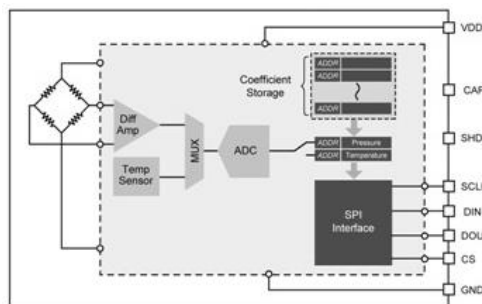
Figure 3.1-10 – MPL115A block diagram with SPI Interface

MPL115A Features		
Digitized pressure	Monotonic pressure outputs	Surface mount
Has +/- 1 kPa accuracy	Integrated ADC	
2.375 to 5.5-volt supply	SPI or I²C Interface	

Additionally, this pressure sensor is able to be sampled, which allows for getting a small quantity to test, which makes it an excellent competitor in the design choice. If bought in bulk, they offer 10,000 at a time, however, each one only costing $1.05.

The MPL3115A2: Xtrinsic Smart Pressure Sensor by Freescale is another option that has been used for monitoring neuromuscluar blockade during anesthesia in the past. It is employes a MEMS pressure sensor with an I^2C interface to provide accurate Pressure/Altitude and Temperature data. The outputs of the sensor are digitized by a high resolution 24-bit ADC. Typical active supply current is 40 uA per peasurement-second for a stable 30 cm output resolution. It is great for measurement with its small size, at just 5.0 mm x 3.0 mm x 1.1 mm.

Figure 3.1-11 – MPL3115A2
Smart Pressure Sensor
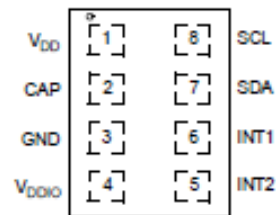
Figure 3.1-12 – MPL3115A2
pin connections
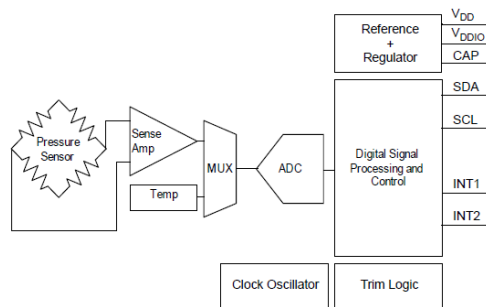
Figure 3.1-13 – MPL3115A2
block diagram

MPL3115A2 Features		
1.95V to 3.6V Supply voltage, internally regulated by LDO	Ability to log data up to 12 days using the FIFO	Fully compensated internally
1.6V to 3.6V digital interface supply voltage	1 second to 9 hour data acquisition rate	Able to program events
Direct reading, compensated pressure of 20-bit measurement	I^2C digital output interface (operates up to 400 kHz)	Autonomous data acquisition

This sensor is also able to be sampled, which makes it a great contender for our design choice. If bought in bulk, one must purchase 10,000 at a time. However, each smart pressure sensor individually costs $1.43.

Although this pressure sensor offers a large amount of information, it measures more data than needed for this project, including the altitude and temperature. Because of these extra unneeded capabilities, this sensor is more costly, and thus, will not be the first choice in the project design.

MPXV5004 Series

With further research, we realized we needed a gauge pressure sensor, which measured pressure in relation to the atmospheric pressure. The pressure sensor measured the strength of the muscle response by how much air pressure resulted from the squeeze of some type of ball, such as a blood pressure ball, that was in the patient's hand. We looked into several types of pressure sensors, but the big thing we needed was something that was accurate because of these small readings as well as had a quick response time, which was important in an accurate measurement of the TOF stimulation. We therefore chose the MPXV5004 series, which is shown below.
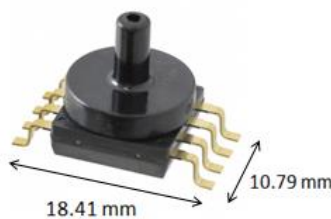

Figure 3.1-14 – MPXV5004 pressure sensor

MPXV5004 Features		
Internal amplification	3.3V and 5mA constant current input	Analog output for increased accuracy
Low pass output to avoid noise	Positive input range: 0-3.92 kPa	10 bit ADC accuracy
Quick response of 1.0 msec	Very little offset	

One main positive with this type of sensor was that it offered a very linear output, as shown below, which was needed for our project when measuring the TOF response.
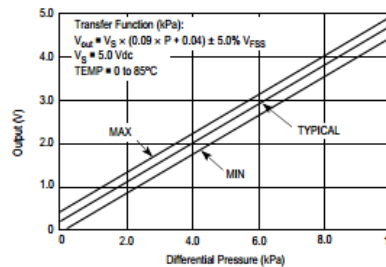

Figure 3.1-15 – Output shown on the datasheet

3.1.C Evoked electromyography

- Records the compound action potential caused by stimulation of a peripheral nerve; surface electrodes are employed to record overall electrical activity of the muscles
- Patents 4,291,705 and 4,595,018
- EMG signal amplitude is typically in the range of 3 uV to 5,000 uV, the duration about 3 ms to 15 ms, and the frequency range 2 Hz to 10,000 Hz.

Pros:
- surface electrodes are convenient and are noninvasive

Cons:
- good electrical contact is difficult to maintain at the skin/electrode interface
- Due to the small magnitude and short duration of the signals, the system is difficult to isolate from electrical interference

3.1.D Force Sensors

A force sensor is defined as a transducer that converts an input mechanical force into an electrical output signal. The force sensor has a variable resistance as a function of applied pressure. These devices are used in mechanomyography (MMG) and measure the strength of muscle response to stimulation of the peripheral nerve. Although it is highly implemented in clinical research, there are several disadvantages to using mechanomyography and the force sensors to measure the output.

Cons:

- cumbersome and costly to implement
- requires patient's hand and thumb be restrained
- may result in nerve or tissue damage if thumb is not positioned properly with respect to the transducer linkage, due to the necessarily rigid connection thereto

Force-Sensitive Resistors (FSRs)
However, Tekscan has offered a new set of force sensors, known as FlexiForce sensors that are ultra-thin and flexible printed circuits, which can be easily integrated into force measurement applications. These FlexiForce sensors are a versatile and durable piezoresistive force sensor that has been made in several different shapes and sizes. For these sensors, the resistance is inversely proportional to applied force.

Benefits of FlexiForce Sensors:
- greater flexibility
- superior linearity and accuracy
- offers a website with expert technical guidance for questions
- wide range of forces
- sensor output is not a function of loading area
- has different sensing area sizes

Cons:
- may be less accurate than needed because these are FSRs (Force Sensitive Resistors)

Below are the ones that could possibly be used and the specs of each, provided by the Tekscan website. The HT201 model was not included in possible sensor options because the design does not require a high-temperature sensor.

Figure 3.1-15- A201 FlexiForce$^®$ Figure 3.1-15- A2301 FlexiForce$^®$ s

Figure 3.1-16 –A401 FlexiForce$^®$
Photos courtesy of Tekscan, Inc.

	A201 MODEL (Spec Sheet)	HT201 (HIGH-TEMP) MODEL (Spec Sheet)	A301 MODEL (Spec Sheet)	A401 MODEL (Spec Sheet)
PHYSICAL PROPERTIES				
Thickness	0.008 in. (.203 mm)			
Length	7.75 in. (197 mm) 6 in. (152 mm)* 4 in. (102 mm)* 2 in. (51mm)*		1 in. (25.4 mm)	2.24 in. (56.8 mm)
Width	0.55 in. (14 mm)			
Sensing Area	0.375 in. diameter (9.53 mm)		0.375 in. diameter (9.53 mm)	1.0 in. diameter (25.4 mm)
Connector	3-pin male square pin		2-pin male square pin	
TYPICAL PERFORMANCE				
Linearity Error	<±3%	<±3%	<±3%	<±3%
Repeatability	<±2.5% of full scale	<±3.5% of full scale	<±2.5% of full scale	<±2.5% of full scale
Hysteresis	<4.5% of full scale	<3.6% of full scale	<4.5% of full scale	<4.5% of full scale
Drift	<5% per logarithmic time scale	<3.3% per logarithmic time scale	<5% per logarithmic time scale	<5% per logarithmic time scale
Response Time	<5 microseconds	TBD	<5 microseconds	<5 microseconds
Operating Temperatures	15°F to 140°F (-9°C to 60°C)	15°F to 400°F (-9°C to 204°C)	15°F to 140°F (-9°C to 60°C)	15°F to 140°F (-9°C to 60°C)
Force Ranges	0-1 lb (4.4 N) 0-25 lb (110 N) 0-100 lb (440 N)**	Low: 0-30 lb (133 N) High: 0-100 lb (440 N)**	≈ 0-1 lb (4.4 N) ≈ 0-25 lb (110 N) ≈ 0-100 lb (440 N)**	0-25 lb (110 N)***
Temperature Sensitivity	Output variance up to 0.2% per degree F	Output variance up to 0.16% per degree F	Output variance up to 0.2% per degree F	Output variance up to 0.2% per degree F

Figure 3.1-17– Specs of FlexiForce® sensors
Photo courtesy of Tekscan, Inc.

Pricing		
Type	*Price (4-pack)*	*Resulting Individual Price*
A201 series	$77	$19.25
A301 series	$65	$16.25
A401 series	$78	$19.50

Because the models were nearly identical in their performances, the biggest differences were the length, sensing area, and the force range. Because we were measuring light forces of a thumb twitch, we needed less of a force range to pick up small differences. Therefore, we wanted to use the 0-1 lb. force range, which left us with the A201 and A301 models. Thus, we ended up choosing the A201 model for testing because it could be cut into different lengths, as well as its long and narrow physical property would be useful when having it strapped from the crook of the thumb to the tip.

3.2 Constant Current Circuitry

Now to move on to the heart of the project, it's shocking circuit; this is the part that triggers the muscle to move so that its response can be measured. Because of the importance of this circuit, all avenues for its build will initially be considered: passive, active, purchased, and any other possibility for the optimally functioning device. Before describing the different build options for this circuit it is necessary to describe its intended characteristics and a good way to do that is by starting with the existing version, which has been touched upon lightly before. The currently used design gets its power from a 9V battery which it uses to deliver one of the three different pules types: the Train-Of-Four, a 1Hz twitch, and 100Hz tetanic contraction. All three types can deliver a variable current between one and fifty milliamps. This range is provided by varying a potentiometer on the side of the device labeled with the numbers 0-10, with zero being off. As the title implies, this must be as close to a constant current source as possibly because of the dynamic nature of human skin. Over the course of any procedure, and possibly any set of pulses, skin resistance can change due to all of the factors discussed previously in this paper; of these variations it is necessary to regulate the current so that the patient incurs no damage due to use of the device. In order to deliver the necessary currents, the device must overcome the possible 250 kOhm resistance of human skin, part of this resistance can be overcome with a thorough cleaning of the skin, as mentioned before, but it should never be assumed that this cleaning will happen. And with these basics down it is possible to move on to a discussion of the possible current circuitry.

3.2.A Passive Circuit Designs

The first instinct with this circuit is to use the K.I.S.S. method and keep things simple, toward that end it was decided to investigate a purely passive circuit that would be able to manipulate the applied voltage and output the required currents. The first circuit suggested was a resistive network with a potentiometer in series with the patient that would allow for the sought after variability in current. The design would simply be a very large resistor in series with the potentiometer; this resistor represents the resistance of skin in a test circuit. Because of the simplicity of this circuit, there will be no diagram, merely a short explanation why it would be foolish to try and make it work. The first flaw of the resistive network circuit, and any purely passive system, is its inability to automatically compensate for varying load resistances, something that more advance circuit can manage easily. This leaves all precision in the hands of the anesthetist who will be focusing on several other things more vital to the patient's survival of the surgery. Moving on, another issue arises with the inability to even tell how much current is being delivered. This becomes a problem because, as mentioned before, different patients not only have different resistances but they also have different tolerances/susceptibilities to current levels. A supramaximal stimulation current of 30mA in one patient may not achieve supramaximal in another, that patient may require 50mA. The only way to know whether a stimulation sequence is doing anything at a specific current level is to first know what current is being used, and

second to obtain baseline measurements before the neuromuscular blockade is administered. With more advanced circuitry a baseline can automatically be calculate at the beginning of surgery with quantifiable levels of paralysis, with this particular circuit all that is available is a rough guess by the anesthetist in charge. Once they've made their guess, they must also make a guess as to which current level they are using because this circuit provides no way of measuring it, even with calculations provided by the microcontroller. The final problem, and possibly the biggest with such a simplistic circuit, is the issue of voltage, given that its source is a nine volt battery some sort of step up circuitry will need to be provided to overcome the exceedingly high resistance of human skin.

3.2.B Active Circuit Designs

With these flaws of the resistive network in mind, the next circuit set to be analyzed is the transistor based constant current circuit. The first of two simple transistor circuits is shown to the left. It can easily be seen from this circuit that there is minimal difference between it and the resistive circuit discussed above. Due to this limited difference, it suffers from most of the same issues as the resistive network minus the possibility of slightly more accurate current tuning by the adjustment of R1 and R2, though the actual current values are still unknown.
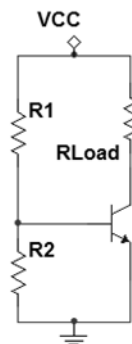
Figure 3.2-1

The second basic transistor circuit, a current mirror, is shown left. Because of the definition of the circuit it provides a way to accurately set the current through the two BJTs by accurately setting their base currents. Assuming that these two BJTs are identical this means that the current through the left and right one match regardless of the value of RLoad. Obviously this logic will need to be modified for the real world and its finite sources, but the idea works. What is does not do is the same as the previous two designs: give the actual current value, step the voltage up, or self-adjust for variations in patients.
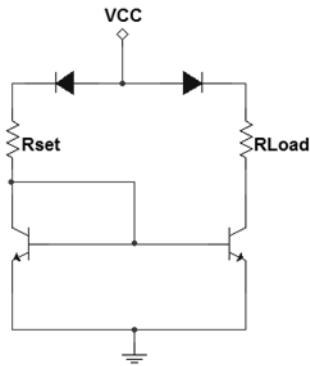
Figure 3.2-2

For a self-adjusting constant current circuit to be built, it is necessary to use a more advanced circuit containing OpAmps. This circuit, Figure 3.2-1, uses just a single OpAmp with a voltage divider to bias the positive input and a negative feedback system to create the adjustment feature needed. This negative feedback voltage is determined by the resistor, Rset, placed between it and ground, the bigger the resistor the smaller the maximum allowed current.
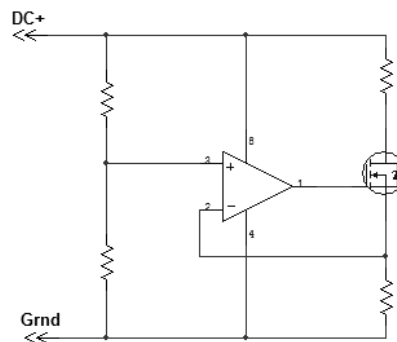
Figure 3.2-3

With this in mind Rset can be replaced by an electronically controlled switch that chooses between several different resistor values. Because the delivery system will be controlled by a microcontroller already, adding this feature gives the device the current select ability it needs in addition to the auto-adjust feature allowed by the OpAmp.

In an effort to be thorough, the team has come across many more homemade circuits that can effectively produce, at least, the required current levels but none of them will be thoroughly discussed here. The reasoning for leaving them out is the shear unpredictability of the circuits; take the "camera flash shocker" for

instance. This particular circuit, harvested from a disposable camera, is more than capable of providing a shock with enough current to create a feasible device. But, for this single advantage, it actually lacks everything the other circuits provide: intentional repeatability with the same values, designable safety features, controllable current, etc. Because of these flaws these circuits were almost immediately ruled out, regardless of the simplicity of adding them to this project's design.

3.2.C Voltage Booster

Returning to the OpAmp circuit, while it has alleviated two of the problems ailing all the previous circuits, it leaves one major problem. The voltage levels for this circuit still need to be stepped up to reasonably high DC levels to create the current required. To do this there are a couple of available option: buy or design a DC/DC boost converter, buy or design a DC/DC charge pump, or find a higher power source to use instead of the main chosen one. The last option, while valid, was immediately ruled out for reasons of safety. Given that the power source most likely to be used is an 110VAC wall outlet, it seems like a poor choice to wire that directly to a patient. Even after converting the AC source to a relatively stable DC source, the current levels present are more than sufficient to burn tissue, if not accidentally kill the patient, if the intended implementation critically failed. Ruling that out, the next component to consider is a charge pump, which intuitively sounds like exactly what the design needs. Unfortunately upon further inspection it became apparent that the integrated circuit versions of these devices were intended for low voltage, low amperage applications. While there may be some use to them in the circuit later on, they cannot be considered here for this application. After which it was decided to possibly look in to a handmade version using bigger, higher capacity devices. Designs for such circuits were found to be readily available on the internet and thoroughly documented, which is always a nice thing. It appeared after looking at multiple designs that the way these devices work is through voltage doubling. This is achieved by running multiple capacitors in parallel with their positive or negative terminals connect across diodes. The terminal that isn't connected to diodes is wired as a floating ground to an inverter. These inverters are wired from the output of the previous to the input of the next. By doing this you get double the voltage of the capacitor before it. And this is where the downfall of the handmade charge pump comes in: a relatively large capacitor must be used at each junction to handle the necessary charge needed for the delivery current and several stages of doubling are needed to get to a reasonable voltage level. On their own either of these issues can be overcome but together they create an issue with the size of the capacitors and the space needed to hold all of them. Because this device requires zero unique parts it can be built and tested but the team's judgment on its feasibility is a unanimous no. So far a bought or built charge pump has been ruled out as well as the direct line driving of the current source. This leaves the last choice of a boost convert to be investigated.

