2013

Wireless electronic scoring of kendo competition matches using an embedded system

Edward B. Hogan
Eastern Washington University

WIRELESS ELECTRONIC SCORING OF KENDO COMPETITION MATCHES USING AN EMBEDDED SYSTEM

by

Edward B. Hogan

In partial fulfillment of the

requirements for the degree of

Master of Science

A thesis presented to

Eastern Washington University

Cheney, Washington

Fall 2013

THESIS OF EDWARD B. HOGAN APPROVED BY

____________________________________ DATE:_________________

KOSUKE IMAMURA, PHD. -GRADUATE STUDY COMMITEE CHAIR

____________________________________ DATE:_________________

DAN TAPPAN, PHD. -GRADUATE STUDY COMMITEE MEMBER

____________________________________ DATE:_________________

RONALD DALLA, PHD. -GRADUATE STUDY COMMITEE MEMBER

MASTER'S THESIS

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Abstract

This paper describes the wireless electronic system for the scoring of competition Kendo matches. This system is composed of an Arduino UNO microcontroller board with force sensing resistor pads located on the outside of the combatants Kendo armor. These pads sense the amount of force applied by each combatant as they strike their opponent. The system also utilizes Window Comparator Chips to determine if the strike is of sufficient force. If the force is sufficient the Arduino UNO board reports the hit via a Bluetooth modem to a laptop. The program running on the laptop records the time of the hit as well as which combatant accomplished the hit. The program then waits for a signal from the head judge to signify if the exchange was legitimate. This system was developed to ensure accuracy as well as consistency in the judging process. While most head judges are trained and experienced, they are still subject to human limitations of bias and speed. In other words, the accuracy of the human eye can't match the accuracy of the wireless electronic Kendo scoring system. This project provides an understanding of the interactions and limitations between real time sensors and computer hardware, which may lead to improvements in material as well as architecture for systems that go beyond martial arts applications, such as measuring the grip of a stroke victim's grip or other forms of patient therapy.

I Introduction

1.1 Goals

The primary goal for this thesis project is the production of a prototype system for the electronic scoring of Competition Kendo Matches. While durability and ease of use are goals, the prototype is understood to not fully meet these requirements due to time and monetary constraints. Possible improvements are discussed. The system is designed around an embedded system with the ability to sense force applied to the appropriate areas on the competitor's armor. Each signal sent from the embedded system identifies the area struck, as well as indicates that the force applied is above the selected threshold. While all competition scoring areas are not included on the prototype, the ability to expand to include these areas is present. The system is adjustable so that different age or skill levels can be accommodated. In other words the pads can be adjusted so as to register hits at lighter pressure for younger or inexperienced competitors. The embedded system is also able to communicate wirelessly with a remote computer. This communication extends for a sufficient range so as to accommodate a regulation competition size area. This area is defined by Okamura et al as "a square court with 9.00–11.00 meter sides [1]." The program written for the remote computer is able to identify which competitor has been struck as well as where the strike occurred. It also adds the time reported for the strike. The program displays this information and waits for further input from a judge. The judge will have the ability to signify the acceptability of the strike. If the judge decides that the strike did not meet the criteria, the combat will continue. Cost and availability of components have been considered and kept to a minimum. This project was also motivated by the need to improve upon the current system of relying on human senses and bias for judging competition matches. Chi outlines in his paper on the use of force sensors in martial arts, a desire for a more standardized and fair system of judging martial arts competition matches. This is why the creation of sensor based electronic scoring has become a priority since 2001[2]. While most head judges are experienced and knowledgeable in the rules and etiquette of Kendo, reaction speeds are much faster and finer grained in the electronic system. For instance, a computer can report strike times in the milliseconds, whereas most humans cannot. This allows for more certain and definitive results. This system also reports results with no considerations. In other words, it wouldn't be biased towards one opponent or the other. Finally, this project explores the relationship between sensors and computers. This field has always had wide ranging implications and applications. As discussed in section 2.3, this relationship even has medical application. Exploring and discussing the different architectures leads to the ability to improve upon current technology in this field, as well as many others outside of the project's scope.

1.2 Kendo

Sakamoto’s paper on the history and practice of Kendo provides the following information [3] . Kendo is a Japanese Martial Arts form originating over 1400 years ago. After the end of World War II it was temporarily banned because it was considered too militaristic by the occupying forces. It was later reinstated in a modified form for competition in the 1950s. The word Kendo means "Way of the sword.” Much more than just the simple combat between two people equipped with swords, it is a well codified form full of ritual and etiquette. The combatants wear armor on the head, referred to as "Men," the torso, referred to as "Do" and the wrists or forearms, called "Kote.” These areas constitute acceptable targets for scoring in Competition Kendo. One final acceptable target is the throat, called the "Tsuki.” It is protected by a flap that extends down from the Men. Armor is also worn around the waist and is called "Tare.” This is not an acceptable target area. See Figure 1 for the description of the armor and names. The lethal sword or "Katana" is replaced with a bamboo version called a "Shinai"(Figure 2) in competition Kendo. Another important etiquette involved with Competition Kendo is the need to state the intended target of the strike, as well as completing the strike with proper force. In other words, as the combatants are striking the target with sufficient force they are required to call out the targeted area. You would shout "Men" for a strike to the head, etc. A competition match is monitored by up to three referees with one being the head judge. The decision of the head judge is considered final and absolute.

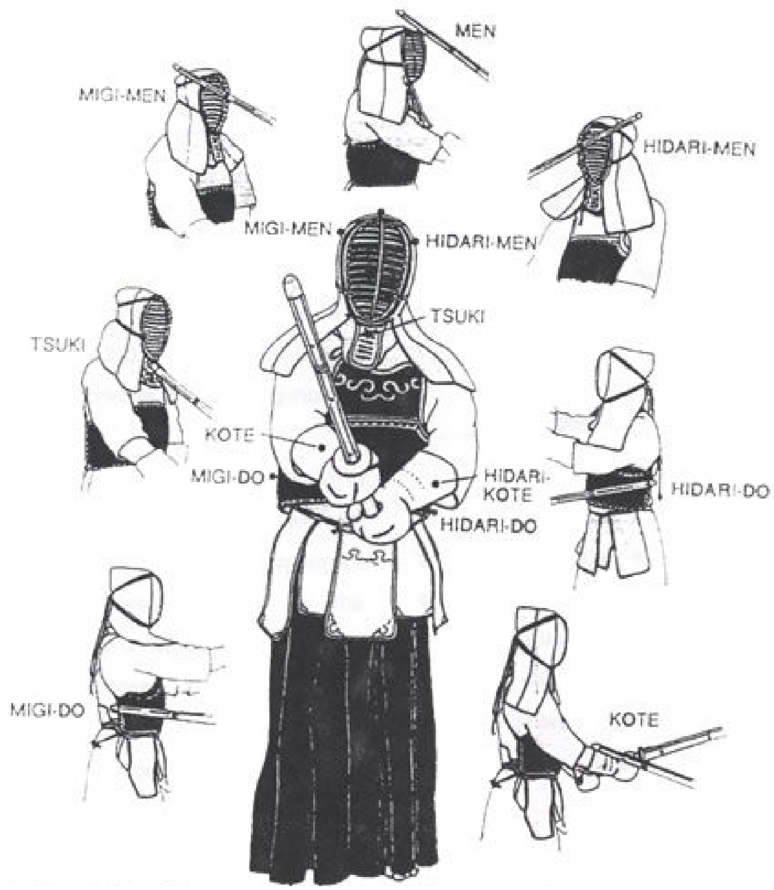

Figure 1 [1] **Kendo Bogu.** http://culture-ethnic.blogspot.com/2011/01/kendo-techniques-of-japanese-sword.html.

[1] In Figure 1, hidari means left in Japanese. Migi means right.

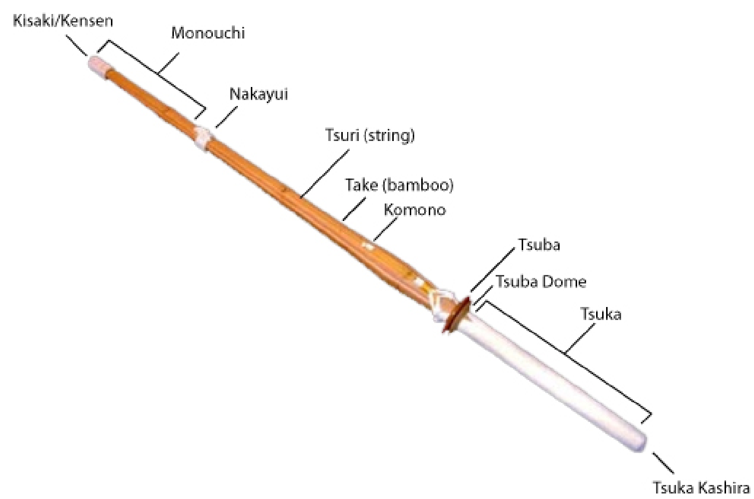

Figure 2 Shinai. http://www.matsukai.org/getting-started/

1.3 Design requirements

Design requirements and equipment used for this project are based on the ritual and rules for Competition Kendo. For example, a Window Comparator Board, which will be discussed in greater detail in section 3.9, is a device used to determine whether a sample signal is within acceptable parameters. In this case, acceptable parameters are a signal produced by applying great enough force on a Force Sensing Resistor pad. These pads will be described in section 2.3. The software program, written in C#, was likewise designed with these requirements in mind. For instance, there is a stopwatch feature that displays the time of each competitors strike, as well as which region was struck. The stopwatch will continue to keep track of time until the head judge halts the competition. This allows the head Judge to determine important circumstances, such as whether a call was made as to the intended target, or if the proper sportsmanship and rituals were observed. Only when a head judge decides the situation is legitimate will a score be registered, and the information reset. These items, along with other parts of the project configuration, will be described in greater detail in later sections.

II Related Work

2.1 Martial Arts and Sensors

The ProQuest database was searched for "Martial Arts and Sensors" and produced 9 articles dated from 2003 to the present. Of particular interest, were the references to patents awarded in this area. J. Forsell and D. Pysden 's work was relevant to this project as it described an electronic scoring system composed of wireless communication between a client using force sensors and a remote computer [6]. It calls for the use of various types of sensors; piezoelectric, tactile conductive cloth-based, as well as shape memory alloy (SMA) sensors. As this is a patent it doesn't go into great detail about the methodology or reasoning as such. However, it does bring up several different possible combinations. H. Lan and G. Chen's patent is also directly applicable to this thesis as it describes an electronic scoring system composed of wireless communication between clients and a remote computer. The sensors called for in this patent are micro electrical mechanical system (MEMS) pressure sensing modules [7]. According to J. D. Olivas and S. Bolin:

> MEMS are typically defined as a class of mechanical actuators, sensors, and other devices that are microscopic in scale and typically fabricated by the techniques used in the manufacture of integrated circuits and semiconductor components. [8]

While the fabrication technique is different from the manufacturing of the Force Sensing Resistor pads in use in this project, the cost and configuration of these devices is very similar. K. A. Reinbold et al created a system that uses sensors attached to boxing gloves [9]. The sensors send information about the force of the blow landed to a remote computer. Of interest is the following observation:

> The current hit includes all of the above-threshold samples, usually occurring within a brief time window, such as about 15 milliseconds to about 25 milliseconds. If the detected value exceeds the maximum for the current hit, then the maximum is updated using the detected value. This process continues until a maximum value is determined for the current hit. It has been observed by the inventors that a single hit may have more than one peak. Accordingly, it is not possible to conclude that the peak has been reached when the current value is less than the maximum for the current hit. To ensure that a hit has been completed, a specified number of successive below-threshold samples must be recorded. [9]

This is an attempt at debouncing the readings. In other words, during this type of measurement the reading may experience more than one peak or signal that could indicate a hit has occurred. In order to prevent multiple signals being sent from a single hit a mechanism is put in place to adjust for this. Other patents have been issued with similar use of force sensors but do not have any new information to share.

The IEEE database was likewise searched using the same term, "Martial Arts and Sensors." Five results were returned dating from 2005 to the present. The system designed by Chi uses piezoelectric sensors to measure force, and a judge's handset to record scoring, but it is otherwise similar to the system described in this thesis [2]. It incorporates wireless communication between the combatants, judge's handset, and the remote computer, as well as a graphical display of registered hits. Methodology discussed includes the need for "gaining the trust of users and judges." This end was furthered by demonstrating the accuracy and durability of the "SensorHogu system.[2]." Comparisons were made to other sports technologies and their acceptance or rejection. Bowling, tennis and baseball have had technology introduced to help with scoring and rules enforcement. Bowling and tennis have systems to observe whether a foot or tennis ball is over the acceptable line. Baseball has a system to decide whether a ball crosses the plate in the "strike zone." For various reasons, the systems designed for bowling and tennis have gained widespread acceptance, whereas baseball's system has not [2]. The exclusion of the use of accelerometers due to the desire to "directly measure the impacting force" was also discussed. In other words, an accelerometer would have measured force but not location. This could lead to false or misleading readings involving hits off target or against the walls or floors [2].

A search of the ACM Digital Library with the same search term resulted in 3 results, the earliest being 2004. These results yielded another paper from the same author of a previously cited paper. While published in the Proceedings of the 17th annual ACM symposium with a different name [10] is the same material as described above.

2.2 Arduino

The IEEE database was searched for the term "Arduino" and 111 results were returned. The earliest results were from 2008, even though the prototyping boards were first produced in 2005. The results are different for a search of the ACM database. 903 results were returned with the earliest being 2006. This is more in-line with the original manufacturing date. This discrepancy may be explained by the separate base of publications for each database. The board itself has proven adaptable for many different applications. Uses vary from patient rehabilitation to sculpting.

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[2] Hogu is the Korean word for body protector.

2.3 Force Sensing Resistor pads

The ProQuest database was searched with the term "Force Sensing Resistor(FSR)." 150 results were returned with the earliest being 1989. FSR pads are used in applications ranging from keyboards and mice to medical devices and musical instruments. They are even being used for airbag deployment in automobiles. A similar search was conducted as with the ACM database. Thirty one results were returned, ranging from 2007 to the present. The topics also included medical-related uses as well as other haptic related devices. A search of the IEEE database produced fifty results, with the earliest one being 1988. The topics were similar to the results from ProQuest with the addition of robotics application and patient evaluation and therapy. Two entries were found to be relevant to this project:

In S. I. Yaniger's review of FSR technology he states "the FSR (see Figure 3) is a flat, flexible device that exhibits a decreasing electrical resistance with increasing force applied normal to its surface [11]." In other words, the harder you strike the pad the higher the voltage returned. While there are different architectures for a FSR pad, the general idea is a spacer mounted between two conductive surfaces. The FSR used for this project has a protective surface over the conductive ones for protection from wear and tear. It will be discussed in greater detail in later sections.

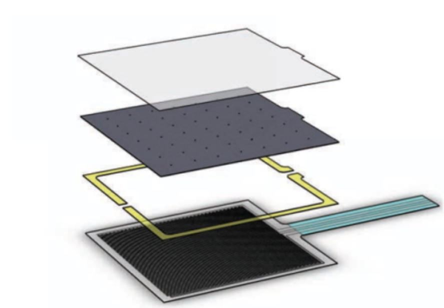

Figure 3 Interlink Electronics, "FSR integration guide," 2013

J. A. Florez and A. Velasquez discuss the calibration of the FSR pads [13]. The formula produced allows for the conversion of voltage returned from the force applied to the pad. While this might seem like a straightforward procedure, there are several factors to consider. The first consideration mentioned in this discussion is creep. In this context it is the undesirable behavior of the pad to decrease resistance over time with no added pressure [13]. It results in the voltage reading increasing when a static weight is applied with no change in the weight. The other factor considered is hysteresis. The Oxford English Dictionary defines hysteresis as:

> [a] phenomenon observed in some physical systems, by which changes in a property (e.g. magnetization, or length) lag behind changes in an agent on which they depend (e.g. magnetizing force, or stress), so that the value of the former at any moment depends on the manner of the previous variation of the latter (e.g. whether it was increasing or decreasing in value); any dependence of the value of a property on the past history of the system to which it pertains.[14]

The authors, J. A. Florez and A. Velasquez noted the lag in voltage reported and the actual force applied [13]. Use of the formula to calibrate the FSR pads will be discussed in section 4.2.