The decision was, initially, to simply buy a high voltage boost converter instead of designing one. This decision was made because of the assumed complexity of the device and the hope that a highly efficient model could be found at a relatively inexpensive price. At this point the team once again turned to TI, among other companies, to find the converter and was shortly presented with a major problem. Though many boost converters of all input and output combinations could be found, it was noticed that the output current levels dropped dramatically as the output voltage increased. This should have come as no surprise, integrated circuits are good for a lot of things but, when it comes to power, an analog circuit can usually handle much higher wattages with significantly cheaper parts. After a second thorough search, which returned no better results, it was decided that if a boost converter was intended to be used the circuit would need to be hand built. Returning to the internet it was found that, by using transformers or inductors, a relatively simple circuit could be built that would create very high voltages in a relatively quick manner. By referencing multiple designs, a modified and slightly simpler 555 based boost converter was created by the team, Figure 3.2-2 shown below. This circuit takes the positive rail and runs it through a large inductor, a MOSFET, and a small high wattage resistor for a period of time. Once a reasonable magnetic field has built up the MOSFET is turned off and the current in the inductor is shunted through the diode and in to the capacitor. This happens because of the basic principle of inductors, their inability to instantaneously change current. Using that principle and using a capacitor to store the shunted current a voltage ten times the rail can be created within seconds depending on the switching speed. The frequency of this switching will need to be determined through extensive trials, but as of now a good frequency is 75Hz. Also shown in the diagram is a simple on off switch to deliver the built up charge to the patient, or the resistor on the right.
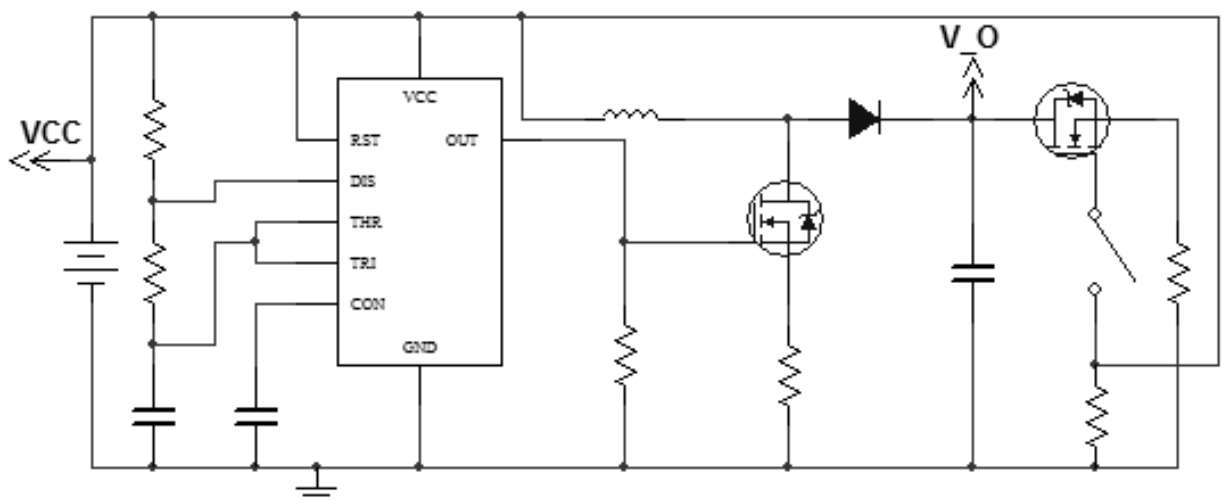
Figure 3.2-2

3.2.D Final Design Choice

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.
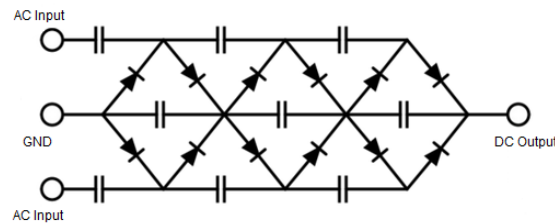

Fig. 3.2-3 The Cockcroft-Walton Voltage multiplier circuit.

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

Based on that equation, 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. 3.2-4 which allows the programmer to gain access to the multiplier at different stages in order to create the choice of different current levels.
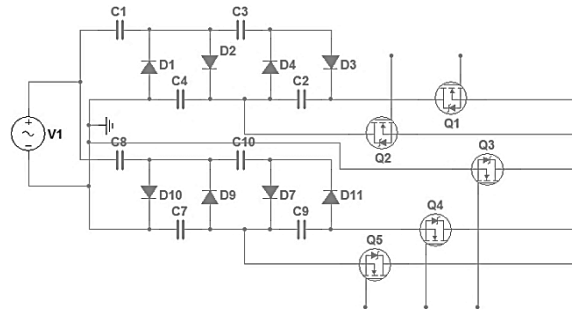
Fig. 3.2-4 Cockcroft-Walton Voltage multiplier in which the positive bias is on the top and the negative bias is on the bottom and there are MOSFETs connected to different stages.

3.3 Controllers

This section of the design paper will go into more detailed design of the microcontrollers that were researched and will look at the pin configurations of each MCU and how each pin will be used in the design of this project and how the other parts will interface with the microcontroller. The last subsection of section 3.3 will reveal a microcontroller of choice and will explain why a particular controller was chosen for the project.

3.3.A Microcontroller

For this project there were two categories of microcontrollers that were researched and considered for the design. One being a single chip that just has an MCU built into it and nothing else and the second category of microcontrollers was SoCs (System-on-Chip) that had the RF wireless module built-in into the same chip making it a very lucrative choice for the MCU of choice. Based on the research that was done on these two types of chips, the top two parts that fit the project better were chosen to go look into design specific and how each can be used for this project. The two that were chosen are: Atmel Atmega128RFA1 MCU with built-in RF transceiver and Microchip PIC24FJ64GA310 MCU.

ATmega128RFA1 – This microcontroller is made by Atmel and features a built-in RF transceiver which solves a problem of MCU and Transceiver interfacing in the design. This chip has a lot of example code right inside the spec sheet and you don't have to look around much to find most of examples need for this project. This is why this MCU will be the most likely choice for the project design. For more detailed features list and description refer to section 2.4.A of this document. Table 3.3-1 below lists all the available pins on this chip and their descriptions.

Relevant Features:

- 1635 Powerful Instructions – Most Single Clock Cycle Execution
- 32 8-bit General Purpose Registers
- Up to 16 MIPS Throughput at 16MHz and ultra-low 1.8V
- 128KB of In-System Self-Programmable Flash

- On-chip Debug Support with the JTAG Interface
- 38 Programmable I/O Lines
- Fully Integrated RF Transceiver as an SoC Solution
- 16KB of Internal SRAM Memory

PIN NAME	PIN DESCRIPTION	USED
EVDD	External analog supply voltage	Yes
DEVDD	External digital supply voltage	Yes
AVDD	Regulated analog supply voltage (internally generated)	
DVDD	Regulated digital supply voltage (internally generated)	Yes
DVSS	Digital ground	Yes
AVSS	Analog ground	
PB7…PB0	8-bit bidirectional I/O port with internal pull-up resistors	Yes
PD7…PD0	8-bit bidirectional I/O port with internal pull-up resistors	Yes
PE7…PE0	8-bit bidirectional I/O port with internal pull-up resistors	
PF7…PF0	8-bit bidirectional I/O port with internal pull-up resistors	
PG5…PG0	6-bit bidirectional I/O port with internal pull-up resistors	Yes
AVSS_RFP	Dedicated ground pin for the bi-directional, differential RF I/O port	Yes
AVSS_RFN	Dedicated ground pin for the bi-directional, differential RF I/O port	
RFP	Positive terminal for the bi-directional, differential RF I/O port.	Yes
RFN	Negative terminal for the bi-directional, differential RF I/O port.	Yes
RSTN	Reset input	Yes
RSTON	Reset output	Yes
XTAL1	Input to the inverting 16MHz crystal oscillator amplifier	Yes
XTAL2	Output of the inverting 16MHz crystal oscillator amplifier	Yes
AREF	Reference voltage output of the A/D Converter	
TST	Programming and test mode enable pin	Yes
CLKI	Input to the clock system	Yes
Table 3.3-1: Pin Description for Atmega128RFA1 – Information from Atmel		

The table above gives a better understanding of what each pin on this chip is responsible for and if it is going to be used at all. The build section of this chapter will go into more details on how each pin is going to be interfaces with other devices in the design (e.g. sensors, antenna and power supply). Now that the pin description is clear, let's take a look at a basic application schematic provided by Atmel. This application schematic was closely studied and it was concluded that it closely matches the applications requirements for this project, so it will be used as reference design that will be built upon to further develop the interfacing between a wireless RF module, power supply and the antenna.
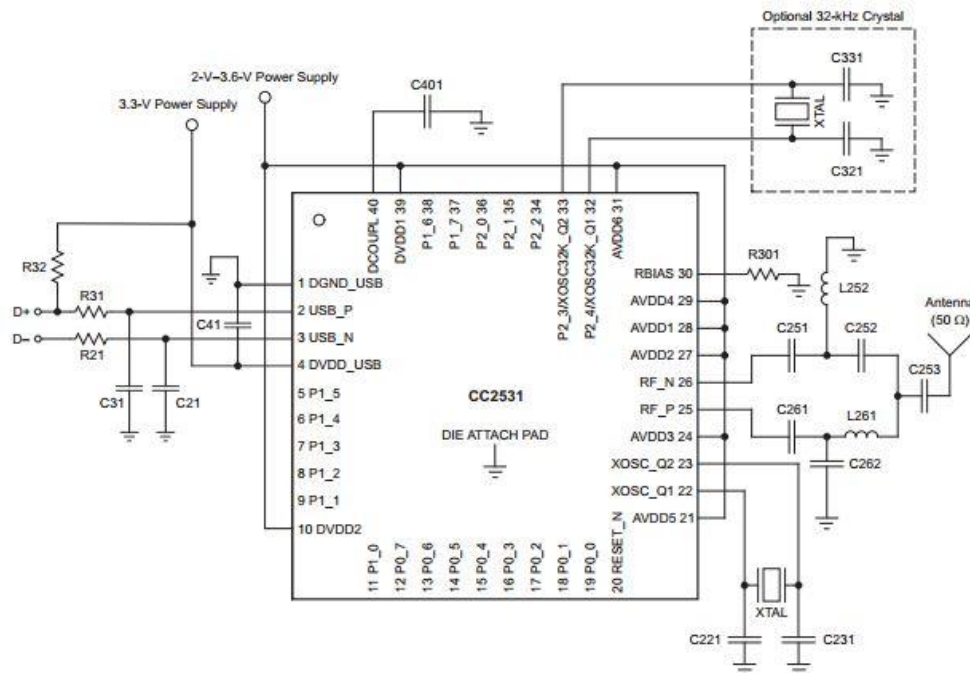
Figure 3.3-1: Basic Application Schematic – Courtesy of Atmel

ATmega328P – This Microchip MCU is also made by Atmel. This chip can be easily turned into a makeshift arduino board and there is a lot of example code on the websites for arduino for both the screen and the sensor. This way we do not have to look around much to find examples needed for this project. This is why this MCU will be the most likely choice for the project design. For more detailed features list and description refer to section 2.4.A of this document.

Relevant Features:

- 131 Powerful Instructions – Most Single Clock Cycle Execution
- 32 8-bit General Purpose Registers
- Up to 20 MIPS Throughput at 20MHz
- 32KB of In-System Self-Programmable Flash
- 23 Programmable I/O Lines
- 32KB of Internal SRAM Memory

Function	Type	ATMEGA328P PIN
SV1 – SERVO1	PWM1 (PCINT1/OC1/PB1)	PIN13
SV2 – SERVO2	PWM2 (D3)	PIN1
SV3 – SERVO3	PWM3 (D5)	PIN 9
SV4 – SERVO4	PWM4 (D6)	PIN10
SV6 – ANALOG IN	AD7	PIN22
MOTOR-DIR1	D14	PIN23
MOTOR-DIR2	D15	PIN24
MOTOR-PWM1	D16	PIN25
MOTOR-PWM2	D17	PIN26
MOTOR-STBY / GRNLED (STATUS)	D18	PIN27
GPS-ON/OFF	D19	PIN28
GPS-TX (OUTPUT)	D1	PIN31
GPS-RX (INPUT)	D0	PIN30
BAT SENSE	AD6	PIN19
LED2 RED (ERROR)	D4	PIN2
! POWER ON/OFF (ACTIVE LOW)	D7	PIN11
!WIFI-CE (ACTIVE LOW)	D8	PIN12
!WIFI-SS (ACTIVE LOW)	D10	PIN14
!WIFI-INT (ACTIVE LOW)	D2	PIN32

PIC24FJ64GA310 – This Microchip MCU was designed to be used for extremely low-powered applications and is very well suited for this project. Although this chip is a little larger than other chips that were researched, it has many open source libraries and examples of code that it will simplify the design in future phases of product development. Below will be a highlight list of important features for this design. For a detailed specifications and features for this MCU refer to section 2.4.A of this document. Below is a table provided by Microchip that lists many important features of this device that will help decide on the final choice for the project and give a quick overview of how the chip is structured.

Features	PIC24FJ64GA306	PIC24FJ128GA306
Operating Frequency	DC – 32 MHz	
Program Memory (bytes)	64K	128K
Program Memory (instructions)	22,016	44,032
Data Memory (bytes)	8K	
Interrupt Sources (soft vectors/ NMI traps)	65 (61/4)	
I/O Ports	Ports B, C, D, E, F, G	
Total I/O Pins	53	
Remappable Pins	30 (29 I/O, 1 Input only)	
Timers: Total Number (16-bit)	5[1]	
32-Bit (from paired 16-bit timers)	2	
Input Capture Channels	7[1]	
Output Compare/PWM Channels	7[1]	
Input Change Notification Interrupt	52	
Serial Communications: UART	4[1]	
SPI (3-wire/4-wire)	2[1]	
I²C™	2	
Digital Signal Modulator	Yes	
Parallel Communications (EPMP/PSP)	Yes	
JTAG Boundary Scan	Yes	
12/10-Bit Analog-to-Digital Converter (A/D) Module (input channels)	16	
Analog Comparators	3	
CTMU Interface	Yes	
LCD Controller (available pixels)	240 (30 SEG x 8 COM)	
Resets (and Delays)	Core POR, VDD POR, VBAT POR, BOR, RESET Instruction, MCLR, WDT; Illegal Opcode, REPEAT Instruction, Hardware Traps, Configuration Word Mismatch (OST, PLL Lock)	
Instruction Set	76 Base Instructions, Multiple Addressing Mode Variations	
Packages	64-Pin TQFP and QFN	

Figure 3.3-1: Features for PIC24FJ64GA306 MCU – Courtesy of Microchip

Now, let's look at the recommended minimum connections to get the chip operating. These recommended connections are provided on by Microchip, the device maker. These are the values of the components used in figure 3.3-2: C1 through C6 is 0.1uF and 20V ceramic, C7 is 10uF with 6.3V or greater (tantalum or ceramic), R1 is 10kOhm and R2 is 100Ohm to 470Ohm. Since this is a critical design point for this project, the schematic in figure 3.3-2 will be used to start basic testing for the MCU.
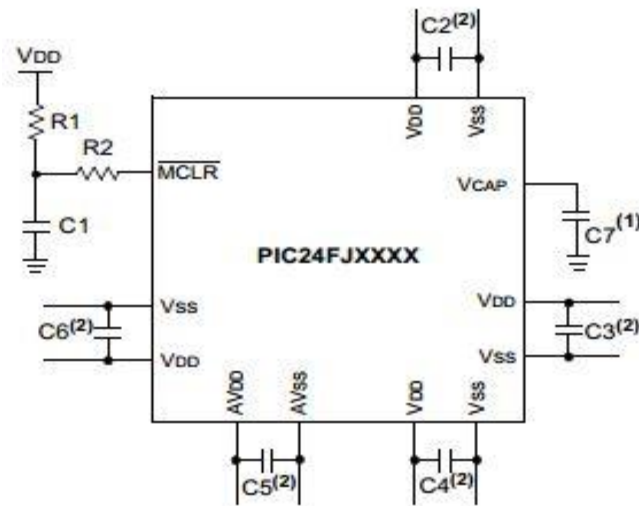
Figure 3.3-2: Minimum Connection Recommendation for PIC24FJ MCUs

3.3.B Final Design Choice

After a lot of research and design trials, the MCU of choice for this project is the Atmel Atmega328P. We chose this chip because it is the one that was used in the Arduino Uno board that we bought in order to test the sensors out. Since we had already written the code using this microcontroller we felt that it only would make sense to see if this controller would also work with the screen which it did because there are versions of the same screen that come with an arduino connector. Knowing that the other parts of our project would easily connect to the microcontroller that was in our arduino board it only made sense that our final design would have this microcontroller as the center part.

3.4 Display

When it comes to a wireless display, it was decided in the research section of this document that the best display technology for this project would be a TFT resistive display. In section 2.5 there were a few displays that were discussed and compared and it was clear from then that the display of choice would be the 4D-Systems uLCD43 (GFX) a 4.3 inch LCD TFT display that has a built in graphics controller and also a micro SD card slot for memory expansion. This is the display of choice without any questions asked.

3.5.A TFT LCD Display

Since the display choice is already known, it would be proper to jump straight into the design aspects and how it will integrate with the project application. Although this display only supports up to 65K true to life colors at a resolution of 480 x 272 pixels it will be more than sufficient to graph the data from the sensor on the XY axis. Luckily this particular display has a lot of documentations in addition to having friends that have worked with a screen from the same family before, it will allow us to have a support system that may be needed it we were to run into any

kinks along the way. Let's take a look at the pin configuration of this display in figure 3.5-1 below.

Pin	Symbol
1, 2	Vin
3, 4	TX
5, 6	RX
7, 8	GND
9, 10	RES
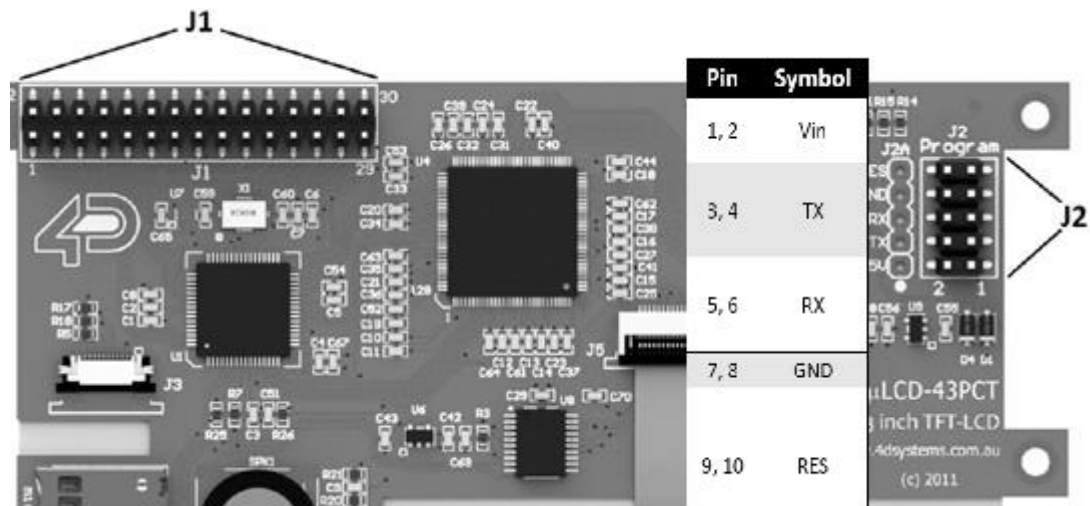
Figure 3.5-1: uLCD43 Pin Configuration – Courtesy of 4D-Systems

Given the above pin configuration let's look at what each pin is supposed to be connected to and its' description. Many of the same screens have similar pin configurations so it should be familiar to a lot of designers.