III Methodology

3.1 Project Setup

3.1.1 Computer

Software and hardware configured for the project was developed on an HP Pavilion dv7 notebook PC with an Intel® Core™ i5-2450 m CPU at 2.5 Ghz with 6 GB of RAM and a 64 bit Windows 7 Home Premium operating system.

3.1.2 Arduino UNO

According to the Arduino UNO's description page:

> The Arduino UNO (Figure 4) prototyping platform is a microcontroller board based on the ATmega328. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started. [15]

The acronym PWM in the above quote stands for pulse-width modulation. In W. Wang et al's article for the publication of Mathematics of Control, Signals and Systems PWM is explained as follows:

> Pulse-width modulation is a technique in which the width of a train of voltage (or current) pulses is adjusted (modulated) by rapidly turning the switch between the supply and load on and off. This technology is used extensively in power electronics and finds wide applications in industry. [16]

Likewise the acronym ICSP stands for "In-Circuit Serial Programming." The Arduino UNO's description page also states "You can also bypass the boot loader and program the microcontroller through the ICSP [15]." These characteristics influenced the decision to use the Arduino UNO for the embedded system. Other factors included its cost effectiveness and ready availability. It is available online from several sources, including Sparkfun.com. It is also available from the local Radio Shack retail stores. The average price is $30. The same is true for other components, such as the FSR pads for $10, the Bluetooth modem for $40 and the window comparator boards for $10 [17]. Furthermore it has a large user supported community with extensive information about the device. Previously compiled sketches designed to accomplish popular tasks such as reading from the analog pins on the board, etc; were easily available and proved accurate and reliable. Furthermore, the libraries available for programming the board are extensive and similar to Java or C++ in use and structure [18].

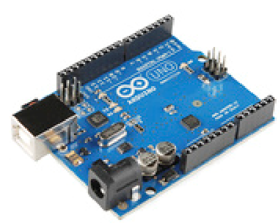

Figure 4 Arduino UNO. https://www.sparkfun.com/products/11224

Other options exist but have financial drawbacks. For instance, Tinkerforge makes a product similar in function to the Arduino [19]. It is based on the concept of modular design. In other words, you build your application with "Bricks" and "Bricklets." For instance, a project might start with a "Master Brick" and then include the necessary "Bricklets" for potentiometers, wireless communication and power. Like the Arduino, extensive Libraries exist that enable the programming of the device to perform various functions. These libraries are implemented in various languages, such as Java, Python, C# and Ruby. The drawback for this system is the price. The "Master Brick" has a cost of approximately $40 and additional "Bricklets" can range in price from $4 to $52, with the additional need to add actual sensors from other sources. One other consideration was the use of the Raspberry PI™ model B. This model represents an actual computer in functionality. It includes 512MB of onboard RAM, as well as USB connections and a Linux operating system [20]. At a cost of $35 it is similar in price and would provide all the functionality needed to complete the project. At the beginning of the project it was thought that this configuration represented more computing power than was needed. Future configurations of the project may incorporate this option if necessary.

The Arduino environment comes with a text editor, preloaded libraries, sketch examples and connection to the Arduino hardware for uploading software and monitoring communication. Instructions for the installation of the developmental environment are readily available from the Arduino website and easy to follow. The download also includes drivers for the Arduino board. Arduino programs, or sketches, can be divided into three main parts: structure, values (variables and constants), and functions [21]. Structure includes the setup section of the sketch that is run once after the board receives power, and the loop, which runs continuously after the setup completes. It also includes "if then" type functions as well as while and switch case statements. Functions operate in similar fashion to other programming languages, like C# or java, and provide modularity. Power to the board is applied when it is connected to the computer via a USB cable. At this point Windows will attempt to auto install a driver. After this fails you will have to point to the downloaded driver for the installation to be successful. Once this simple task was completed communication with the board was established and a sketch was uploaded. An additional design feature is the use of an object called a "ProtoShield" with "Breakaway Headers" (see figure 5). According to the Sparkfun website "the ProtoShield mates with an Arduino development board and gives the user a small soldering area, two general LED footprints, access to a BlueSMiRF socket... [17]." The ends of the "Breakaway Headers" are inserted through the holes of the "ProtoShield" and are soldered in place. This provides the feet for the shield that are inserted into the Arduino UNO. The advantage of using this shield is it provides 5 extra VDC power and ground outlets as well as making connection to the wireless communication device more compact.

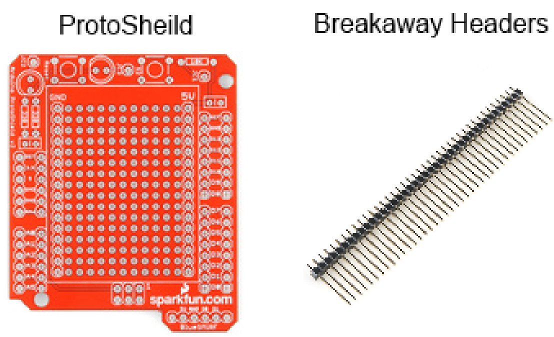

Figure 5 https://www.sparkfun.com/products/11665, https://www.sparkfun.com/products/10158

3.1.3 Bluetooth Modem

In order to fulfill the goal of wireless communication a BlueSMiRF Silver model number WRL-10269 Bluetooth modem (Figure 6) was selected from the Sparkfun website [17]. Bluetooth technology was selected for familiarity, as well as ease of configuration. XBee communication devices represent wireless modular communication and are similarly priced; however, configuring the device within a Windows environment takes additional work. The HP Pavilion laptop comes with the ability to use and configure Bluetooth devices built in. With a range of 54 feet and relatively small size, this modem provides the necessary functionality for this project.

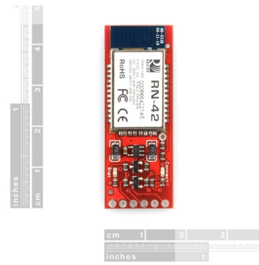

Figure 6 Bluetooth Modem. https://www.sparkfun.com/products/10269

Connecting the modem to the Arduino UNO involved soldering the male right angle connectors to the end of the Bluetooth device and the female right angle connectors (see Figure 7) to the socket access area, which is the six holes on the bottom area of the shield. This connection provides power to the Bluetooth device, as well as access to the RX (receive) and TX (transmit) pins on the Arduino UNO. At this stage the device is recognized by Windows and the driver is automatically installed. In order to be correctly configured a pairing code of "1234" needs to be entered. This is the default code and can be changed if necessary.

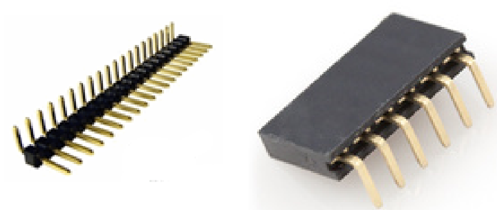

Figure 7 Male Right Angle Pins https://www.sparkfun.com/products/553, Female Right Angle Pins https://www.sparkfun.com/products/9429

3.1.4 Visual Studio Professional and C#

In order to test communication between the Arduino and the laptop a software program was developed. "DreamSpark" is a program offered by Microsoft that makes several of its software packages available for free or at reduced prices to Eastern Washington University Computer Science students. Microsoft Visual Studio Professional 2012 is one of those titles and was chosen as a development environment, with C# as the language. While other choices were viable, Visual Studio has many features that make program development faster and easier and is well supported. As well as low cost, C# is also a well-known language and did not require a steep learning curve.