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.

Figure 3.5-2

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.

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. 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.

Shown in figure 3.5-3 and figure 3.5-4 are the screen shots of two different user menus. Figure 3.5-3 shows the screen for the settings where the anesthesiologist can choose the current level and the interval between the twitches or set of twitches.
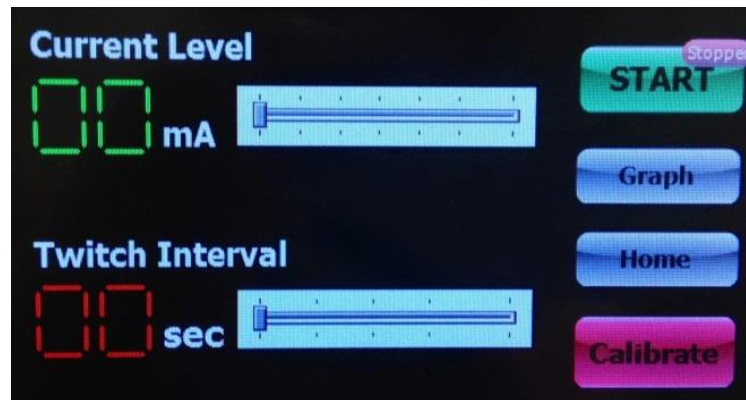
Figure 3.5-3

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 figure 3.5-3. 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 figure 3.5-4. 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 figure 3.5-3 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.

Figure 3.5-4

3.5 Power Supply

For the last section of the project a power supply must be chosen to withstand the demand and accuracy required. The current device uses a simple nine volt battery that, through manipulation, supplies the required current levels of

anywhere between 1mA and 100 mA. Other possible power supplies are larger rechargeable and non-rechargeable batteries and, as a last resort, using an AC wall socket directly.

Before getting in to what power supply would most aptly suit the needs of the project, it is prudent to examine loosely what its needs will be at peaks times. Planning for peak usage guarantees that any and all power needs will be met when running under normal conditions. In point of fact, taking the peak power requirements and adding a certain percentage would be particularly useful if we intend to avoid brownouts. In normal circumstances, brownouts will not damage any of the components intended for the stimulator but they can, and probably will, cause the controller to enter a reset sequence. Any reset sequence while being used on a patient will ruin the data collected up to that point and will possibly render using the device during that operation pointless. The table that follows will give a visual of expected maximum power requirements for each of the main parts of the device.

Part	Min. V	Max V	Min. I	Max I	Manufacturer
LCD	3V	3.6V	20mA	30.3mA	Newhaven Display
Res. Touch Controller	2.5V	5V	60uA	17mA	Microchip
RF Transceiver	2.4V	3.6V	2uA	23mA	Microchip
PIC uC	2.2V	4V	80uA	300mA	Microchip

Table 3.6-1

From this table it can easily be calculated that a minimum of 5V and 370mA needs to be available to the device at all times just to maintain the main components. In addition to these things, the actual neuromuscular stimulation circuitry will need upwards of 100mA just to perform its limited duties. Thus, for caution's sake, stimulator will be designed to maintain 5V at a maximum current draw of 1A. Due to the unpredictable nature of human interaction, the stimulation circuitry will have an unpredictable effect on the circuitry and because of this it is necessary to plan for double the calculated current draw. With these numbers in mind we move on to choosing an appropriate power supply.

3.5.A Battery Power

 As mentioned before, one of the bigger reasons that this device and its cousins aren't more commonly used is because of the difficulty of their use. In an attempt to minimize the differences between the currently used device and the new design, reducing the hassle of completely relearning the device, it was proposed to attempt to use a 9V battery as the main source. At most the design should require less than three of these batteries at a time to minimize its size and weight. A standard nine volt alkaline battery will nominally supply 9V at 565 mAh while Lithium supplies 9.6V at 1200mAh. Given a precision design the device might manage to make a single battery a sufficient source, though this project is likely to require at least two and in doing so already begins to diverge from the current standard. In an effort to be as thorough as possible other battery sources

were considered as well, those options will be briefly listed in the table below next to the 9V for comparison.

Type	Alkaline (mAh)	NiCd (mAh)	Lithium (various; mAh)	Nominal Voltage
C cell	8000	4500-6000	N/A	1.5V
D cell	12000	2200-12000	N/A	1.5V
Lantern (Spring)	26000	N/A	N/A	6V
CR–V3 (Camera)	N/A	N/A	1300-3000	3V
9V	565	120	500	9V-9.6V

Table 3.6-2 (Taken from Wikipedia, need to find better source.)

As can be seem from the table above, even with the spectacular power that a D cell can deliver over time its voltage makes it unusable as a source for this project. A feasible implementation would be to chain several of these batteries in series to get the voltage to a reasonable level, but in doing so the weight of the device becomes unreasonable. Also, if chaining D cell batteries were the primary option it would be simpler and safer to purchase a laptop battery and use it instead.

Failing to find a sufficient disposable battery the next step was looking in to higher power rechargeable batteries. One reasonable suggestion was to use a small standard laptop battery, such as the one used by the Asus Eee. These batteries can have anywhere between 4400 to 7200 mAh for the standard and extended battery pack, respectively, with a nominal 10.8 volts. Considering these new parameters, a device could easily be made to work exceptionally well, even when considering a less than optimally efficient design. Unfortunately, the main drawback to this new choice in power will, obviously, be its cumbersome size. Even the reasonably small Asus Eee's battery has rough dimensions of 1"x2"x8", far too large to strap to someone's arm. Another significant drawback to using any kind of battery is the simple fact that, at some point, is will die. With your standard alkaline battery you can just throw it away and buy a new one, but a rechargeable battery must be plugged it in for upwards of three hours to obtain a full charge. And, even then, they eventually need to be replaced as batteries have a preset number of charges they can take before the individual cells begin to die.

3.5.B AC Power Supply

Following the issue of recharging or replacing batteries, it was decided to just remove the battery from the equation entirely. As has been mentioned

previously, Dr. Looke arranged a viewing of the current neuromuscular device in action in an operating room. From the visits made by individual members of the team, it was observed that, not only are there plenty of AC outlets available but using a battery wasn't even necessary to smooth operation. With that information and the exclusion of a standard battery source, a new design was formed that used the available wall outlets to the advantage of the project. This decision removed the overly strenuous requirement to conserve every electron possible as well as giving the project the ability to grow beyond its original definition. The question now becomes: how to convert the 110VAC wall outlet in to a manageable voltage for the stimulator to distribute as necessary.

Fortunately for this project, the low power nature of the device allows for several different AC power supply designs. With many options available it became necessary to consider other requirements when choosing an appropriate component, such as individual and bulk pricing and simplicity of design. Once these were taken in to consideration, choices were limited to the following categories: an RC network, an AC-DC step down circuit using transistors, or a DC-DC step down IC. Each of these will be considered in the following with its associated pros and cons.

The first and simplest option would be to build a simple RC network to divide off what we don't need. The first challenge with this design would be rectifying the AC power so that it can then be smoothed to a reasonable DC approximation, and as this will need to be applied to the second circuit it will be discussed here. The simplest manner in which AC rectification can be achieved would by applying the signal to a Diode Bridge, shown below, on opposite sides so that no matter the polarity of the power, the current will always travel in the same direction. This orientation is shown in the diagram with a resistor wired as a general load.
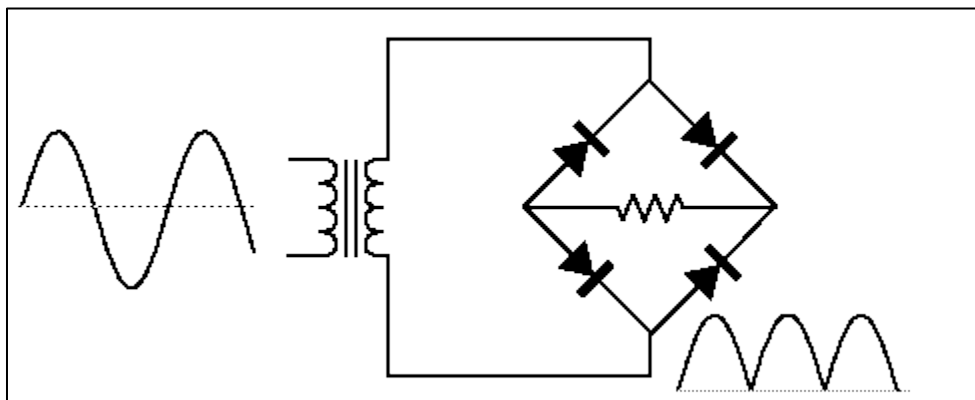
Figure 3.6-1 (Stolen from HyperPhysics)

As you can see from the diagram above the diode bridge rectifies the signal, but in no way makes it DC. At this point we need to add a fairly large capacitor to smooth the ripple down to less than ten percent. As an example, given a twelve volt AC source a twenty percent ripple means that the lowest expected voltage

after rectification will be 10.8V at any given moment. Inductors can also be used for this purpose, but it has been determined for this project that to get an effective inductor the size would once again become cumbersome. Once a rough rectification has been managed, calculations will need to be done to determine the appropriate resistor values. Because this method creates entirely too many losses, and very probably too much heat, it was almost immediately written off for more efficient designs.
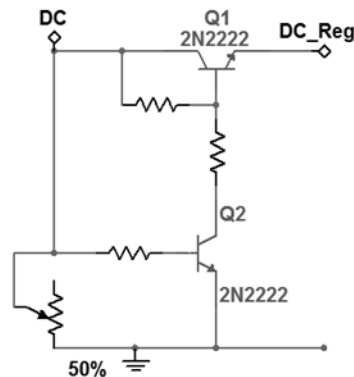
Figure 3.6-2

Knowing that resistors were a poor choice but liking the idea of a handmade voltage converter, team decided to attempt a simplistic transistor design that would rectify the voltage and then step it down as needed. Towards that end, the diode bridge will again be utilized before connecting its output to the input of the very simplistic following circuit.

This circuit utilizes two transistors and a potentiometer, as well as various resistors, to produce the reduced voltage. Various other resistors can be used to set a minimum or maximum regulated voltage. Again, even here, the problem of severe inefficiency occurs. With this design, though, the inefficiency comes up from two things, first from the potentiometer and second from the wasted power at anything other than the highest voltage. The apparent nature of the second issue makes it simpler to describe first. Because of the simplicity of the circuit, any voltage that isn't needed is drained straight to ground instead of potentially storing it for when a higher voltage is required; this goes a long way towards unnecessarily wasting power. The potentiometer, on the other hand, leads to a cons-outweighing-the-pros problem. While having the potentiometer control the voltage level gives the circuit the ability to precisely tune the regulated voltage at the output, it also requires that the potentiometer be exposed, or easily accessed, so that it can be modified after manufacturing. The issue will eventually arise that the potentiometer has modified itself, turning either up or down, in such a way that it prevent normal operation or, even worse, destroys the device due to power overload.

Seeing that all analog, manually adjustable devices will eventually need to be tuned it was proposed to find a solid state solution to this regulation problem. Upon further research, it was found that a voltage regulator or converter can found to fit any application imaginable and as such seems to be the obvious choice. In addition, as an added safety feature, it was suggestion that the device be decoupled from the wall unit to prevent any unfortunate accidental shocks caused by a faulty circuit component. Decoupling this device can actually serve two purposes, it can prevent catastrophic failure from hurting the patient and it can also perform an initial step down to the voltage. Fortunately a simple transformer will provide both of these functions in one component. Transformers of all kinds are also widely available and as such will be relatively inexpensive to purchase, especially in the situation of mass production. For this, the chosen setup, the circuit will need a diode bridge, a capacitor, a transformer, and the chosen voltage regulator. The basics of this circuit will be in the diagram below with values removed for reference.
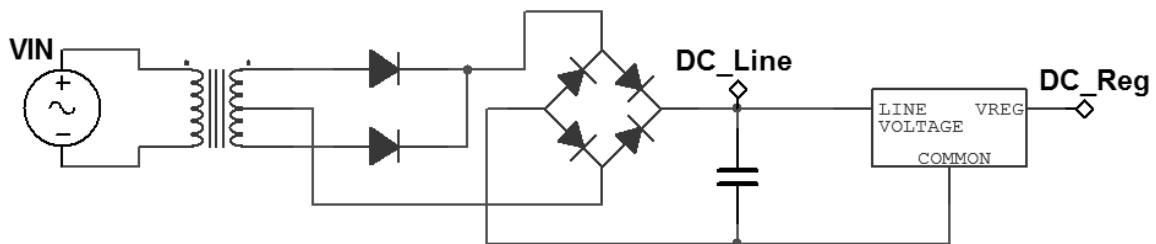
Figure 3.6-2

3.5.C Design Summary

Now that a decision has been made about how to power the device, the actual design must be taken in to consideration. Because this project will be entered in Texas Instrument's Analog Design Competition, initial part searching began with them and, as it turns out, they make all the IC this project will need. The chosen regulators are listed in the following chart with a schematic of their proposed wiring.

Part	Vin	Vout	Ii Max	Io Max	For	Part #
Bridge	<=200V	N/A	35A	N/A	Rectifying	GBPC3502W
Diode	<=200V	N/A	30A	N/A	Power Uni	NTSJ30120CTG
Inductor	N/A	N/A	25A	N/A	2mH Smoothing	RB8522-25-2M0
V. Reg.	9-26V	3V3	N/A	1A	uC; RF; LED	PT5103A
V. Reg.	9-38V	5V	N/A	1.5A	Res. Touch	PT78ST105H

Table 3.6-3
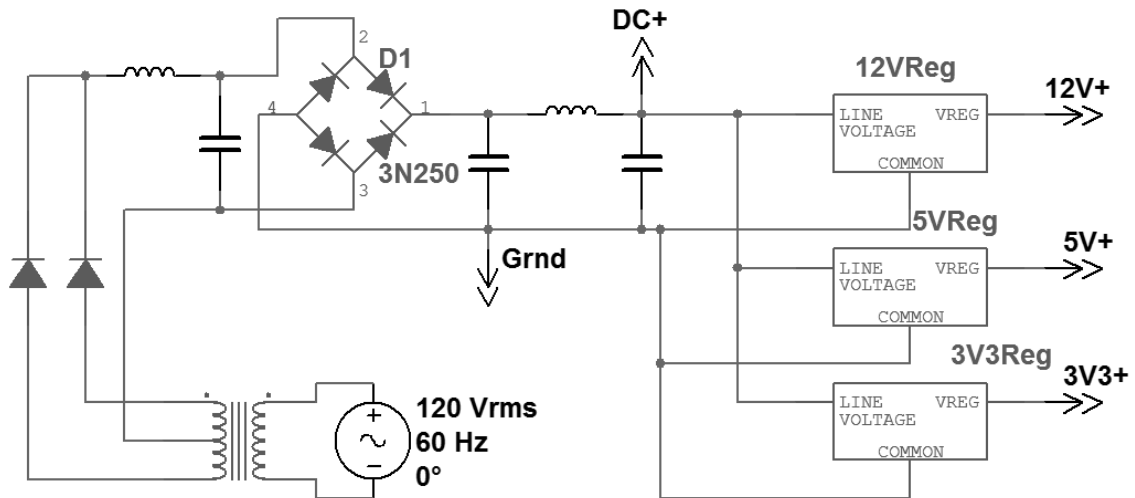
Figure 3.6-3

3.6 Patient Medical Safety Concerns

The main goal as stated earlier is that the Paralytic Twitch Sensor device be ready to use in the operating room. In order for the device to be used in the operating room the group needs to follow the guidelines that are set for the operating rooms when deciding on what parts to use for the project.

3.6.A Sterilization Concerns

The main concern that the group had was to obtain a sensor that worked well but, also followed the sterilization guidelines that the operating rooms have to follow. All surfaces or devices that have come into immediate contact with the patient have to either be disposed of or cleaned with an approved hospital grade disinfectant. These measures are in place to keep the cross contamination from patient to patient to a minimum so that the spread of diseases is not going from one patient to another. This is why the electrodes and the sensor were given careful consideration when the group looked at them.

The electrodes needed to be cheap enough that they are able to be thrown away when they are done. Now they cannot be so cheap that they do not allow the current to pass from the current supply to the nerve that is being stimulated for the reaction. The reason that these need to be discarded is because there is not a viable way to put a protective layer between the skin and the electrode that will also allow the current to pass. This additional layer would either add additional noise to the system that would be impossible to get rid of when the group is trying to program the output display.

The pressure sensor that was chosen did not need to come in contact with the skin, which allowed the group to pick the sensor that would work well no matter who the patient was. This also allowed the group to spend a little more money on the sensor. However the device that we hooked to the end of the tubing in which the patient would apply pressure to in order to obtain the results needed had to come in contact with the patient. The pessary which is shown in figure 3.7-1 attached to the pressure sensor was chosen as the device that would be placed in the patients hand in order to receive the data from the force that was being applied while the general anesthetics were wearing off. This actually allowed the group to change gears and instead of looking for something that was disposable and instead the idea of just wearing a protective disposable glove was hatched.

Figure 3.7-1

The best part about having this glove or protective covering is that it keeps the pessary from actually touching the patient. The pressure applied to the pressary is the same whether there is a glove between the hand and it or not. This made perfect sense when the group was thinking about sterilization because it allowed the use of something that was working as it was being tested in the final design without having to change the design because of sterilization. Plus having a latex glove that needs to be placed over a patents hand is a cheap solution to what could have been a very large problem.