In the software solution for the laptop a serial port object was created. This object, part of the System.IO.Ports namespace, was configured to match up with the Bluetooth device. An event handler was also initialized to listen in on this object for incoming data. A simple sketch was created, compiled and uploaded to the board. Unfortunately, no information was received by the laptop. After carefully checking the code on both sides for accuracy, investigation switched to the Bluetooth modem. Research of the Arduino community forums revealed that the BlueSMiRF Silver modem had a factory set baud rate of 115,200. The particular version of Arduino UNO board being used was only able to read at a baud rate of 9600. This discovery necessitated a change of the modem configuration settings. In order to access these settings the modem was connected directly to the laptop via a FTDI cable with a mini USB connection (see Figure 8). The Telnet program "Putty" was used as the serial port interface. The BlueSMiRF data sheet, available on the sparkfun website states that in order to enter command mode the characters "$$$" must be sent within 60 seconds of powering up the modem. If the command is not sent within this window they will be ignored. When entered properly the modem responds by sending the characters "CMD". Once in command mode the correct instruction is "SU, 96". If the command is accepted the modem will respond with "AOK"; if not it will send "ERR". Successful completion will set the baud rate to 9600. To exit command mode, send the characters "---" [22]. At the completion of these steps the communication was checked again with success, communication had been established between the Arduino UNO and the laptop.

Figure 8 FTDI Connection. https://www.sparkfun.com/products/9873

3.1.5 Force Sensing Resistance pads

Initial efforts for the project centered around connecting two FSR pads to the analog pins on the Arduino UNO. A 10K ohm resistor is used between the pad and the analog pin (see Figure 9). This resistor acts as a voltage divider and allows for the measurement of the change of resistance on the pad. Capturing and interpreting the data from the pads is done on the board. In other words, the analog signal sent from the pad passes through the analog to digital converter (ADC) on the Arduino UNO. Since the signals are analog in nature, even when converted to number values, an algorithm was needed to identify the highest value in the current stream. The board then determines if the highest signal sent was great enough to constitute a hit. If so, it would send a serial message to the laptop. For this project, Interlink's model 406 FSR pad was used. Interlinks FSR integration guide states:

> The most basic FSR consists of two membranes separated by a thin air gap. The air gap is maintained by a spacer around the edges and by the rigidity of the two membranes. One of the membranes has two sets of interdigitated fingers that are electrically distinct, with each set connecting to one trace on a tail. The other membrane is coated with FSR ink. When pressed, the FSR ink

shorts the two traces together with a resistance that depends on applied force. [12]

In this context the word "interdigitated" indicates that one of the circuits printed on the membrane weaves around the other (see Figure 10). This allows for the aforementioned shorting when the membranes are pressed together. Resistance is inversely proportional to the amount of force applied to the pad: The lower the resistance, the higher the analog reading.

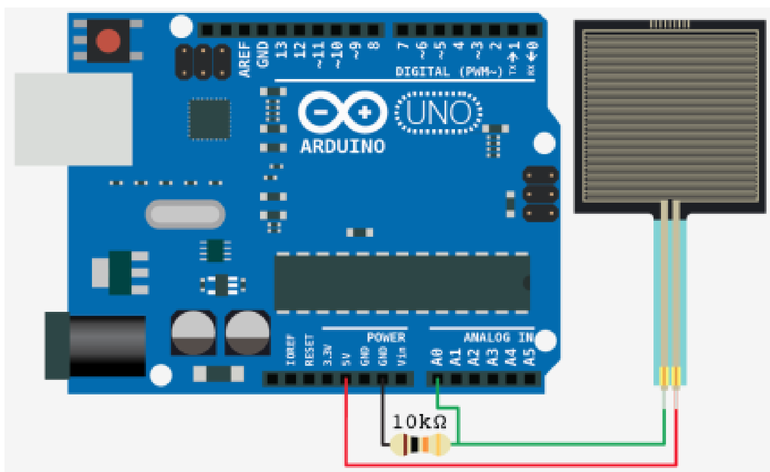

Figure 9 Arduino UNO and FSR Pad. http://bildr.org/2012/11/force-sensitive-resistor-arduino/

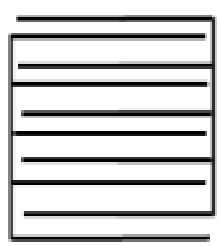

Figure 10 Interdigitized Fingers

3.1.6 Analog to Digital Converter (ADC)

According to the ATmega328P microcontroller data sheet::

> [ATmega328P] features a 10-bit successive approximation ADC...the ADC contains a Sample and Hold circuit which ensures that the input voltage to the ADC is held at a constant level during conversion ... The ADC converts an analog input voltage to a 10-bit digital value through successive approximation. [24]

In this case successive approximation means that the ADC performs a sort of binary search algorithm to compile the digital value of the analog input. In other words, it continuously splits the range it is searching in half until it finds an approximate discrete value for the continuous analog value it is given. The reference value used in this case is the maximum voltage sent through the FSR pad to an analog pin. For this project it is 5 volts. A mid range, in this case 2.5 volts, is selected and the sample voltage stored in the "sample and hold circuit" is compared to it. If the sample voltage is higher, the most significant bit (MSB) is set to 1 and the next mid range is set. If the sample voltage is lower the MSB is set to 0. This process is continued for the next bit and so on until the desired resolution is obtained. This particular ADC has a 10 bit resolution and a sampling rate of 76.9 kilo samples per second (KSPS). Once this process is completed the resulting value is returned. See Figure 11 for a sample run. When set to its default "single conversion" mode the next conversion will start as soon as the previous one is finished. The ATmega328P microcontroller data sheet identifies the absolute accuracy of the conversion process as ± 2 LSB [24]. A ten bit resolution means the values are mapped to a range of 0 - 1023. The data sheet also states that the time for this conversion process takes 13-260 microseconds [24]. The ADC interfaces with the Arduino UNO through

6 Multiplexed Single Ended Input Channels interfaced to the 6 analog pins. The ADC is able to convert signals from one pin at a time. In other words, while it is converting the signal from one pin, the other pins are not stored. According to the Atmel Technical Support Team "the ADC hardware does not as such induce a delay while switching from one channel to another [25]." This indicates no time is added between the readings. However, since the sample signal is stored in a holding circuit it may be necessary to allow the signal to stabilize. In other words, to prevent the readings from interfering with each other, some time is needed between them. According to the ATMEGA 382 data sheet if it is not allowed to stabilize an inaccurate reading can occur [24]. One method is to introduce a delay in the software. This delay is measured in milliseconds. A simple sensitivity analysis of this factor was conducted. In this analysis the number of values returned was counted and the highest value was recorded. This process was repeated for both pads attached to the Arduino UNO. It was noted that the number of values returned was reduced, but the highest value did not change by very much. This may indicate that the variable is not sensitive for the overall implementation of the project since we may still be getting the correct highest value for each hit. However, this analysis does introduce the possibility of inaccurate readings. Another method is to take two readings and discard the first. This method adds very little time to the process and still produces consistent results. Both issues will be discussed in greater detail in section 3.2.1

In this example sample voltage = 3.6		
Condition	Value	Bit Status
Is sample voltage > = 2.5	Yes	1
Is sample voltage > = 3.75	No	0
Is sample voltage > = 3.125	Yes	1
Is sample voltage > = 3.4375	Yes	1
Is sample voltage > = 3.59375	Yes	1
Is sample voltage > = 3.671875	No	0
Is sample voltage > = 3.6328125	No	0
Is sample voltage > = 3.61328125	No	0
Is sample voltage > = 3.603515625	No	0
Is sample voltage > = 3.5986328125	Yes	1
The end result is a binary value of 1011100001 which equals 737 in decimal		

Figure 11 ADC Sample Run

3.2 Project Configuration

3.2.1 Configuration Issues

Since more than one pad per area of the armor is needed to provide adequate coverage, it was necessary to consider alternative configurations of the project for future use. The Arduino UNO has 6 analog pins for use with the pads. Since the pads connect to the Arduino UNO through the analog pins it proved necessary to increase the number of pins. One way to expand the amount of analog pins is to use a multiplexer. In this instance a multiplexer is simply a device that can combine several input sources into one output. There are many different configurations of multiplexers that are usable by the Arduino UNO. Some come preconfigured on shields similar to the ProtoShield (Figure 5) mentioned earlier. One example of this is called a MUX shield (see Figure 12) and it allows the user to simply plug the multiplexer into the Arduino UNO board and have access to more analog pins. Other configurations allow for daisy chaining the multiplexers for even more pins (see Figure 13). While both of these configurations are unique, both utilize the High-Speed CMOS Logic 16-Channel Analog Multiplexer/Demultiplexer from Texas Instruments. Unlike the multiplexer for the ADC, the data sheet for the multiplexer states that it utilizes "Break-Before-Make" switching [26]. This describes the way the multiplexer monitors the pins for signals. It will break contact with the pin it is currently monitoring and then make a connection to the next one in line. It will cycle through the pins before returning to the current one.   The "Break-Before-Make" switching introduces a delay of 6 nanoseconds per pin. This suggests that a cycle will take 36ns before taking another reading on a designated pin. This calculates out to 27,777,777 such cycles per second.

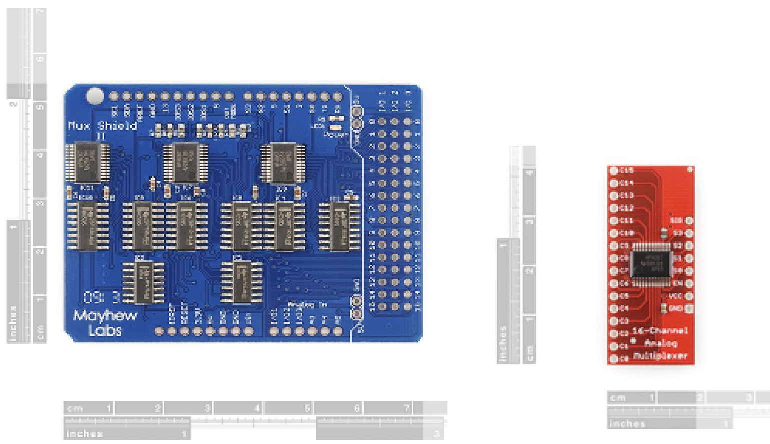

Figure 12 Multiplexer Shield. https://www.sparkfun.com/products/11723, Multiplexer Board. https://www.sparkfun.com/products/9056

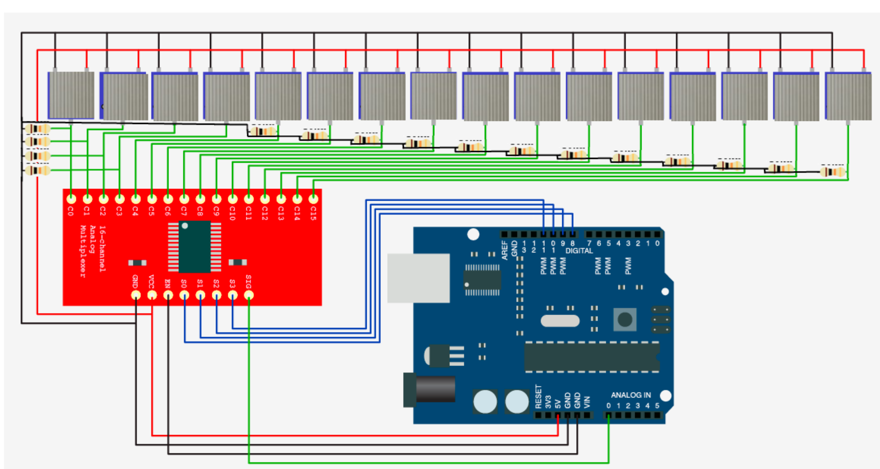

Figure 13 https://www.sparkfun.com/products/9056 (authors composite)

This particular configuration of the project has four factors that require consideration in reference to the overall reliability and consistency of the readings used: (1) the absolute accuracy for the conversion process of the onboard ADC, (2) the time this conversion process takes, (3) either the need for a delay between these readings, or the need to discard the first reading and (4) the break-to-make delay between pin switches for the add-on multiplexer. Of these four, the first three were discussed previously and rejected as sensitive variables on their own. The equipment was not available physically to perform a sensitivity analysis of the fourth factor. However, theoretically, the compounding of delays that would be present in a daisy chaining of multiplexers could result in a situation that would call into question the consistency of readings. Of particular interest would be a way to avoid conversion times or other delays when recording hits on the body armor. Another factor to consider is the durability of such a configuration. During the course of this project it has become apparent that the pads do not hold up well under repeated strikes. Any type of crease in the material causes them to become unresponsive. The leads of the pads are also weak points when it comes to withstanding strikes. Using a multiplexer and multiple pads would require the routing of more wires and leads across the armor as it is worn during combat.

3.2.2 Comparators and Op-Amps

These factors suggest an alternative configuration is necessary for the project to be viable. Many of these factors would require alternative materials and strategies to implement. Most of these will be discussed in the next section; however, one alternative actually implemented was the use of a comparator between the FSR pad and the Arduino UNO digital pin. T. Kuphaldt's online book "All About Circuits" states:

> A comparator circuit compares two voltage signals and determines which one is greater. The result of this comparison is indicated by the output voltage: if the op-amp's output is saturated in the positive direction, the noninverting input (+) is a greater, or more positive, voltage than the inverting input (-), all voltages measured with respect to ground. If the op-amp's voltage is near the negative supply voltage (in this case, 0 volts, or ground potential), it means the inverting input (-) has a greater voltage applied to it than the noninverting input (+). [27]

While some comparators use dedicated circuits, most still rely on op-amps to perform voltage comparisons. In this example the op-amps are used as inverting and non-inverting (see Figure 14). According to F. Nachbaur's paper "A hands-on approach to OP-AMP basics":

> the opamp has two inputs: One input, marked '+', is called the noninverting input, and the other, marked '-', is called the inverting input ... The input signal can be applied to either input, thereby giving a choice of inverting or non-inverting amplification. In a non-inverting amplifier (signal applied to the + input), the output phase is identical to the input phase; i.e., as the input goes positive, the output also goes positive, and vice versa. Conversely, in an inverting amplifier (signal applied to the - input), the output phase is inverted from the input phase; i.e., as the input goes positive, the output goes negative. [28]

The positive and negative power supplies represented in the diagram provide the ability to amplify the signal. According to Chris Gammell "as long as the signal at the input (or more accurately the difference between the inverting and non-inverting input) is smaller than the power at the (positive and negative supply) terminals, then the op amp can amplify the signal [29]."

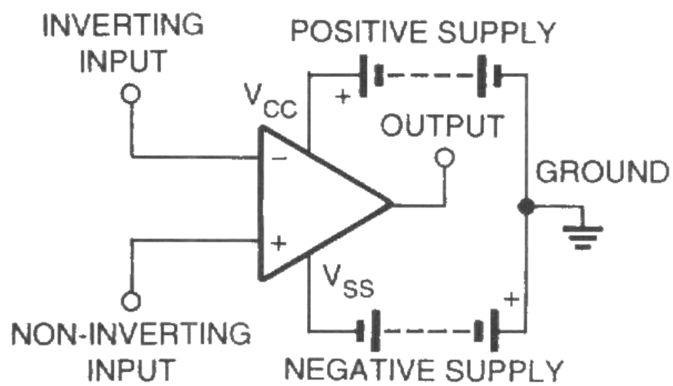

Figure 14 Comparator Circuit.
http://search.proquest.com.ezproxy.library.ewu.edu/docview/197157170?accountid=7305

Several comparator options were considered for this project, such as the Texas Instruments LM339 quad comparator chip (see Figure 15). While this chip has several superior features to the comparator eventually used, it proved to be harder to incorporate into the project. This chip will be discussed in greater detail in section 4.4.