3.7.B Reusability

The sterilization concerns were closely related to finding a sensor that is reusable if needed. The most important part of this Paralytic Twitch Sensor is the sensor itself. But, the device itself also has to be reusable. It has to be able to work in the operating room. This device was created to help the anesthesiologists with the work that they do. So it was important that they have a device that is both reusable and functional.

Each part of the device has to be used on a daily basis. This was being created mainly for use in the operating rooms and therefore it needed to be able to be sterile and capable of being used multiple times a day without having to worry about overheating. The only two parts that really caused any concern for the reusability requirement were the electrodes and sensors because those are the

parts of the device that touch the patient and therefore special consideration had to go into those parts and how the group could make them sterile.

The electrodes were the easiest part of the device design to make reusable. Not that the electrodes are reusable but they can be easily disposed of after they are used so that the anesthesiologists do not need to worry about having to disinfect them making it easier for them to use making the reusability of the device that much better.

The sensor was the part of the device that was a little more difficult to create ease in the eyes of the anesthesiologist in reusing them. From what the group could tell from the research conducted the best bet is to either invest in the top notch sensors and have only a few on hand at the hospital and then at the end of the day having the sensors sterilized so that they will be ready for the next wave of surgeries or creating something or just having a rubber glove between the patients hand and the sensor so that there is nothing on the device that is touching the patient. This may increase the reusability of the device and make it easier to use.

Lucky for the group the pressure sensor that was chosen allowed the device to have a pessary be the only part that comes in contact with the patient. This meant that the only thing that was necessary to make this device reusable on the end of the sensor was a simple latex glove that went over the patients hand so that the skin never came in contact with the pessary.

The devices reusability and the ease of its use became a major concern for the group during the design because this was the main reason why the group decided to work on this particular project. Anesthesiologists are not using the devices that they have now because of the fact they are not very reusable and they are not user friendly.

3.7.C Patient Variability

The fact that these anesthetics that are given to patients are so unpredictable in even the best cases make it seem like the variations in patients very a great deal more than just by the age and their overall fitness. That's why the biggest factor that shows that this Paralytic Twitch Sensor is needed is the fact that each patient is different when it comes to the general anesthesia medicine response. Even in the most ideal cases where the patient is young, healthy and fit there really is no real way of conclusively telling whether or not the medicine will work as it is prescribed.

The reason that this is so unknown is that the chemical makeup of these drugs reacts differently to each person's body chemistry as does other medications. However, in the situations that these drugs are used the anesthesiologist needs

to be able to have some way of monitoring the drugs because it is imperative that the body of the patient is paralyzed while the surgeon is working.

Monitoring these patients starts to become really important once the surgery starts. The risks from the anesthesia depend on patient's age, health, medicine they are currently taking, and how they respond personally to the medicine. The anesthesiologist can know the drug like the back of their hand and can have studied the patients records yet still not know when to give an additional dosage of the medicine. The records that the anesthesiologist will go over are very important. It is important that the patient answers all the questions honestly. This in-depth history is important so that the anesthesiologist can make sure that the dose of anesthesia that is given is appropriate and safe for the particular person.

Like many other drugs that are used today there are risks involved when the patient is taking other medicine, smoking, and drinking alcohol can increase the chances of having problems. Medicines like ones that Kelly takes for seizures, can actually make the anesthetics that are used wear off quicker. But, some patients can have a metabolism that for some unknown reason is able to reverse the effects of the anesthesia faster than others. The opposite is also true. The anesthesiologist could administer the amount of drugs that a patient needs based on what their charts say in relation to their height, weight, and medicines that they are taking at the time and end up with a slight overdose where it takes to long for the anesthesia to wear off and then this patient takes too long to recover. In this instance the patient is paying for additional neuromuscular blockading drugs that were not even needed in the first place and there is a space taken in the recovery room that could be used for another patient. These issues could all be resolved it there was a device like the Paralytic Twitch Sensor to monitor the general anesthesia levels in patients.

These are just some of the cases when being able to test the force of the twitch is essential so that the anesthesiologist can periodically check the patient in an easier fashion. If there were an easier way to test, the fears that patients have about waking up and being able to feel what is going on will help them out. It will also keep the surgeons from having to tell the anesthesiologists that the patient is waking up.

Chapter 4 Build

Section 4.1 AC/DC Power Supply

Now that all of the individual components have been considered and chosen it is time to assemble them. It seems wisest to begin with the most essential component of the entire project, its power supply. Recapping the design section, it was decided that building a custom power supply for the project was the best idea. This was for multiple reasons, not the least of which being a way to prove that all the members of the team possessed the basics of power management. It was also decided that leaving the power to an unpredictable battery source was unwise, so an AC source would be used. 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. Once plugged in to the terminals the hot wire will be connected in series with a current limited resettable fuse. This fuse will be limited to seventy-five percent of the nominal current rating of the components it directly connects to. This device will provide a safety mechanism to prevent accidental shorting from annihilating the rest of the components. The neutral and ground will also be used in the circuit to provide the "negative" and an emergency ground. Should any component decide to short out all of its power will be redirected to ground instead of across the patient.
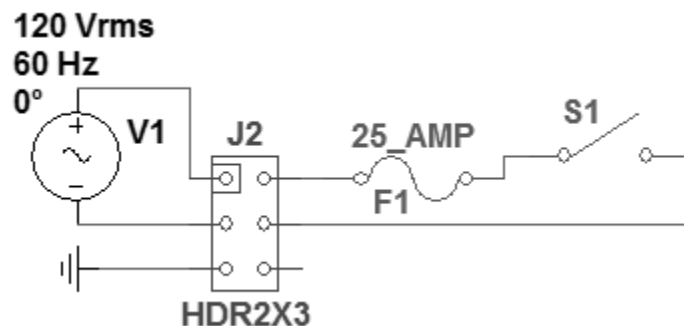
Figure 4.1-1

Figure 4.1-1 shows these pieces and how they shall be connected. It can be seen that a switch is also built in to the design; this is to disconnect the main power from the device. Consider it an On/Off as well as a second to last resort to cut power to the device should it experience catastrophic failure.

The next piece of the power supply will be the actual manipulation of voltage that gives the circuit ability to create a constant DC signal. The lead from the switch 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 exists 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. While a power surge is unlikely in a hospital setting, it is better to be safe than sorry, 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 a 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.
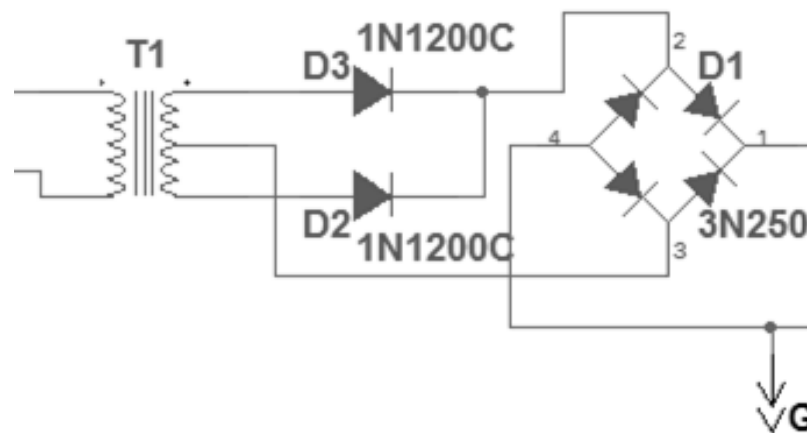
Figure 4.1-2

Now back to a less grim topic, the transformer. 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 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.

At this point the diode bridge comes in, as can be seen above the bridge is wired in such as was as the diodes look like they're pointing in the direction of the current. This is how the bridge works, allowing current to flow in their forward active direction and preventing it from ever flowing in the opposite direction. The post-rectification part of the circuit, otherwise known as the DC side, will be wired to that the current always flows in to its positive side and out of its negative. The rectified AC signal will be wired to the other two poles of the diode bridge; once the DC side has been hooked up it is actually irrelevant which lead goes to which pole, here it is chosen in the simplest manner with the common on the bottom.
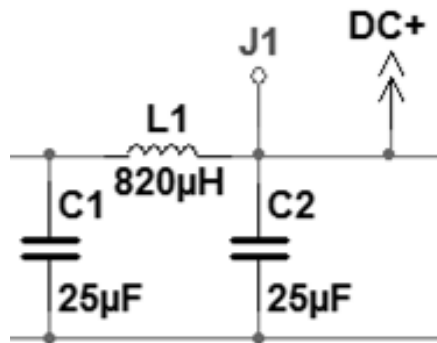
Figure 4.1-3

After the diode bridge an inductor is added in series to the circuit while two capacitors flank it branched between the DC+ and DC-. This capacitor/inductor section of the circuit serves to smooth out the ripple that is left by rectification. Ideally all ripple will be removed, but a ripple of less than ten percent is reasonable for this purpose; this is because >85% precise DC/DC converters will be used as necessary to regulate this new DC voltage to levels useful to the ICs of the project.
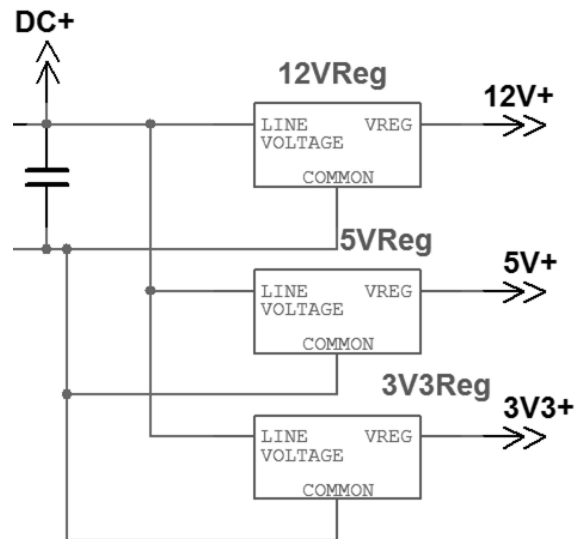
Figure 4.1-4

And with the mention of the regulators, now would be an ideal time to introduce their circuitry connection. Because of the ample power now available to the rest of the circuit, several voltage regulators can be used in parallel without any worry of brownouts, or occurrences where the voltage falls to low to be useful, in individual components. A wiring diagram is provided below to show the method in which these will be connected.

Note: Care should be taken when looking at voltage levels. Because the ground of the DC side of the circuit is relative to the common, there exists a dinstinct possibility that this is not earth ground. Any component that expects earth ground can be wired directly to the earth ground of the AC socket. The design of the circuit will attempt to eliminate the need for a true earth ground, instead leaving it for emergency grounding purposes.

Putting these pieces together in a single circuit diagram may help alleviate any confusion that may have developed.
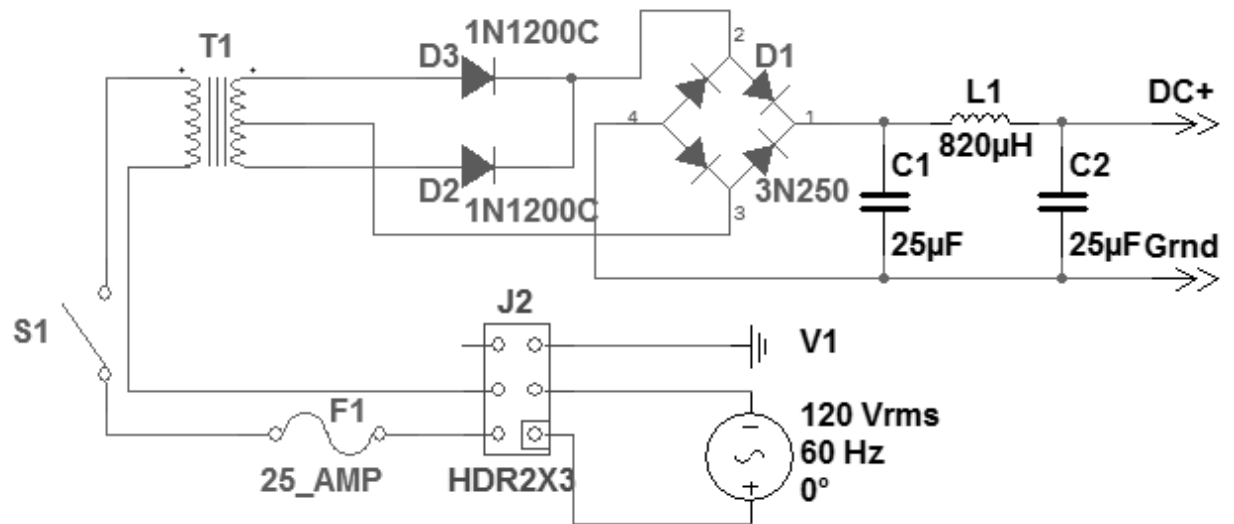
Figure 4.1-5

4.2 Design for the Sensors

4.2.A Pressure Sensors

MPL115A by Freescale

With the SPI interface, MPL115A operates as a half duplex 4-wire SPI slave capable of bus speeds up to 8 Mb/sec. Freescale offers a sample eval board in SPI called the KITMPL115A1SPI. Below is a simple PCB board with sensor parts, associated pullup resistors, and decoupling capacitors already soldered onboard. This provides a quick sample tool to run evaluations of the small device, given its land grid array (LGA). As able to be seen, the pins for 'shutdown,' 'serial clock input,' 'serial data input,' serial data output,'and 'chip select line' will be connected to the microcontroller of the design. The V_{DD} pin is for the power supply connection, which can range from 2.375V to 5.5.V. Connected to this node is a 1 uF capacitor that is connected to ground. The maximum ratings of voltage for SHDN, SCLK, CS, D_{IN}, and D_{OUT} is from -0.3V to V_{DD}+0.3V. Following the diagram is a table of the pin functions for the pressure sensor. Lastly is the MPL115A1 (SPI) interface board, or KITMPL115A1SPI.
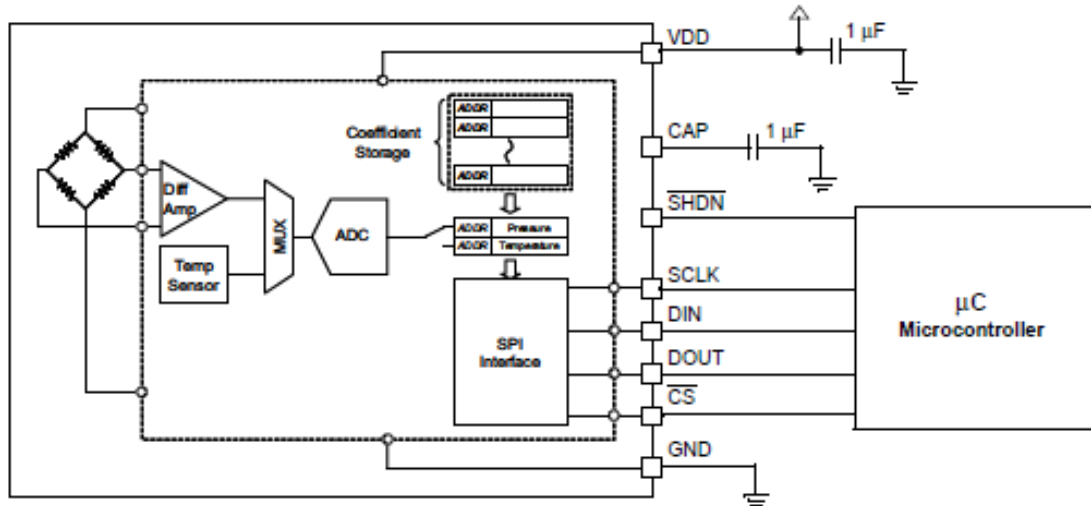
Figure - MPL115A block diagram with pin outputs

Pin	Name	Function
1	VDD	VDD Power Supply Connection: VDD range is 2.375V to 5.5V.
2	CAP	External Capacitor: Output decoupling capacitor for main internal regulator. Connect a 1 µF ceramic capacitor to ground.
3	GND	Ground
4	$\overline{SHDN}$	Shutdown: Connect to GND to disable the device. When in shut down the part draws no more than 1 µA supply current and all communications pins ($\overline{CS}$, SCLK, DOUT, DIN) are high impedance. Connect to VDD for normal operation.
5	$\overline{CS}$	$\overline{CS}$: Chip Select line.
6	DOUT	DOUT: Serial data output
7	DIN	DIN: Serial data input
8	SCLK	SPI: Serial Clock Input.

Figure 4.2-1 – table of pin descriptions for the MPL115A
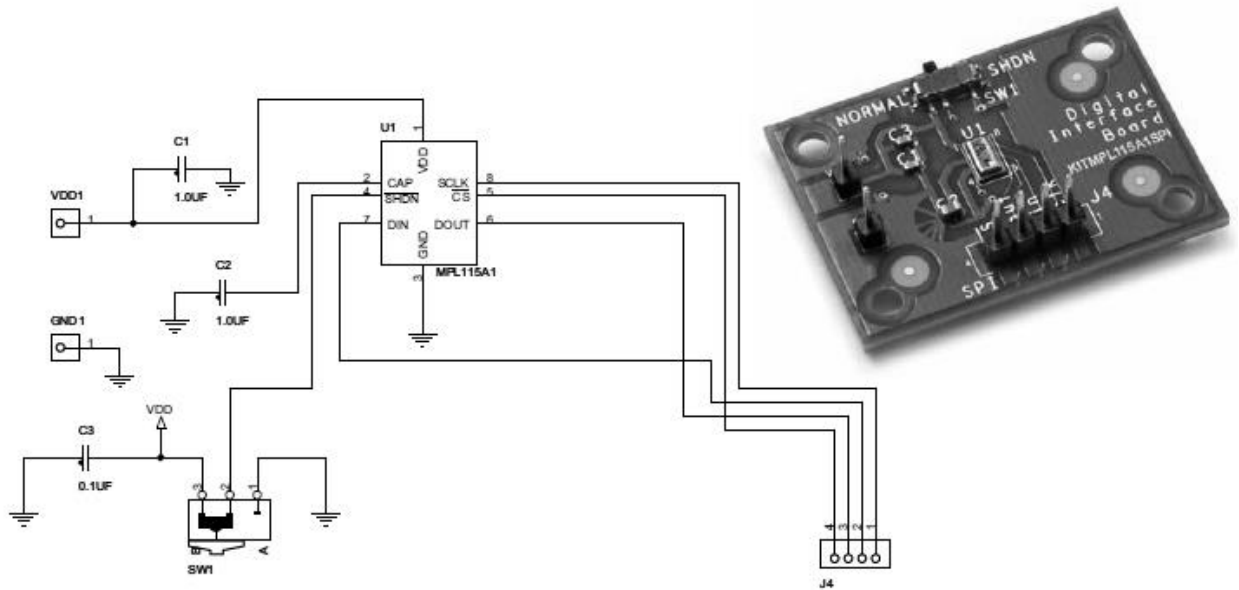
Figure 4.2-2- KITMPL115A1SPI: MPL115A1 (SPI) Interface Board

MPL3115A2 by Freescale

Freescale's Xtrinsic MPL3115A2 offers several features in its design. This sensor offers an on-board intelligence design with a flexible sampling rate up to 128 Hz. The device power is supplied through the V_{DD} line, shown at Pin 4. Power supply decoupling capacitors (100 nF ceramic plus 10 uF bulk or 10 uF ceramic) should be placed as near as possible to pin 1 of the device, which is shown connected from Pin 1 to V_{DD}. A second 100 nF capacitor, connected from Pin 2 to Pin 3, is used to bypass the internal regulator. The functions, threshold and the timing of the interrupt pin, INT1 and INT2, are user programmable through the I^2C interface. The V_{DD} power supply connection can range from 1.95V to 3.6V. Connected to Pin 7 is the I^2C serial data and to Pin 8 is the I^2C serial clock.
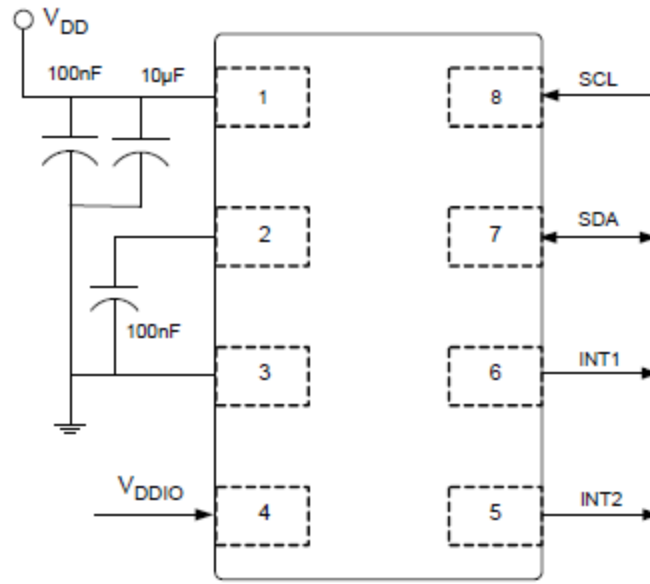
Figure 4.2-3 - Pin connections for the MPL3115A2 pressure sensor

Below is the table of the functions for each pin shown above. Then, a figure of the MPL3115A2 circuit board.

Pin	Name	Function
1	V_{DD}	V_{DD} Power Supply Connection (1.95-3.6V)
2	CAP	External Capacitor
3	GND	Ground
4	V_{DDIO}	Digital Interface Power Supply (1.62-3.6V)
5	INT2	Pressure Interrupt 2
6	INT1	Pressure Interrupt 1
7	SDA	I^2C Serial Data
8	SCL	I^2C Serial Clock

Figure 4.2-4- Pin descriptions for the MPL3115A2 pressure sensor

Figure 4.2-5-MPL3115A2 circuit board

4.2.B FlexiForce Sensors

The following is a recommended way to integrate the FlexiForce sensor into an application. In this case, it is driven by a -5V DC excitation voltage. It then produces an analog output using an inverting operational amplifier arrangement that is based on the sensor resistance and a fixed reference resistance (R_F). Once this measurement is found, an alalog-to-digital converter can be used to change this voltage to a digital output. In this circuit, the sensitivity of the sensor can be adjusted in one of two ways: by changing the reference resistance (R_F) and/or the drive voltage (VT). The sensor can become less sensitive by lowering the reference resistance (1kΩ min.) and/or the drive voltage (-0.5 V, -0.10 V, etc.), thus it will increase its active force range. This recommended drive circuit results in a linear (±3%) output from FlexiForce sensors.
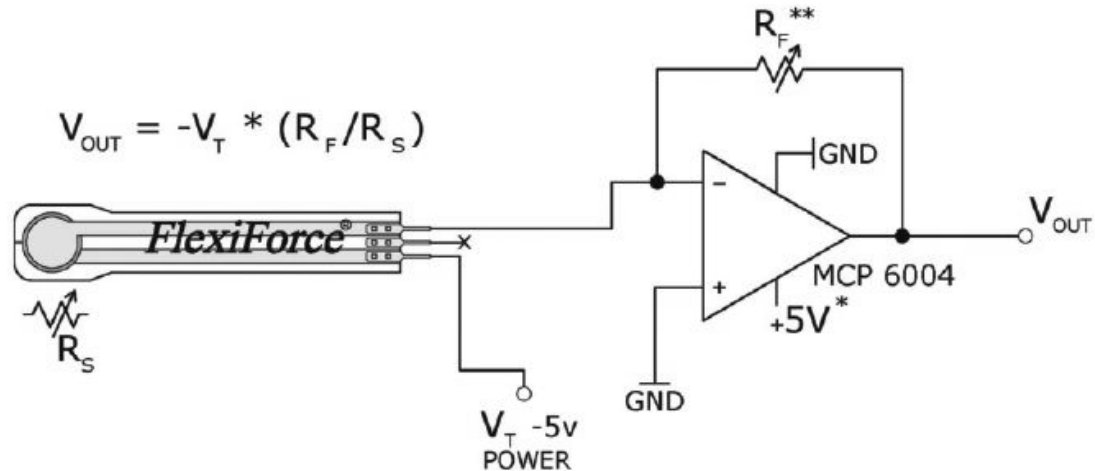
$$V_{OUT} = -V_T * (R_F/R_S)$$

- • * Supply Voltages should be constant
- • ** Reference Resistance R_F is 1kΩ to 100kΩ
- • Sensor Resistance R_S at no load is >5MΩ
- • Max recommended current is 2.5mA

Figure 4.2-6 - Recommended drive circuit for FlexiForce sensors

4.3 LCD

This part of the design document will go over some of the LCD requirements and features that were discussed in detail in the research and design sections of this document, but will mostly focus on the methods that will be used to program the LCD module and display the data received from the thumb sensor. The below table with pros and cons that are relevant to the build of this display (IDTB02-4.3).

PROS	CONS
SD Card Socket	Only 65K Colors
Built-in Controller	Limited Documentation
Supported by UTFT Library	16-bit Data interface instead of 24-bit
4-Wire Control Interface	
Table 4.4-1: Pros and Cons for ITDB02-4.3 Display w/Controller	

Earlier in section 3.5.A the pin configuration and description was detailed and to make it more clear and relevant to the build of the LCD a schematic of the 40 pin LCD interface will be given below. This schematic was provided by Itead Studio for the use in the design of applications like this project.
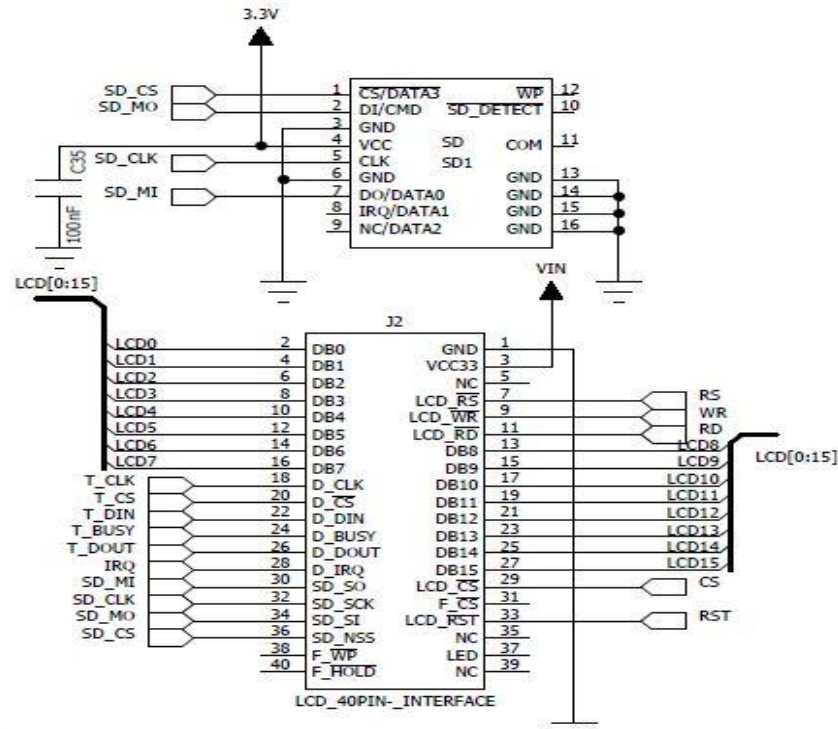
Figure 4.4-1: 40-Pin LCD Interface Schematic – Courtesy of Itead Studio

4.3.A Programming

Here is the outline of the functions that will be used to program and control the display of sensor data on the LCD module. These functions are subject to change during the course of prototyping phase of this project.

Function Name	Function Description
Double getXCoordinate(touch_input)	Function calculates the X coordinate value when pressed on the screen
Double getYCoordinate(touch_input)	Function calculates the Y coordinate value when pressed on the screen
Int getInputCommand(touch_input, task)	Functions takes in two parameters: the touch input, and a task based on where you pressed and returns the command as an integer
Double getInputData(data, coordinate)	Function will return the input data from the touch screen if the user changes any parameters
Void graphData(array_of_doubles)	Function will graph the data from the sensor
Table 4.4-2: Outline of Function for the Wireless Display	

4.5 PCB

On the PCB, we included everything that was a part of the design. Because the final choice for the sensor was not decided until after the PCB was ordered, it was not placed on the board.
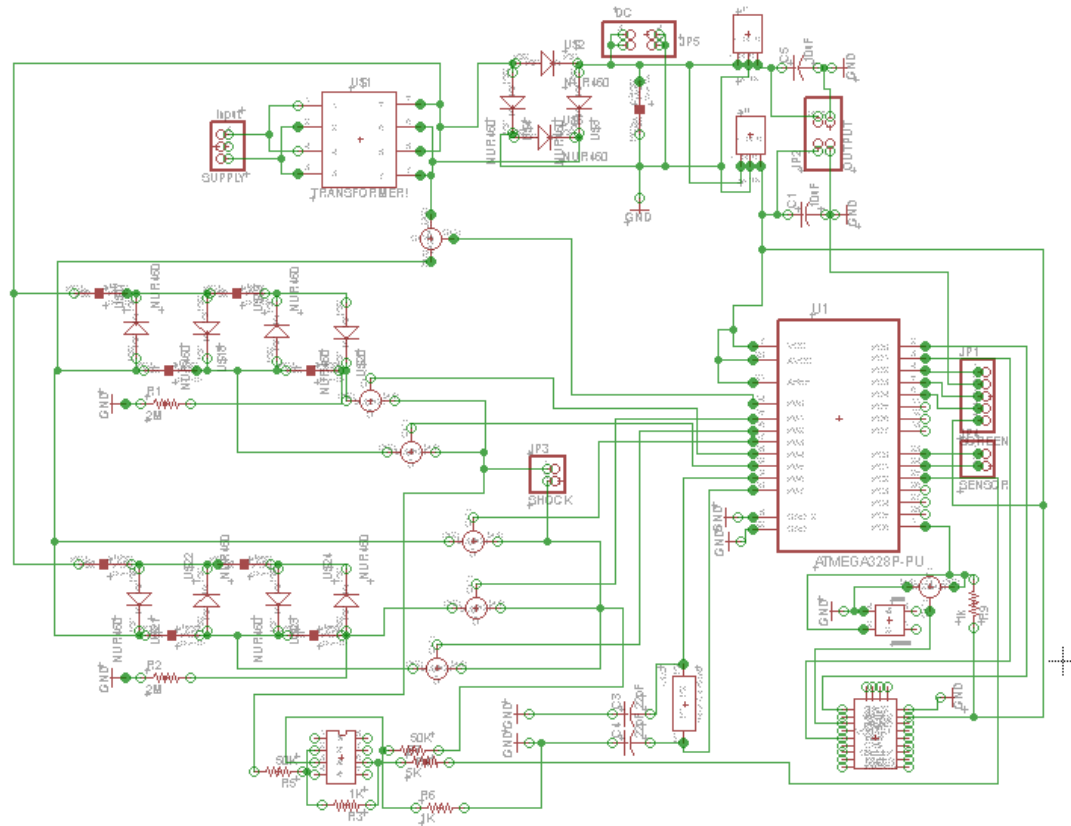
Figure 4.6-1: Schematic for the PCB

In Figure 4.6-1, the full schematic for the layout of the board is shown. On the left, the positive and negative bias for the Cockcroft-Walton voltage multiplier is shown. The top has the initial power supply with the transformer and the voltage regulators.
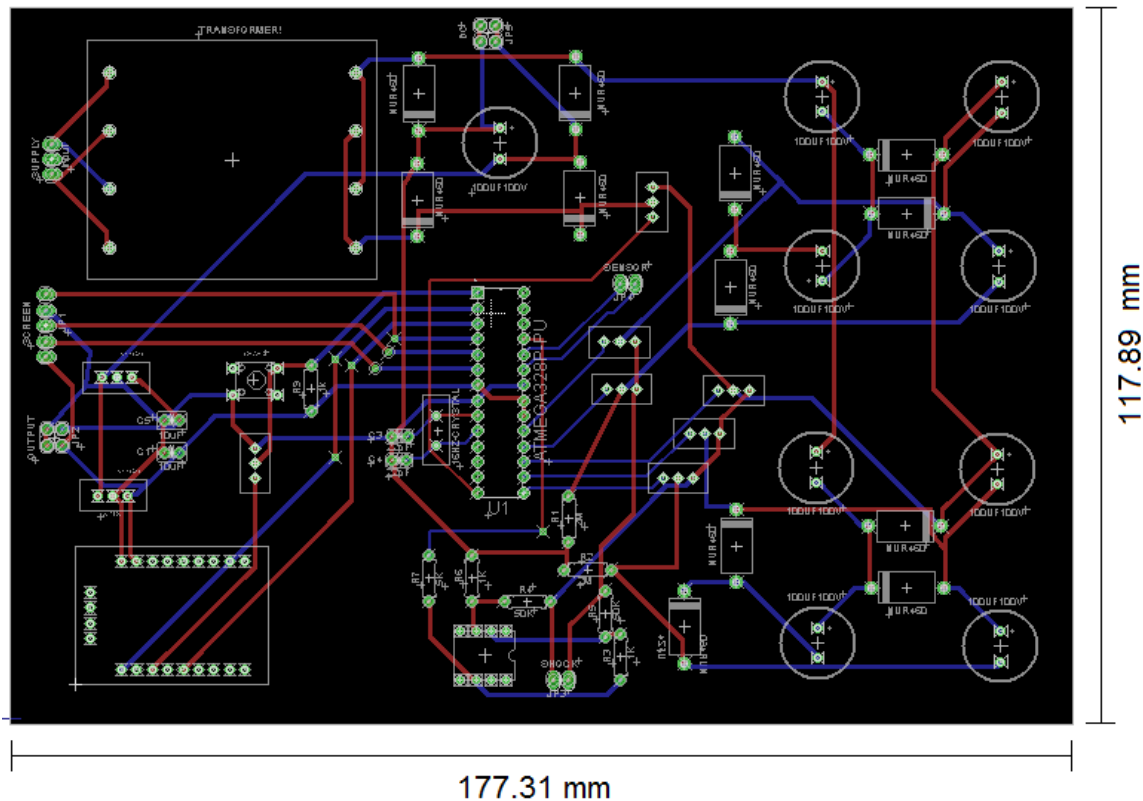
Figure 4.6-2: The final layout for the PCB

Using EAGLE the PCB schematic was turned into the final board that is depicted in Figure 4.6-2. This board unfortunately is larger than what the group was hoping for but, sometimes designs change as the project enters the final stages and it starts to come together.

4.6 Coding

The two coding subsection below will be mostly dealing with sensor control and pulse control to get accurate readings with the least amount of noise. The main point of these functions is to synchronize the electric pulses with sensor polling. This kind of synchronization will reduce the amount of noise and will eliminate unnecessary polling from the sensor when there is no pulse sent to the person's thumb. So here is the basic idea of how it functions: when the pulse is active and current is applied to stimulate the muscle the sensor data is pulled at the same time. Going with this approach you make the device more robust and less error prone to inaccurate twitches.

4.6.A Pulse Control

Now that the synchronization of the sensor polling and pulse activation is in place, let's look at some functions that will control that. The following table shows the outline of each function.

Function Name	Function Description
double getTimeStamp(System_time)	This function will pull the system time off the chip
double pulseTimer(current_time)	This function will create a pulse timer based on the given specifications for either a TOF pulse or a constant pulse for a given period of time.
void sendPulse(time)	Functions will active the pulse and send the muscle stimulating current to the electrodes
Table 4.5-2: Outline of Function for the Wireless Display	

4.6.B Sensor Polling

Function Name	Function Description
double getSensorData(sensor_output)	This function will get sensor data from the sensor output pins and return it as a double
void synchronizePolling(time)	This function will synchronize polling with the pulse timer to reduce sensor noise
double sendSensorData(data_array)	Functions will prepare the sensor data and format it to send it to the wireless screen.

Chapter 5 Test Plan

A major part of this project was to make sure that it worked when it was presented in front of the committee chosen by the group. With this knowledge the group went through great lengths to test the Paralytic Twitch Sensor to make sure that it would work on the day and time that it needed to. Unfortunately one of the major problems that were faced when testing the project was that there was no real way of testing the project as a whole. This presented the group with obstacles to overcome but in the end it all worked out.

5.1 Power Source

Because the power source is base for every other component of this project it was tested first. Testing this piece on its own allowed the group to verify that everything was wired appropriately and that there were no cold solder joints creating partial open circuit conditions. Referring to the AC/DC diagram it was obvious that the first test will simply be two plug the source in.

WRONG.

Unless the intention was to get electrocuted, never assume everything functions properly and start playing with high voltages. The first test was actually to use the continuity setting on the multimeter to make sure that all wires were functional and that all the connections made won't spontaneously appear and disappear. When we found loose or bad connections we fixed them to make sure that they were not the cause of additional problems as the group kept testing.