Figure 15 LM339 Quad Comparator. http://www.radioshack.com/product/index.jsp?productId=2062593

3.2.3 WIG-10101 Window Comparator

The Sparkfun web site, which supplies several other project components, provides the window comparator WIG-10101 (see Figure 16) used for this project. It combines the function of the window comparator with ease of integration into the project. The manufacturer of the component is not known. It may be a device constructed by a member of the Sparkfun organization or a contributor. Outside of the schematic (see Figure 17) there is very little information available about the window comparator. However, the schematic does yield some information concerning the parts populated on the board. It indicates that the two op-amps are provided by a single Texas Instruments LMV358 dual, low voltage operational amplifier chip with rail-to-rail output swing [31]. It also shows two MMBT2222 NPN General Purpose Amplifiers manufactured by Fairchild Semiconductor [32], as well as two unidentified 10K SMD trimpots, or trimmer potentiometers. One of the trimpots is connected to the HREF high circuit (IC1A) and the other to the HREF low circuit (IC1B). These provide the window of voltage values for the comparator. If the sample signal is between the two reference signals both op-amps go negative with their output. This will turn the Q1 amplifier off allowing the logic to go high producing a digital one. If either op-amp produce a positive output Q1 will be on and thereby force the logic to go low, producing a zero. The compact form and convenient connection markings made incorporating this device into the project easy and straightforward. It requires a connection to ground and a 5VDC supply. The connections for VREF high and low were only connected for reference and not for actually setting the window voltages because the trimpots were used. A small program was written to monitor the digital value as the trimpot was turned. This allowed for better control and accuracy when setting these values. The "signal" connection was supplied by the FSR pad. This is the sample signal used for comparisons. Finally, the logic connector was sent to the digital pin on the Arduino UNO board.

Figure 16 Window Comparator. https://www.sparkfun.com/products/10101

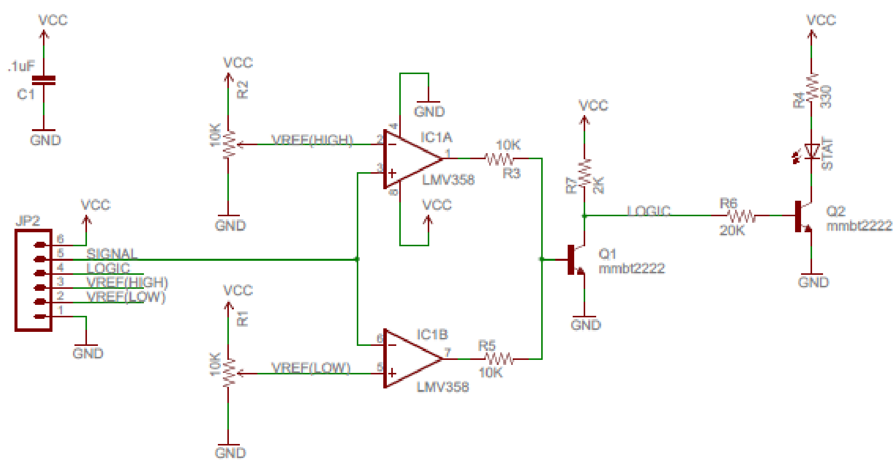

Figure 17 Window Comparator Circuit.
https://www.sparkfun.com/datasheets/Widgets/Window%20Comparator-v15.pdf

3.3 Final Configuration and Construction

The final configuration of the prototype for the electronic scoring of Kendo matches utilizes two window comparators connected to each of two FSR pads. The comparators interface with the Arduino UNO board via digital pins 12 and 13. The digital pins are monitored by the Arduino UNO and if either is set to a digital value of one a signal is sent wirelessly to the host laptop over a Bluetooth modem. There are two Arduino UNOs per competition match. The software configuration monitors the com ports for traffic. Information received over the com port is interpreted for identification of the region struck as well as competitor. The software marks and displays the time of each strike and allows the head judge the option of accepting the strike or disallowing it.

The following is a list of the parts used for the construction of the project:

Item	Part No	Number	Supplier	Reference
Arduino UNO	DEV-11021	2	Sparkfun.com	Fig 6
Proto Shield	DEV-11665	2	Sparkfun.com	Fig7
Breakaway Headers	PRT-10158	4 (Rows of 40)	Sparkfun.com	Fig 7
Stackable Headers (6 pin)	PRT-09280	4	Sparkfun.com	
Breakaway Headers, male right angle	PRT-00553	2	Sparkfun.com	Fig 9
Breakaway Headers, female right angle	PRT-09429	4	Sparkfun.com	Fig 9
BlueTooth BlueSmirf Silver Modem	WRL-10269	2	Sparkfun.com	Fig 8
FSR pads	SEN-09376	4	Sparkfun.com	Fig 3
Window Comparator	WIG-10101	2	Sparkfun.com	Fig 18
Jumper Wires, MM FF		Various		
Hook Up wire		Various		

Populating the proto shield is subject to personal preference, with the correct orientation of pins being the most important consideration. For instance, using a stackable header for the interface with the window comparator requires one side to be connected to ground and the other side connected to power. One "foot" of the header could be in the grounding row of the shield and connect the other pins accordingly or one "foot" in the 5V row, etc. This project uses stackable and male headers for ease of replacement. The bottom-most six pin connection on the proto shield is pre-set to use with the BlueSmirf modem. These connections are already wired to connect the TX (transmit), RX (receive), ground and 5V pins to the appropriate pins on the Arduino UNO board. Another important consideration is the use of a 10K ohm resistor as a pull down resistor between the signal connection on the window comparator and the ground row on the proto shield. This project uses hook-up wires for connections between the proto shield and the various parts. It would also be possible to create a connection through other means, such as soldered connections, etc. Finally, the length of the jumper wires used to connect the FSR pads is also subjective and should be measured according to need.

IV Results/Conclusions

4.1 Goals

The final configuration of the prototype designed for the project meets the criteria as described. The prototype provides a means to electronically score Kendo matches. The Arduino UNO board provides the embedded system and basis for the project. It is able to sense the force of the hit, as well as whether it occurs in an acceptable scoring area, by use of the FSR pads and window comparators. The window comparator also provides the ability to adjust the level of pressure needed to score a hit on the target. The present configuration also provides the means to increase the amount of pads thereby covering all legitimate scoring areas. In other words, the project has two FSR pads connected to two digital pins on the Arduino UNO. There are enough pins to accommodate more pads for more areas. The prototype is also able to communicate wirelessly with a remote laptop through use of a Bluetooth modem. The modem also has the required range to fulfill the need to cover a competition size area. The software, in conjunction with the hardware, provides the means to identify which combatant has registered a hit, as well as the region struck and the time of occurrence. Furthermore, the software provides the means for the head judge to make the final decision as to whether a hit was legitimate or not. Full control of the competition is left in the judge's hands.

While durability has not been a requirement for this project, future consideration and improvements in materials will be discussed. For instance, it is evident that more durable material is necessary for registering hits. Two individual pads used during formulation and testing developed creases and were unusable. This indicates that they would not stand up under the more rigorous demands of a competition match.