Once all of the repairs were made the next step was to connect the AC terminals to the positive and negative of the DC power source. Because a transformer was used to create the isolation from the AC wall socket, it was necessary here to current limit the DC source. Once current limited the source was then turned up to 24 volts. This voltage transferred across the transformer and through the diode bridge. With the source hooked up, the next step of testing was to go through and check all relevant voltages. Because a DC source was used it was necessary to mentally compensate for that. The point here was to make sure everything was working at lower voltages before plugging in to 110VAC.

This, as it happens, was the next step after everything checked out at the end of the last two parts. For this step, a cautious person would find some insulated gloves to wear on the first plug in as a safety precaution. If something were to fail, this would be the time to fail catastrophically. However, the group did not have these gloves so Ryan, being the brave person he is, carefully plugged it in. He made sure that the rest of the group members were close by just in case anything was to happen. Luckily everything was as it needed to be and it worked the first time without something horrible happening. Now that nothing appeared to have failed upon energizing the circuit, it was time to retest the voltages with

the multimeter. At this time all the voltages were checked again to make sure that they read near their expected values. Near was critical here because all components have tolerances that cannot be controlled by the end user but, on the flip side of that coin, all values should be well within the planned tolerances of the project. When we had problems where certain parts were not working as they should then the first thing that was done was to de-energize the circuit and pull out the spec sheet for the device. When we looked at the sheets, assuming that they were correct in what they said, the group double checked that all of the pins were connected properly and that nothing was left to unintentionally float, or another common problem. After getting the PCB back, the group realized that there were a few instances where there was a floating ground that needed to be fixed. Luckily most of the issues that we ran into at this point were relatively easy fixes because of the fact that the group opted for through hole components. There were times when the part just was not working and we realized that the component was probably DOA and just needed to be replaced.

Once the part was replaced or fixed the test was rerun in order to make sure that what was fixed was the only issue. When it did not work the second time that the test was run, then the group kept checking parts until it was completely working the way that it was needed. From here the next step in testing was to test the current source.

5.2 Voltage Boost Circuitry

This particular part of the circuit was actually the trickiest; this was because so few of its principles were taught to or learned by members of the group. This meant that a significant amount of time was spent on just figuring out the basics of this circuit. So, to be thorough, every possible failure scenario must be considered before the group was able to move onto the next part of testing. For this circuit the first thing that was tested was its ability to hold up to a low DC voltage, to test this the charge capacitor was removed leaving on the bleeder resistor between the inductor and ground. Then a nine volt battery was hooked up to the two input leads and the group tested the 555 Timer's output for a decent square wave of the appropriate frequency. These steps were the simple part; if something was wrong here it meant that either a resistor or capacitor was soldered poorly, or that the 555 Timer does not work. Once this issue was isolated and fixed the circuit needed to be rerun and the voltage across the bleeder resistor needed to be measured to make sure that the inductor is functioning as was expected. At this point it was necessary to pay attention to the battery as well as the circuit to see if everything worked properly. If all the correct voltages were measured at the junctions prior to the inductor, which they were, then it was safe to say that everything was electrically correct there. This does not mean that the circuit will necessarily be able to work though as this setup has a tendency to draw a lot of current for a significant amount of time. Which is why a few times at the beginning it worked or did not work and the group had a hard time figuring it out at the beginning. However the group was finally able to realize

what was going on and was able to make sure that it would work every single time after that. This was why paying attention to the battery was so necessary, if the battery began to get hot it indicated that a significant current was being drawn and that there existed the possibility that the switching time on the 555 needed to be adjusted.

Because the multimeter did not find any components that have shorted out or failed in some manner and the battery did not meltdown in five seconds then the group assumed that it was safe to move to a higher voltage source. The next one that was tried was 24V. When connected to this new source the circuit was rerun with the same voltage tests again to ensure that everything still worked as it did with the lower voltage. Once again the 555's output was checked first and then the voltage across the bleeder resistor. Because both of these roughly represented what was expected then the group added the capacitor back into the circuit and restarted testing with the nine volt battery. This time an oscilloscope was useful to testing. The 555 output along with the voltage build up in the capacitor needed to be watched. It was important to check the rise time on the capacitor to make sure it was fast enough to be useful with the tetanic pulse since that is the fastest measurement type that the group used in the final project. Now that nothing has gone critically wrong, it was time to move to the constant current circuit.

5.3 Constant Current Circuitry

For this circuit, due to its simplicity, the test was fairly straightforward: it was hook up to power with a potentiometer in place of the skin contact and vary the resistance reasonably. The input voltage here can be whatever is high enough to be read with a multimeter, so as long as the resistance was not excessively large it worked with a nine volt battery in place. The idea with this test was to make sure it functioned properly, not to test it to its limits. The components were chosen with a factor of safety of at least two so that they can handle whatever the full circuit can throw at them.

5.4 Sensors

In order to test our sensors, we utilized the Arduino Uno development board, which we had ordered online. For all of our sensors, we utilized through-hole technology for testing. The pressure sensors we experimented with were surface mount parts. However, to allow for easier testing, we soldered wire to the necessary pins. Testing with Electromyography required electrodes, which we then attached alligator clips to connect it to a breadboard. Once we connected the sensors onto a breadboard and with the Arduino Uno, we wrote a series of simple code modules in order to test the sensors.

Force Sensor

Our focus at the beginning of this project was to use a sensor that could be used even if the patient's arm had to be tucked to the patient's side for a surgery. This therefore made the force sensor a great choice. We tested the 1 lb. Flexiforce sensor, model A201, by Tekscan. Per instruction by the company's website, we tested the sensor on a flat, hard surface and calibrated the sensor with 110% of the maximum load until we were able to maintain a steady output before actually beginning our testing. We also used the company's recommended circuit, shown below, for testing.

$$V_{OUT} = -V_T * (R_F / R_S)$$

- * Supply Voltages should be constant
- ** Reference Resistance R_F is 1kΩ to 100kΩ
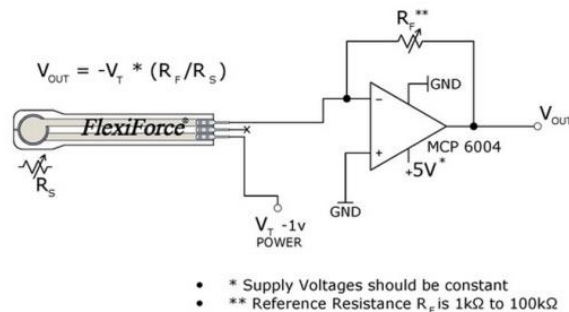
Figure 5.4-1 – recommended circuit provided by Tekscan.

Supply voltage was kept at a constant 5 volts, but we varied the reference resistance between 10kΩ and 1MΩ. Although we seemed to receive good outputs when we tested the different forces exerted by our thumbs, we were unsure how accurate and reliable these values actually were. Because the diameter of the sensing area was only 0.375 inches for these sensors, it was unsure how the outputs would change when we maintained the exerted force in that small area. To get a better understanding of the accuracy of the outputs, we used a metal shot glass and soldered a small, metal shim with a 0.325-inch diameter to the center of the bottom of the shot glass, as shown below.
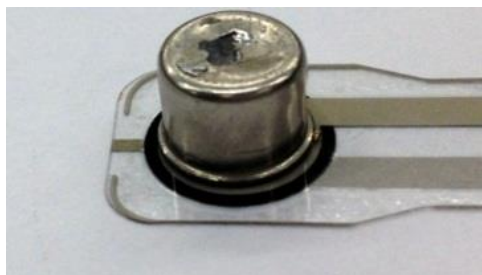
Figure 5.4-2 – metal shim with a 0.325-inch diameter.

Figure 5.4-3– shim attached to shot glass

We then used lead pellets that are often used as fishing weights to put in the shot glass to see how the increased load affected the output. We continually incremented the amount of lead pellets by 3 and recorded the amount of force exerted, in Volts, on the sensor. The graph below shows the output values with a reference resistance of 100kΩ and 1MΩ.
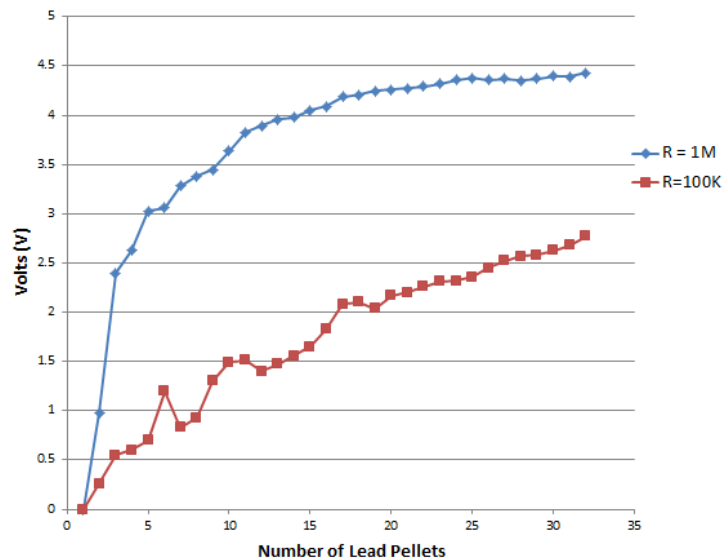
Figure 5.4-4 – output from testing
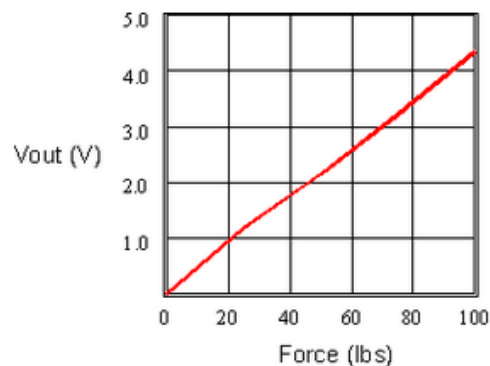
Figure 5.4-5 – expected output from datatsheet from Tekscan

Unfortunately, once we were able to more accurately measure the force that was exerted, we saw that with a constant force applied, the output would rarely ever settle. It would have wide ranges that were not good for our project, which needed a very precise and steady reading. Additionally, it was very hard to get the same output value when we tested the Flexiforce sensor in the same way numerous times, showing that it was not a reliable sensor to be used in our project.

Accelerometer
During our project testing, we also worked with an MMA8452Q, a triple-axis accelerometer, which we obtained from Sparkfun. A reservation we had with using this sensor was that current neuromuscular monitoring already used these types of sensors. Additionally, for everyday clinical use, it proved to be limiting because the thumb of the patient had to be able to freely move since it measures the thumb's acceleration, and as mentioned previously, sometimes the arms of the patients are tucked to the sides of their body. However, we tested these sensors just to experiment and to see if they were even a sensor that would be good to use. Unfortunately, we were unable to get the Z direction of the sensor to read any changes. We spent some time trying to adjust the code to fix the problem, but because it was not our first choice to use anyway due to all the downsides, we stopped our focus on the accelerometers.

Electromyography (EMG)
We had EMG sensors as an optional sensor for our project but it became inconsistent with the readings. In addition, we did not want to deviate from the main sensor we had decided to use, which was the pressure sensor. Therefore, we were able to get it working, but because of its inaccuracy, we decided not to use it in the project. Additionally, we tested it after the pressure sensor, which was our final choice, and because we preferred the pressure sensor and the way it worked, we did not want a back-up way of sensing that was not as accurate as the main choice.

Pressure Sensor
With little time left in the semester, when we are finally able to analyze the ability of accuracy of the Flexiforce, we realized we were going to have to test another sensor. We came up with a few ideas, one being measuring through pressure. We had sampled a few gauge pressure sensors. We used gauge because gauge pressure sensors measure pressure compared to atmospheric or ambient pressure. Additionally, we only wanted a positive input range because we would never be measuring anything less than atmospheric pressure. We needed something with a very small accuracy error rate as well as a quick response time for measurements such as TOF stimulation. We first used a self-measure blood pressure kit, and wanted to have the blood pressure ball in the patient's hand with the attached tube connected to the pressure sensor. However, after testing, we saw that the blood pressure ball was too resistive and wouldn't be good for

the weak feedback that would be demonstrated from the patient. Therefore, we were able to find a medical device to substitute, called a pessary. It is an inflatable round ball that is made of a tough, but soft, rubber. The pessary was attached to IV tubing we sampled which was attached to the pressure sensor. The pressure sensor measured the strength of the muscle response by how much air pressure resulted from the squeeze of the pessary in the patient's hand. We tested the MPXV5004 pressure sensor first, but realized it reached its max value too quickly because it only had a max of 3.92 kPa. We then sampled two more pressure sensors we had narrowed it down to: the MPXV5010, which had a max pressure of 10 kPa and the MPXV5050, which maxed out at 50 kPa. Although both worked really well and were accurate, the MPXV5010 showed a more noticeable change for smaller variations in twitches. However, because our design has the patient being calibrated at the beginning, which is where they are given a stimulation at max current before the neuromuscular blocking agents are given, we ended up choosing the MPXV5050 because it allowed the ability to show that larger range, from the small outputs when under anesthesia to the max output when calibrated and getting the threshold value of the patient. In our project, the MPXV5010 fried right before demonstrating, so we only showed the MPXV5050. However, we actually ended up constructing the project to have both sensors. It would be an easy switch by moving the IV tubing to whichever pressure sensor the anesthesiologist wanted to use. This was for the use of the anesthesiologist, so that he could use the MPXV5010 for weaker patients, such as children and older men and women. The MPXV5050 would be used for stronger patients that had a stronger force feedback when given the stimulation to the nerve. Below is the pessary connected to the IV tubing connected to the pressure sensor.

Figure 5.4-6– pessary in patient's hand attached to pressure sensor

We used a flat surface on top of the pessary when testing to evenly distribute the force applied on the pessary. We measured with a constant force by adding lead pellets, to the glass that was on top of the pessary. We applied these weights evenly over the pessary, and incremented the force applied at a constant rate. The measurements showed a more linear result than the Flexiforce, which was important for the TOF ratio that was calculated for the patient. Below is the output that we got when we incremented the weight at a constant rate.
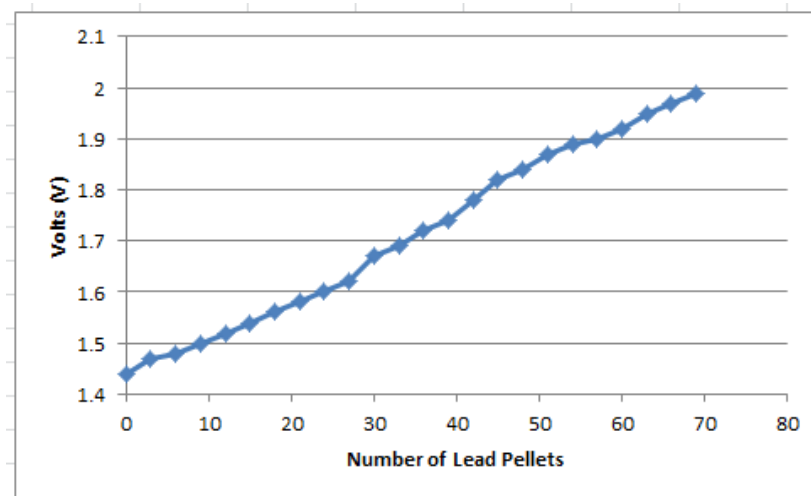
Figure 5.4-7 – Testing output from pressure sensor

This was much closer to the linear output that we wanted to see, which measured up fairly closely to the graph that was shown on the datasheet for this pressure sensor, which is shown below.
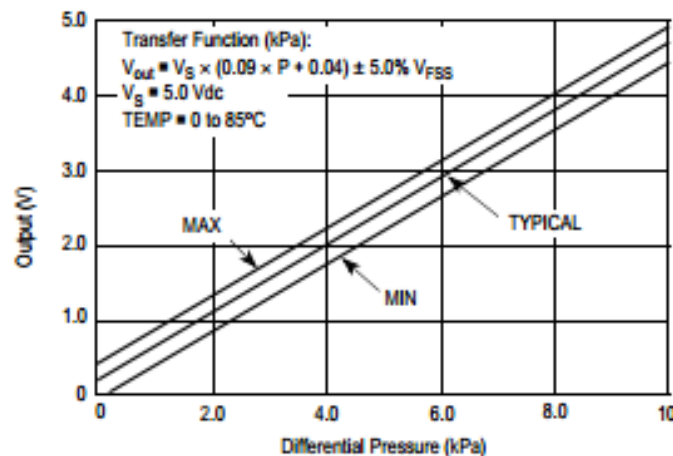
Figure 5.4-8– output expected from datasheet of the pressure sensor from Freescale

5.5 LCD

The LCD unit was tested early in the prototyping phase, because any faults or errors could delay this project. This was tested right when the uLCD43 arrived along with the 4D-programming cable. The 4D systems workshop program was downloaded onto Sergey's computer and he started learning the code right away. In order to do the initial testing on this screen he needed to know a little more about the screen and the programming type that it used. Once he was more familiar he went through a few tutorials and implemented some of the features that were described just to make sure that video and the buttons would work on

the screen. Knowing that these types of features already worked on other screens of the same type it helped the group make sure that the screen that was purchased and obtained was functioning properly.

Once the initial testing was completed code for the actual Paralytic Twitch Sensor was started and as more code was written and features were changed on the display the code was uploaded to the SD-Card and tested on the screen just to make sure that the progress that was seen in the code was actually producing a result on the screen and was functioning properly.

Testing the final code for the LCD required an ad-hock setup of the components before everything was in its final build state. The main reason for testing the LCD was to see if graphing the sensor data on an XY plane was possible and if it was not the goal was to figure out why.

First a single point check was done to see it gets graphed properly on the screen then more points were added gradually. If a single point was not getting graphed then there was a potential that data is not transmitted to the display and in this case back tracing each part one by one to find the broken link. In addition to all this a proper power measurement test should be done for the LCD to make sure it is getting the right amount of power and that power levels stay within the specified operating range. This is where the group ran into a problem. The spec sheet was looked at to double check to see if the current that was being pulled by the screen was the right amount but, the screen ended up pulling double the amount that the spec sheet said it would. This concerned the group members because if the spec sheet was correct the screen would have been fried but it was not. At that point it was just assumed that the spec sheet was in fact wrong and that another transformer needed to be added to deal with the added current that was needed for the screen.

When the LCD module did not display data the next step was to double check every pin connection and make sure that each pin was connected to the right data bus and it was getting the data from a correct device. When all failed the last option was to check the software that runs the display and make sure there was not a simple syntax error, which happened more often than not. For more detailed software testing please refer to section 5.8. Due to the simplicity of the design and interfacing of the wireless display the only other options are failed external parts that would need to be checked individually and the test for each of those are described in different sections of this chapter.

5.6 PCB

The testing of the PCB, outside of the components already covered, was limited. The first test, because it was made by someone else, was to make sure that all the connections and pins were present when it arrived. Because nothing looked terribly wrong at that point, testing was continued by hooking up the one power

supply line and the ground. This was done with relatively low voltage as this test is just for continuity. Once continuity has been established and obvious shorts have been identified, the board can be assembled. After assembly, or even piece by piece, the board was rechecked for shorts and faulty wiring.
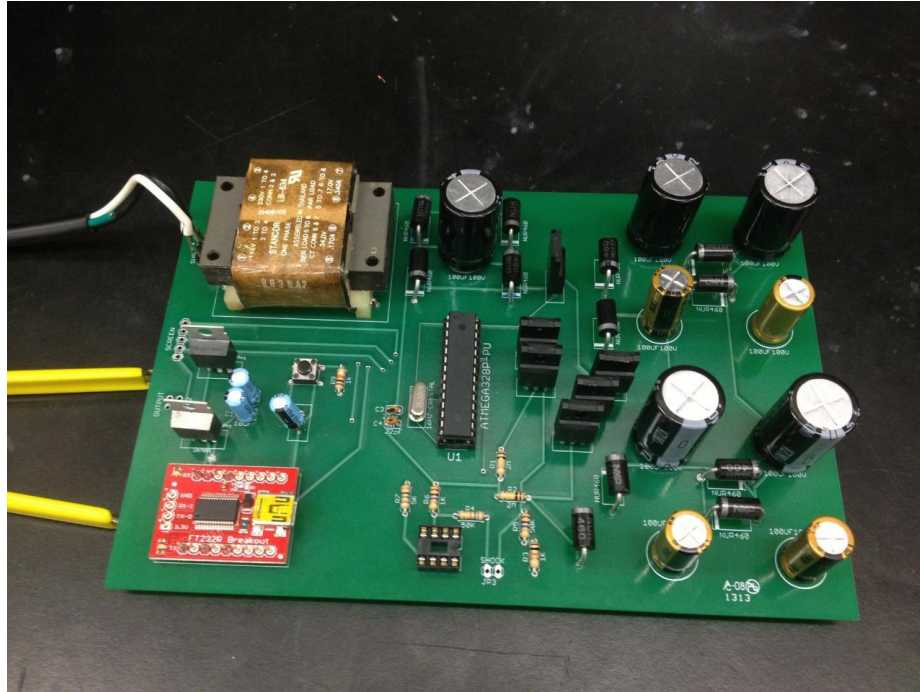
Figure 5.7-1—PCB with all the components

In the figure above the PCB is show with the components in place but not very many of them are actually soldered into place. This is how the testing was done on the PCB to make sure that the lines were right. Unfortunately during this testing the current sensor that was being used kept frying. In turn when it fried it took out the microcontroller along with one of the voltage regulators. This was finally scrapped in the final design because there were not enough microcontrollers to keep trying to figure out what was causing the current sensor to go.

5.7 Software

When it came to testing each module or function of the software code, the best way was to break down the code into the simplest bits and functions and test each one of them individually. The very first thing that was checked was the communication between the microcontroller and the sensor. The goal was to make sure that before going further into coding that there is communication between the MCU and the sensor. It did not really matter what sensor was used for communication testing, it just had to be serial data output from the sensor of the choice. After the communication was tested and functioning, the next thing to

be tested was the touchscreen input responses. The main goal was to make sure that each touch input is registered and seen by the microcontroller.

Once the two crucial tests were complete the modular code testing was the next step. In these tests each function like: Train-of-four, single and tetanic were all tested separately. Each of the four functions below were tested modularly and also as a whole unit when each of the respective functions passed their tests. To test the functionality of each function below, unreal test data was used to identify any logic errors or coding faults. During testing phases, debug print statements were used in abundance to pinpoint where the code breaks or stops its execution.

1. *Train* of four function - the function had to graph each twitch on the LCD display as a bar graph and also have a set delay (set by the user on the settings screen or on the main graph screen) between each set of train-of-fours. As there is no way of testing the device on an actual patient all testing was done using simulation input from random pressure applied by awake person's hand.

2. *Single Mode* – the function had to be tested to make sure that, it continues to run until the user chooses to stop it manually and it will graph the sensor output as a bar graph on the LCD and will have a set delay between each sensor reading.

3. *Tetanic Mode* – the extent of testing for this function was very limited because this is a very simple function with a very specific task. The task is to apply a 100Hz continuous shock to the patient's arm for a maximum of two seconds to register the largest twitch in that time interval.

4. *Full Mode/Automatic Mode* – this is where things get a little more complicated. This function will be the combination of single and train-of-four modes. The two main testing case was to test if the twitch goes above twenty percent of the maximum threshold of the twitch then the function would run the train-of-four portion of the code until the TOF ratio drops below 0.10.

In each test above the values used were not scientific or in any way reflected the actual data that would be gathered from a real world patient under anesthesia. Because there was no way of doing that, many of the variables in the code had to be manually hardcoded to compensate for the lack of proper testing.

5.9 Full Assembly

5.9.A Initial Power

Once all of the pieces for the device were tested individually and with their related components the final hurdle came with a full assembly test. For this section the test was run as though the anesthetist were performing routine

checks, this should test the full range of functions and provide feedback about the functionality of the entire device.

The initial requirement for this section was to fully assemble the device under the impression that everything will work once it is assembled. Once fully assembled the first test was a simple power on. Once the device was plugged in nothing popped or smoked or sizzled so the group assumed that nothing was miss wired upon assembly; just in case a thorough check with a multimeter was necessary to ensure that all components were getting the power that they needed.

Once everything appeared to be working properly, testing was then moved to section 5.8.B for what happened for the functional power up. However the first few times there was an issue with the power feeding to a specific part. The issue at this point took two roads: was the component being fed zero volts, or was there a partial voltage. Assuming that all of the previous power tests have succeeded, the problem here was that something was miswired. The faulty piece was disconnected, the wiring diagram was checked, and the part was reassembled to the whole device. This fixed the problem in most cases. For components like voltage regulators, there should be no partial voltages because they are hardwired to the power source. When this was the case then it was highly probable that the component was faulty to begin with and loading it has caused it to fail. In this scenario there will also most likely be a considerable amount of heat and possibly smoke coming from the part. When that occurred we just used one of the extra parts that was ordered for that reason and trashed the one that was causing the problems. Now that all these issues are ironed out and the parts have the proper voltages it was then time to move on to the startup sequence.

5.9.B Functional Power Up

At power up the turn on sequence should initiate. Here the test was not for the content of the sequence but simply to see if it happen; because the sequence has already been tested previous sections it was known to work, but with everything wired up it was not known whether there will be a low power failure due to some miscalculated circuit section. Assuming the LCD worked, move on the section 5.8.B; if it does not then the first thing to check was the wires of every component from the power to the LCD, making sure that every piece was where it needed to be and that they were securely fastened. Failing to find the issue there the next component to check was the AC/DC converter. Starting with it, check the voltages of every component directly linked from the DC source to the screen. Components included the following: five volt regulator, LCD controller, and microcontroller. Because all of the individual components up to this point have been tested individually, if they are getting the power they require then the next part of the test is a rebuild.

Most commonly on first assembly if everything was working beforehand, and it appears that all the components worked after disassembly, then there was just a simple wiring issue that was overlooked. Instead of attempting to find one wire in dozens it is simpler to disassemble and reassemble the section that isn't working. This should fix the problem. If, in fact, it turns out that the section in question does not work post assembly then most likely there was an unexpected power overload. If this is the case then every piece needs to be re-checked individually to ensure that it was not also ruined. Now, assuming that all pieces are still functional and reassembly fixed the startup sequence with the LCD two important facts are known: first that the LCD is connected properly this time, second the microcontroller is operating up to this point as it is intended.

Chapter 6 User's Manual

Because this device will be particularly user friendly, unless someone manages to shock themselves, this user manual will mostly be intuitive things that should be evident to a user who is used to the old designs.

6.1 Normal Condition Operation

For normal conditions the device should resemble that of an automatic blood pressure monitor. Once the device is plugged into the wall outlet the LCD screen will power on and the welcome screen will appear. This welcome screen will display a single button in the lower right hand corner that says settings and that will be the button that needs to be pressed in order to proceed to the next screen that will allow the anesthesiologist or whoever else is using the device to decide what they would like to do.
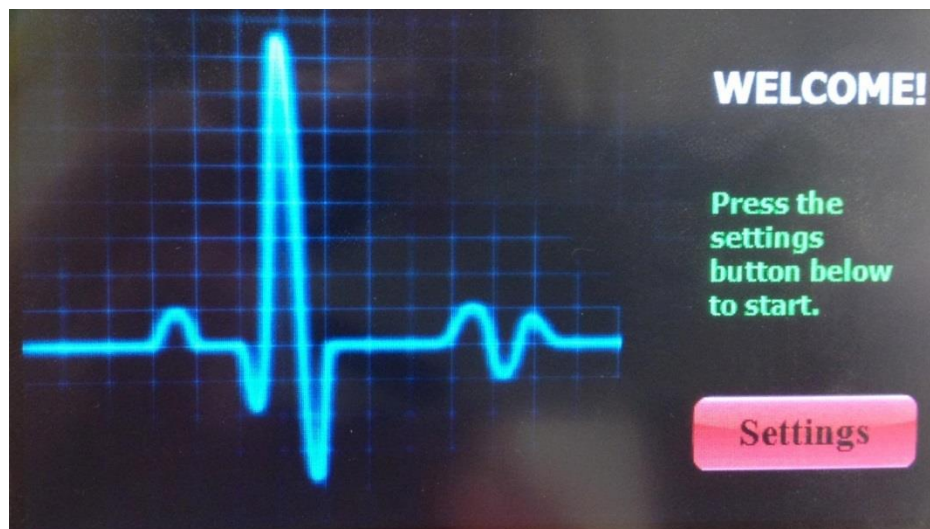
Figure 6.1-1: Main welcome screen

When the device is connected to a patient, the first thing that should be done after the settings button is pressed is to press the calibrate button that is in the lower right hand corner of the next screen that is depicted in figure 6.1-2 below. This button is in charge of the command for the baseline test; this allows the device to get a basic reading of the patient's reaction to the TOF. With the baseline test the anesthesiologist will know what the patients 100% mark is. This will also allow the device to know that it should not allow the anesthesiologist to choose a current that would cause the patient harm because of knowing what this base line is. Without this test when the TOF is put into action there would not be a value to compare the ratio from that test to in order to see if the patient needs more anesthesia or not.
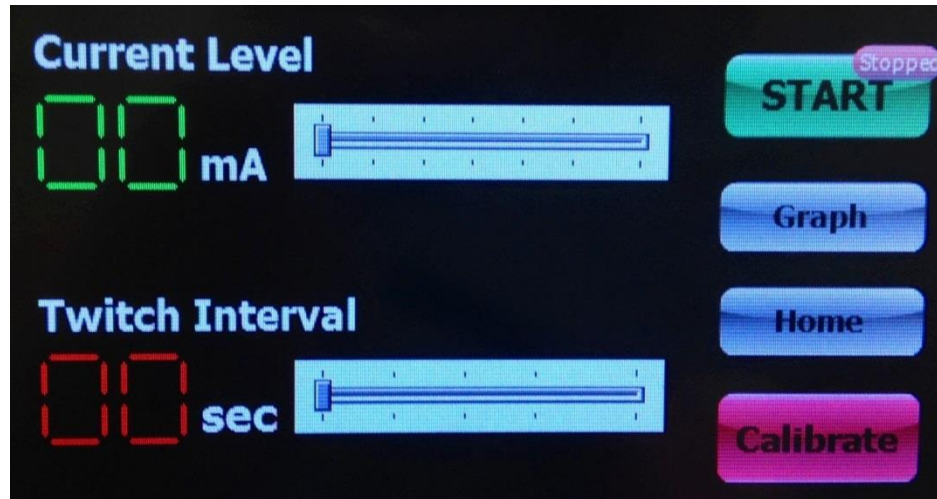
Figure 6.1-2: Settings screen from the LCD display

After the baseline tests have finished running there are three different operation modes that the device can be set to: TOF, Twitch, and Tetanic. These will be discussed individually in the following sections. If none of the modes are desired or the device is not to be used at this time then to shut down the device all that is needed to be done is to simply unplug it.

To be able to choose the type of stimulation mode that the user would like to use all that is needed to be done is to press the Graph button that is located on the right hand side of the screen. That will bring the user to the graph screen that is shown below in figure 6.1-3. On this screen you can choose any of the three stimulation types and you can see the results graphed on the screen along with the TOF ratio.
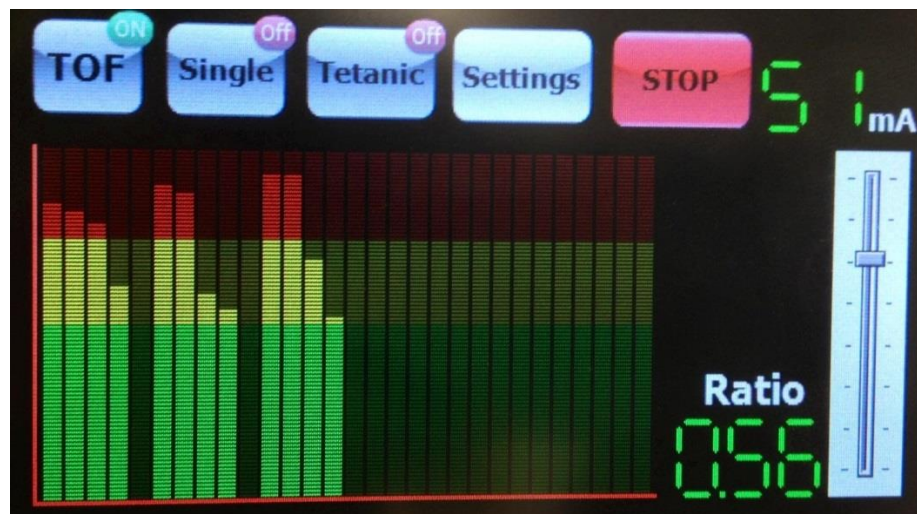
Figure 6.1-3: Graph screen (current setting TOF)

6.1.A Train of Four

For this setting the device will issue four pulses of 200us duration at a frequency of 2 pulses per second. This is the setting most commonly used to test whether the patient has begun to wear through the original bolus injection of sedative. The options available for this setting begin with the current strength. A setting of preselected values from 1mA to 50mA are available, choose one. The next setting will be whether to make this TOF a continuous repeating pulse, a one shot function, or to run it a certain number of times. If the one shot option is selected then this will be the last setting available for this pulse type.

If the option is selected to run a specified number of times then the next screen presented to the user will be to enter the number of times that the pulse train is intended to run. This setting is suggested to be used when patient is waking up because it allows for a short repeat test of whether the patient has a return of muscle control.

If it is selected that this pulse should repeat itself then a time must be chosen where the pulse will run at the start of every counting sequence, i.e. if a time of 20s is selected, then every twenty seconds the TOF will run. This must be kept in mind because the time frame selected must not be so short that the TOF sequence never gets a chance to end pulse 4. If a time period this short is attempted to be entered there will be no warning. This setting is suggested when attempting to monitor the patient while keeping then paralyzed. A single twitch of the four should be seen at every issue of the pulse train.

6.1.B Single Twitch

Moving on to the Twitch setting, if it is selected; this setting is intended to be used over long periods of time. It creates a single supramaximal current pulse to test whether there is any return of muscle movement. This setting is most commonly used in multi-hour surgeries where a neuromuscular blockade drip has been administered to maintain sufficient levels of paralysis.

Once selected, the first setting that is presented to the user is the time frame for every pulse. This can be as short as every half second to as long as once every four hours. If these extremes are intended to be used it might be wiser to use another pulse types to perform this function. A reasonable time frame is once a minute for surgeries less than two hours; and once every five to ten minutes for those greater than that.

A second option will be presented once the timing has been decided though it can be skipped if no changes are required. Because the supramaximal stimulation varies patient to patient, it is given as an option to change the current strength. If this option is skipped then it will automatically be set to 50mA, the greatest current that the device will manage. Once these two options have been set the done button can be pressed to apply the setting and return to the pulse screen.

6.1.C Tetanic

When this setting is selected, there will be no options. This is because this has only one purpose and is operator time limited. When pushed a 50mA, 100Hz pulse is issued to the patient to create a full muscle contraction. This is done to see if, once the hand is contracted, the muscles have enough control back to maintain contraction. This is normally the last test before fully reversing the neuromuscular blockade and removing the breathing tube. There will be a mechanical time limit applied to this device that limits the length of time that it can be used; doing this prevents permanent damage from being induced on the patient because of a careless operator.

6.2 Trouble Shooting

In the event that the stimulator does not work, this section will cover all of the generic testing procedures that an operator can perform mid-operation. To being with, if the startup sequence is not flashed to the screen and the device does not appear to have suffered substantial damage, the most likely cause is a lack of power. Check both the power cord and the On switch. If both of these are as they should be then check the cable connecting the screen to the device. Any damage to the line has the ability to ruin the entire thing. If this does not resolve the issue, then there is nothing else to be tried.

If it appears that the stimulation circuitry is not working properly, the first step in correcting this is to ensure that the electrodes are as close as possible to the nerve area. If they are where they should be, use the tetanic shock to see if movement is observed. Because of the intention of this mode, the patient should have complete contraction of the muscle group. If this is not the case then it is likely that the pads will need to be removed and replaced in their correct position. If no contraction is seen from the patient entirely, then the patient should be disconnected from the device. Trusting that the device will not harm the user, it is suggested now to apply the device to a portion of skin and try the tetanic pulse that way. This will give the user definite feedback as to whether or not the device is working. If it is and the patient exhibited no reaction to it then s stronger pulse strength will need to be selected, or a weaker nerve/muscle combination will need to be selected. This concludes the troubleshooting section.

6.3.C Acceptable Alternatives

This section is added to the user manual in the even that a particular part cannot be found in time to be used in surgery. There are a few generic pieces that can be swapped out and used from other devices.

The power cord used on the device will not be a special or custom piece; it will be a standard computer power cord. This means that in the even the original cable is lost another can be used in its place so long as the plugs match on the device. The current rating on the cable will need to be at least 15 amps to be able to safely handle the draw from the device.

The electrodes used are, likewise, also currently generic. If the provided electrodes are too big or have run out, a number of other options exist to replace them. The initial suggestion would be to use ECG pads as a replacement because they operate closely to how the stimulators work. The difference is pads will require the baseline to be modified for the patient, but this should impose no extra problems. One precaution that is suggested when using nonissue electrodes is the need to clean the area that the electrodes will be applied to. This is necessary in the event that the electrodes have unknown built in resistances.

If the leads for the stimulator are lost and new ones are needed, a simple replacement will be, temporarily, using alligator clips. These are available everywhere today and there may even be a stock available in the hospital.

All other replacements or fixed should be left to those who know what they're doing, not hospital staff, as the possibility of causing grievous harm to the staff or patient increases exponentially.

Chapter 7 Administrative Content

7.1 Budget

As with any good idea there is always a price tag that comes along with it. The aim of the group was to keep this design "cost effective" there was not any skimping on the sensors or any other part for that matter just to save a few dollars here and there. The table below shows the estimated amount of money that the group was expecting to spend on this project in order to obtain a product that is completely functional. When this budget was created the group did it's best to try and overshoot as much as we could in estimating how many of what parts would be needed just in case there was something that broke or needed to be replaced with a different part because the one that is on the table is not going to work out anymore. This table is just a ballpark figure as to how much we can expect to spend in the course of the project and to the groups dismay it has already increased from what was initially put in the document that was submitted in September. The group is planning on applying to the TI competition which will allow the group to get $200 in credit that can be spent on any parts that need to be acquired through TI. This does not mean that the group is not going to try and see if TI will give extra samples to us. It never hurts to try. The rest of the budget is being supplied by Dr. Looke. He has approved a budget of just under $800 so there should be little out of pocket expenses for the members of the group.

Initial Budget			
Part	Quantity	Price	Comments
PCB Board		$150	
Batteries		$50	
Microcontroller		$125	
Wiring		$20	
Display		$140	
Accelerometer		$15	Not all of these sensors will be used in the final product they are just being purchased for testing. The final price will only be based on using the Force Meter.
Flexion Sensor		$15	
Piezoelectric Sensor		$15	
Force Meter		$45	
Display Housing		$100	
Electrodes	100	$38	The final price per patient would be $0.76 knowing that each patient needs two.
Experimenter Board (TI)	1	$149	
Bluetooth Evaluation Kit (TI)		$99	
USB Debugging Interface (TI)		$99	
Total:		$1,060	

Figure 7.1-1 Initial Budget

Unfortunately due to unforeseen circumstances like the fact that the printed circuit board ended up being around $400 because of making the copper ounce two instead of the normal one ounce that we had originally priced it for. Also, we had to make additional changes that added additional costs to the project because of the screen pulling more power than was printed on its data sheet. There was also the additional cost of shipping when parts blew at the end and we needed to pay to overnight some of them. So in the end our budget ended up being a total of just over $1200.

Part	Quantity	Price Paid	Actual Price
LCD Display	1	$159.44	$159.44
4D-Programming Cable	1	$26.04	$26.04
SD-Card	2	$16.47	$16.47
USB Cable	1	$15.90	$15.90
Sensors			
TekScan Fleziforce Sensor	4	$25.81	$42.06
Pressure Sensors	24	$67.19	$270.13
Flex Sensor	1	$16.76	$16.76
Triple Axis Accelerometer	1	$13.64	$13.64
Breakout board (FT232RL)	4	$63.71	$63.71
ACS712 low current sensor breakout	2	$29.52	$29.52
Circuitry			
ATmega328P	1	$0.00	$3.16
Arduino Uno	1	$33.64	$33.64
Capacitors, Diodes, Resistors		$176.30	$176.30
Transformer	2	$0.00	$27.88
PCB			
Advanced Circuits PCB	1	$358.32	$505.60
Solder Board	4	$21.59	$21.59
Miscellaneous (wires, headers, ect)		$177.49	$177.49
Total		$1,201.82	$1,599.33

Figure 7.1-2 Final Price Paid

However, the group realizes that the final price that was paid to create this device does not really show the amount that it cost to create one device. The amount of money that the group would have spent if it were not for the mishaps of trial and error during our testing then the budget that is shown below in figure 7.1-3 would be the cost of the unit. This is also assuming that the programming cables such as the 4D-programming cable were already purchased, along with all of the other materials such as the Arduino Uno that were needed for building the final project.

Part	Quantity	Price Paid	Actual Price
Screen			
LCD Screen	1	$159.44	$159.44
SD-Card	1	$16.47	$16.47
Sensor			
Pressure Sensor	1	$5.00	$12.29
Circuit			
ATMega328P	1	$0.00	$3.16
Capacitor (470uF)	6	$6.06	$6.06
Capacitor (100uF)	4	$1.96	$1.96
Diodes	16	$5.78	$5.78
Crystal	1	$0.95	$0.95
Voltage Regulators	6	$11.40	$11.40
Heatsinks	6	$15.64	$15.64
PCB			
PCB	1	$358.32	$505.60
Total		$581.02	$738.75

Figure 7.1-3 Price to Make One

7.2 Project Milestones

Depicted below are the projected project milestones for the Paralytic Twitch Sensor Device. While the dates for the fall semester are accurate, the spring semester milestones may change to fit the needs of the group's members. The majority of senior design one was left to research. There was a large portion of the engineering part of the design that needed to really be researched because the group is implementing different parts to the design that none of the members had a class on, like the wireless. Not only that but a major part of this project falls on the medical information that is necessary to know and understand in order for the device to be fully functional in the way that the group needs it to be.

The research topics were distributed equally among the group members, each topic was researched by two members that way there was always somebody to confer with on what was being researched so it was never just a solo member working on something that they couldn't ask for help with. The team met every Thursday before class for approximately three hours in order to catch up and fill the rest of the group in on ideas of things that were believed to be able to help the project and things that we did not need to worry about anymore. These meetings served as brainstorm opportunities and greatly helped with motivating the group to keep on task. Figure 7.2-1 shows the progress of the group throughout senior design 1.

Project Part/Phase	Start Date	End Date	Duration (Days)
Fall Semester			
Initial Document	4-Sept-12	11-Sept-12	7
Research Important Medical Topics	12-Sep-12	12-Oct-12	31
Research Previous Designs	12-Sep-12	12-Oct-12	31
Research Sensors	10-Oct-12	10-Nov-12	31
Research Constant Current	10-Oct-12	10-Nov-12	31
Research Controllers	10-Oct-12	10-Nov-12	31
Research LCDs	10-Oct-12	10-Nov-12	31
Research Wireless	10-Oct-12	10-Nov-12	31
Research Power Supply	10-Oct-12	10-Nov-12	31
Operating Room Visits	10-Nov-12	16-Nov-12	6
Writing Senior Design Paper	11-Oct-12	1-Dec-12	51

Figure 7.2-1

Depicted in Figure 7.2-2 was what the group expected to spend on each stage of the project for senior design II. The group realized that these dates were not set in stone and it was not be the end of the world when something ended up taking a little more time than expected. The goal for senior design II however was to keep as close to this timeline as possible, but mainly be able to have at least one test where everything is connected so that the device can be tweaked before the final senior design presentation in April. Over the break into the first week of classes the group hoped to acquire the majority of the parts that were needed. The most important parts to get in as soon as possible were the sensors so that the decision of which sensor is being used in the final design can be finalized so the group can start working on how to integrate it into the other parts of the design. The majority of the time was then spent on building and testing with the last month or so dedicated to full design testing and finalizations being made so that the device works at the end of the semester.

Project Part/Phase	Start Date	End Date	Duration (Days)
Spring Semester			
Acquire all sensors	12-Dec-12	11-Jan-13	31
Test Sensors and make final decision on which one to use	11-Jan-12	18-Jan-13	8
Create and Test Circuit for Power Supply	18-Jan-13	31-Jan-13	14
Design and Test Constant Current Circuits	21-Jan-13	5-Feb-13	15
Acquire PCB and Test	5-Feb-13	15-Feb-13	10
Acquire Display and Controls	10-Feb-13	20-Feb-13	10
Test Microcontroller with Display, and Sensors	20-Feb-13	25-Feb-13	5
Assemble First Prototype	1-Mar-13	7-Mar-13	7
Test First Prototype	7-Mar-13	14-Mar-13	7
Fix Prototype Issues	14-Mar-13	24-Mar-13	14
Housing for Final Prototype	20-Mar-13	24-Mar-13	4
Assemble Final Prototype	25-Mar-13	28-Mar-13	3
Fix Final Prototype Issues	28-Mar-13	8-Apr-13	12
Test Final Prototype	8-Apr-11	16-Apr-13	8
Final Documentations	1-Mar-13	18-Apr-13	49

Figure 7.2-2

This seemed like it was a great plan at the end of the fall semester however, just like on many other projects when goals are set out time seems to get away from you. Unfortunately, the majority of the times on the table that is above are completely wrong because there were issues that came with building the board because the right capacitors weren't chosen yet or the sensor was not finalized because of unforeseen issues with testing. Eventually those items were addressed and the PCB was ordered without the sensor being a part of it and realizing that the group was going to have to build their own PCB in order to attach the sensor. Yes having a time table did help show the group that there really was not as much time in the semester as we thought and after a few long nights at the end it worked.

7.3 Closing Comments

The Paralytic Twitch Sensor device that the group has been working on throughout senior design I and senior design II will allow for future ease in monitoring patients in the operating rooms when they are under the effects of neuromuscular blocking drugs. This device will allow the anesthesiologist to monitor the patients more effectively because not only will they be able to have a sensor that will measure the force for them the device will hopefully work under the most difficult circumstances. These are the ones where the anesthesiologist was unable to get to the patient in the previous designs because they had to monitor the patient's reactions to the current with their hands. Now they should be able to apply the sensors of this device even if the arm is tucked to the side of the patient.

The main focus of senior design I was making sure that all of the research that was needed was completed. The research portion of this project allowed the group members to become familiar or more familiar with the different technologies that need to be implemented and utilized within our design. This has allowed the group to expand their knowledge of engineering design and research phases in the work place. Learning to work together and as a team has proved to have its ups and downs but in the end it made the learning more enjoyable as well as important. Now that there is an added pressure of other members counting on the parts that certain individuals have researched and worked on makes it that much more important to know what you are talking about. Senior design I has allowed the group to come together as a team. The group has come to realize each individual member for everything that they bring to the team and it has allowed us to accomplish what is set before the group and we are ready to conquer senior design II.

Once the research is finished the move to senior design II with the obtaining of parts and actually building the pieces will be smoother. The main and most important part of this design came down to the sensors. That's what most of the research time went into, it was also the part of the design that our sponsors spent the most time harping on how important a good sensor is to the implementation of the group's design. The sensor is what initiated the need for this new design. Senior design II required trial and error on the part of the team.

Senior design II lead the group to learn new things about circuits and software and how to make it all work together. Upon completing this Paralytic Twitch project the group as a whole realized how much they have learned both from the medical point of view and the engineering. There are definitely things on this project that we would like to have changed knowing what is known now, but that was the point of this project to learn. If we had known what we know now then, I'm sure there would be other things that we could change. Everything comes in full circle at the end.

Group 14 would like to extend a thank you to Dr. Samuel Richie, Dr. Thomas Looke and Dr. Zhihua Qu for their support and the opportunity to expand our engineering learning experience with this invigorating project. The group learned so much through the course of this year and it was all thanks to your motivation and guidance.

<u>Appendices</u>

Appendix A – Reference / Works Cited

<u>Added Required Medical Knowledge</u>
http://www.encyclopedia.com/topic/Anesthetics.aspx#1

http://www.surgeryencyclopedia.com/A-Ce/Anesthesia-General.html#b

http://emedicine.medscape.com/article/1271543-overview#showall

faculty.smu.edu/jbuynak/**GeneralAnesthetics**-powerpoint.ppt

Validation of muscle relaxation measurements (PDF located in Dropbox→Articles→ Printed out)

<u>Neuromuscular monitoring during Anesthesia</u>
http://faculty.washington.edu/ramaiahr/Chapter_39_Neuromuscular_Monitoring.pdf

Book

Ch 47. Neuromuscular Monitoring (PDF located in Dropbox→Articles→Printed out)

Monitoring of Neuromuscular Junction (PDF located in Dropbox→Articles→Printed out)
http://medind.nic.in/iad/t02/i4/iadt02i4p279.pdf

Train of Four Monitoring (PDF located in Dropbox→Articles→recent)
http://neuromonitoring.files.wordpress.com/2011/02/neuro-musc-blockers-slp-train-of-four-monitoring-1.pdf

http://ionphysiology.com/ssep%20settings.htm

http://www.mainlinemedical.com/mm/bluestar-enterprises-hand-adapter.html

Electrodes
http://www.biopac.com/disposable-paired-electrode-foam-25pairs

http://faculty.smcm.edu/wihatch/courses/436web/436resources/bsl_hardware_guide.pdf

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Sensors

Piezoelectric
Comparison with M-NMT
C. Motamed, K. Kirov, X. Combes and P. Duvaldestin (2003). Comparison between the Datex-Ohmeda M-NMT® module and a force-displacement transducer for monitoring neuromuscular blockade. European Journal of Anaesthesiology, 20, pp 467-469. doi:10.1017/S0265021503000735.

Force Sensors
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http://www.tekscan.com/flexible-force-sensors

Pressure Sensors
http://www.freescale.com/webapp/sps/site/application.jsp?code=APLANAMON

MCU and Wireless Research
http://embedded-lab.com/blog/?p=3557

http://www.scribd.com/doc/98700331/Wireless-Radio-Frequency-Module-Using-PIC-Microcontroller

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http://newbiehack.com/MicrocontrollerIntroductionABeginnersGuidetotheAtmelAVRAtmega32.aspx

LCDs
http://yampblog.blogspot.com/2009/08/resistive-vs-capacitive-touch-screens.html

http://www.geeetech.com/2012/04/interface-3-2tft-lcd-module-to-arduino/

http://www.digikey.com/us/en/techzone/microcontroller/resources/articles/designing-with-tft-displays.html

Appendix B – Permissions

(a) Atmel – permission pending

(b) Itead Studio – permission pending

(c) LS Research – permission pending

Email Inquiry

First Name *

Sergey

Last Name *

Cheban

Email (we will keep your email completely private) *

ce.seriy@knights.ucf.edu

Country *

United States

City *

Orlando

State/Province *

Florida

Zip/Postal Code

Company *

University of Central Florida

Industry

Medical ▾

Comment or Question *

Hi, I am a student at University of Central Florida. Our group
is working on a senior design project and would like to get
your permission to used your schematics, diagrams and material
of that sort for the parts we will be using in our design
document. Please get back to me as soon as you can.

Thanks, Sergey Cheban

Submit

(d) Solomon Systech – permission pending

Hi, I am a student at University of Central Florida. Our group is working on a senior design project and would like to get your permission to used your schematics, diagrams and material of that sort for the parts we will be using in our design document. Please get back to me as soon as you can.

--
Thank you, Serge C.

(e) STmicroelectronics – permission pending

Hi, I am a student at University of Central Florida. Our group is working on a senior design project and would like to get your permission to used your schematics, diagrams and materials of that sort for the parts we will be using in our design and be able to use them in the design document. Please get back to me as soon as you can.

--
Thank you, Serge C.

(f) Texas Instruments

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(g) Newhaven International

From Atif Khan <nhtech@newhavendisplay.com>

Subject **RE: Message from Newhaven Display International, Inc.**

To Me <ce.seriy@knights.ucf.edu>

Cc customerservice@newhavendisplay.com

Hi Sergey,

You may use our NHD-4.3-480272MF-22 controller board's image and part number in your documentation for reference.

Sincerely,
Atif Khan | Engineering
Newhaven Display International, Inc.
www.newhavendisplay.com
2511 Technology Drive, Suite 101
Elgin, IL 60124
Phone: 847-844-8795
Fax: 847-844-8796

-----Original Message-----
From: Sergey Cheban [mailto:customerservice@newhavendisplay.com]
Sent: Tuesday, December 04, 2012 8:44 PM
To: nhtech@newhavendisplay.com
Subject: Message from Newhaven Display International, Inc.

From: Sergey Cheban
Email: ce.seriy@knights.ucf.edu

Hi, I am a student at University of Central Florida. We are working on our senior design project and will most likely use your graphics controller board for one of your 4.3 inch TFT displays (NHD‐4.3‐480272MF‐22). We are asking for your permission to use the image of the controller board on the main product page in our design document. Please get back to me as soon as you can.

Thanks, Sergey Cheban

(h) Microchip

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(i) Sparkfun: accelerometer

SparkFun Electronics
6175 Longbow Drive
Suite 200
Boulder, CO 80301

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Our offices are open **Monday through Friday 9AM to 5PM MST (GMT -7)**

For technical questions about a specific product, please see our Technical Assistance page.

You can also converse in real time with SparkFun employees and customers using IRC by connecting to **irc.freenode.net** and joining the **#sparkfun** channel.

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If you have an urgent inquiry you may also contact us directly at: **1-303-284-0979** (No phone orders please!)

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(j) Tekscan: Flexiforce Sensors

Request for Permission

Maura Logan [MLogan@Tekscan.com]
Tuesday, April 02, 2013 1:43 PM

To: kellyboone5@knights.ucf.edu

Hi Kelly,

We received your request for permission to reference information about our product FlexiForce in your research paper. We are happy to give you permission to use FlexiForce information in your research, we just ask that you reference the company name and product name correctly and include a photo credit if you use a photo.

Proper citation:
For the photo: Photo courtesy of Tekscan, Inc. and for our sensors it is: FlexiForce® sensors .

Also, if you could send us a copy (to this email address) that would be helpful.

Thanks you!

Maura

*****
Maura Logan
FlexiForce Marketing Specialist
Tekscan
617-464-4500 x223
mlogan@tekscan.com

(k) Freescale: Pressure Sensors