4.2 Calibration of FSR pads

J. A. Florez and A. Velasquez's paper on the calibration of FSR pads defines the final formula used to compensate for the factors described in the review of related work as RFSR = $129.32*P^{-0.695}$, where RFSR is the resistance of the FSR pad in kiloohms and P is millimeters of mercury (mmHg)[13]. See Figure 18 for a graph of the formula in use. Some conversion is necessary in order to use this formula for this project. For instance, mmHg would have to be converted to pounds per square inch (PSI) and then plugged into the formula. For example, 20 psi would equal 1034 mmHg. This would yield $129.32(1034^{-.695})$ which equals 1.03 K ohms which is the amount of resistance the FSR pad would have if 20 psi was applied to it. As discussed, the voltage divider circuit consists of the FSR pad as the + resistor and a 10K ohm resistor for the - resistor. If the value,1.03K ohms, calculated from the above formula is plugged into the formula it yields, (10/11.03)*5, which equals 4.533 volts. The final conversion requires the mapping of this value to the digital number returned by the ADC for a reference. This results in (4.533/5) * 1023, which equals 927. This number indicates the accuracy of the formula proposed by Florez and Velasquez as it matches attempts at calibration performed by hand [13]. It is important to note that these authors indicate that even with this formula each individual FSR pad will need its own calibration [13].

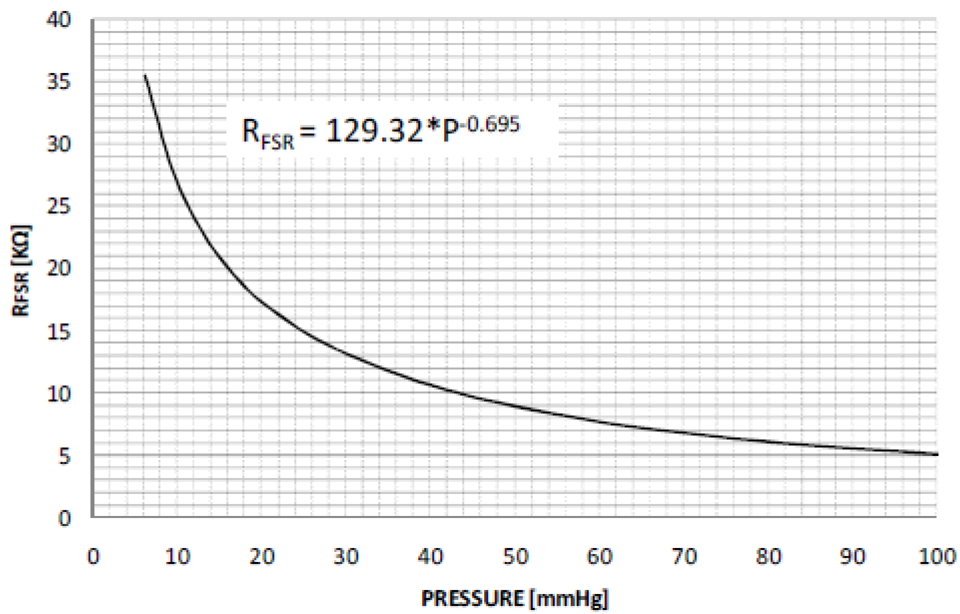

Figure 18 Graph of Formula. J. A. Florez and A. Velasquez. Calibration of force sensing resistors (fsr) for static and dynamic applications.

4.3 Force sensitive material

As previously discussed, it is evident that different materials and configurations are necessary for the project to work under realistic conditions. One such alternative configuration could include the use of a different material for sensing force. F. Xu et al in their paper "The Design of a Novel Flexible Tactile Sensor Based on Pressre-conductive Rubber" suggest a flexible tactile sensor composed of pressure-conductive rubber and flexible plastic sheets with wires [33]. Pressure-conductive rubber is not as fragile as the FSR pads and can be conformed to the shape of the armor. Furthermore, it would be able to cover a larger area with fewer exposed wires and connections. According to the authors "pressure-conductive rubber is a kind of conductive polymer function material [33]." The polymer itself is nonconductive with an added conductive filler such as carbon black. The Encyclopedia Britannica states carbon black is "soot from partial combustion of hydrocarbons ... used in protective coatings, plastics, and resistors for electronic circuits [34] ." In the configuration suggested by F. Xu et al the rubber is divided into small round sections and sandwiched between two flexible plastic sheets felted with wires [33] (see Figure 19). The wires on the top sheet runs in one direction, for instance, north to south, while the wires on the bottom sheet run in the other, for instance, east to west. Voltage is applied to one row of wires on one side of the sensor and the other is grounded. The carbon black as it is suspended in the polymer has resistance when the rubber is not compressed. However, when the material is compressed the carbon black forms a chain which lowers resistance and allows for the sensing of force in the form of increased voltage (see Figure 20). The configuration suggested by F. Xu et al is designed to provide more detailed information than would be needed for this application [33]. For instance it is able to provide directionality, as well as the precise location of the force applied. Since this is more information than needed, it should prove to be adaptable for this project. While this material does not seem to be commercially available it may prove possible to manufacture and modify the material for this project locally, at an economical price. F. Xu et al also provide formulas for the conversion of the reference voltage and the pressure [33].

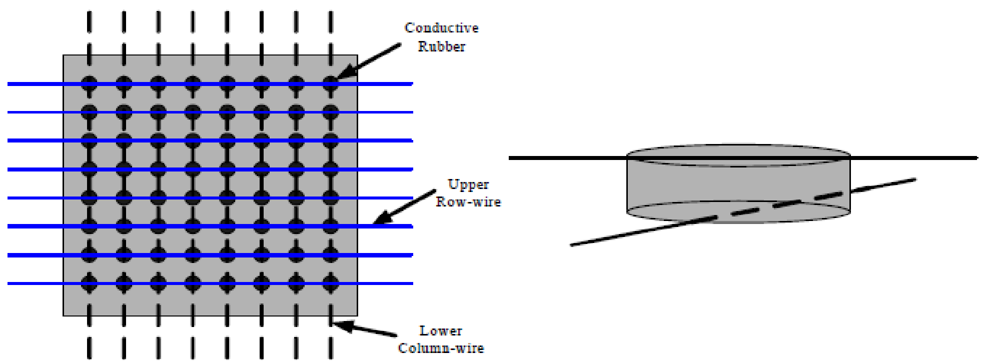

Figure 19 Pressure Conductive Rubber Diagram. F. Xu, Y. Ge, Y. Yu, J. Ding, T. Ju and S. Li, "The Design of a Novel Flexible Tactile Sensor Based on Pressure-conductive Rubber,"

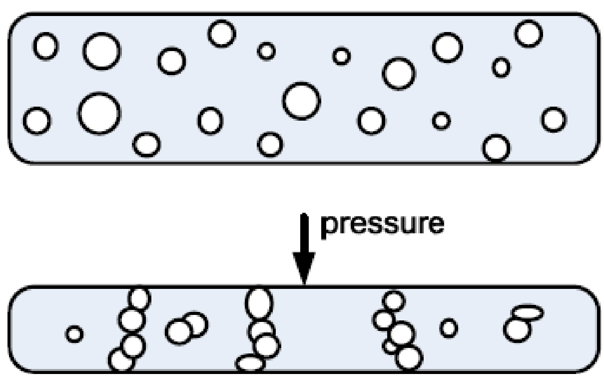

Figure 20 Use of Pressure Conductive Rubber. F. Xu, Y. Ge, Y. Yu, J. Ding, T. Ju and S. Li, "The Design of a Novel Flexible Tactile Sensor Based on Pressure-conductive Rubber,"

Another possible configuration would be to use a type of e-fabric instead of the pressure-conductive rubber mentioned previously. Several companies manufacture a form of e-fabric, however, these products are very proprietary and information is hard to come by for some of them. One company that does provide information is Peratech and their product is called Quantum Tunneling Composite (QTC™). According to the Peratech website their fabric works in a similar fashion to pressure-conductive rubber with one significant difference:

> Carbon particles used in the pressure-sensitive rubber are rounded in shape. This means that particles are always in contact providing a path of conductivity and thereby reducing resistance when the rubber is not pressed. As the rubber is compressed pathways tend to build up. This process is known as percolation. What gives QTC™ material a different property from percolative composites is that the metal particles are given an irregular structure with a spiked surface which is wetted i.e. electrically insulated by the silicone rubber. The wetting allows the metal particles to get close but not touch even when the QTC™ Material is squeezed or densely loaded. (See Figure 21) [35]

When the material is squeezed together "tunneling" occurs. Tunneling is the name Peratech uses to describe the conductive process. The website goes on to explain:

> Spikes on the conductive filler particles produce a localized increase in the electric field at the tips which effectively reduce the barrier's width and allows conduction to occur. This is known as field-assisted tunneling. As QTC™ Material is compressed, the conductive particles are brought closer together and barrier widths reduced further. This leads to an exponential increase in the probability of tunneling and an exponential decrease in electrical resistance.[35]

In this case, the barrier is provided by the polymer part of the composite material. This means that voltage would be allowed to flow even though the conductive particles are not actually touching. It allows the material to work as a pressure sensor even though it is relatively thin and flexible.(see Figure 22)

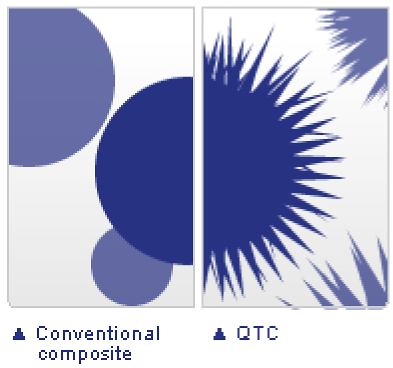

Figure 21 QTC Comparison. http://www.peratech.com/qtc-science.html

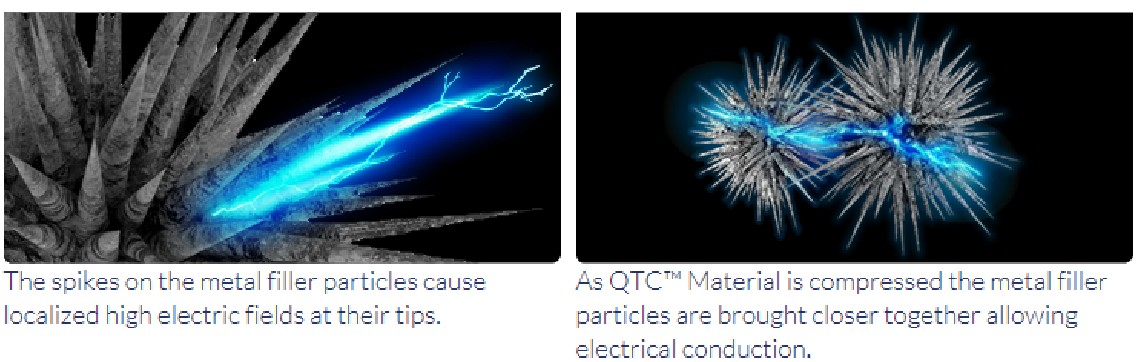

Figure 22 QTC in Use. http://www.peratech.com/qtc-science.html

4.4 LM339 Quad Comparator

Texas Instruments' data sheet for the LM339 states "[the LM339] consist[s] of four independent voltage comparators that are designed to operate from a single power supply over a wide range of voltages" [36] (see Figure 23). This comparator offers several upgrades over the window comparator used for this project. It has a cost of approximately $2.50 and is available from most Radio Shack retail stores. This is in comparison with the $10 per window comparator, which is only available from Sparkfun.com. Since the window comparator can only monitor one voltage signal at a time as opposed to the 4 signals for the LM339 the actual savings would be at least $37.50 per combatant. It is also a single reference comparator. While this may not seem like a large issue, having to set just 4 trim pots is less of a problem than setting 8. It may also be possible to use the Arduino UNOs ability to utilize pulse width modulation (PWM) as the reference for the comparator. As defined earlier, PWM is a way of using a digital signal to work like an analog one. This is accomplished by rapidly turning the signal on and off at a speed that does not interfere with the item being used. This process is usually applied to running servo motors or LEDs but it may prove adaptable for this project. One more consideration is size. Populating the ProtoShield with the four window comparators does not present a problem. However, in conjunction with the next topic, it will be necessary to use less space, which this particular chip will.

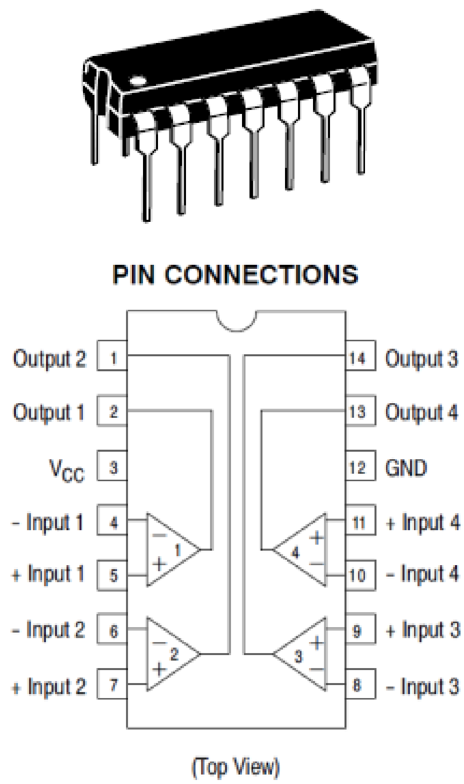

Figure 23 LM339 and Pin Out. http://www.ti.com/product/lm339

4.5 Arduino Mini

In this project's final configuration size should be a consideration. Not only will the force sensing material be located on the armor, the Arduino UNO will be as well. While several options exist for encasing the board in a hard, durable cover the overall dimensions of the board, shield and comparator chips are relatively large. In a sport that requires mobility and speed it may not be desirable to have a large encumbrance. The Arduino Corporation does manufacture several different configuration of boards. One of these is a miniature board that has many of the same features as the Arduino UNO. According to the Arduino Website Overview:

> The Arduino Mini is a small microcontroller board ... intended for use on breadboards and when space is at a premium. It has 14 digital input/output

pins (of which 6 can be used as PWM outputs), 8 analog inputs, and a 16 MHz crystal oscillator. It can be programmed with the USB Serial adapter or other USB or RS232 to TTL serial adapter. (see Figure 24) [37]

Several differences still exist between the Arduino Mini 05 and the UNO other than the size. For instance, input voltage is limited to 9V. This is particularly important when using a battery as would be needed for wireless configuration. Due to its size, the pin outs are different and not as conducive to the use of any type of pre-made proto shield that would support this project. In other words, the proto shield provided for the mini by sources like Sparkfun would not have the space for either the window comparator chips or the LM339. Similarly, the Bluetooth modem does not have the premade connections found on the Arduino UNO proto shield. It would be possible to create one from scratch if necessary from a blank board. The savings in size should still offset any minor differences or difficulties. The mini is approximately 1.25 inches long by .75 inches wide. This is a significant savings in size from the Arduino UNO, which is approximately 2.7 inches long by 2.1 inches wide. The enclosure for the mini utilizing the LM339 comparator chip would present a much smaller profile than the Arduino UNO with four window comparator chips. This should prove to be more popular with potential combatants during a match.

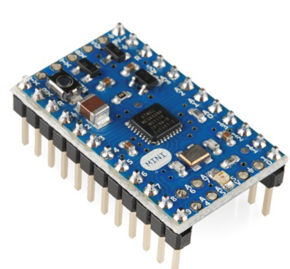

Figure 24 Arduino Mini. https://www.sparkfun.com/products/11303

4.6 Security

As mentioned previously, several sports have adopted electronic scoring as an option. Fencing has gone as far as to allow its electronic scoring to be used in Olympic events. It has also been subject to attempts to overcome its security. In the 1976 Summer Olympics in Montreal Canada, Boris Onischenko from the Soviet Union altered his fencing sword to register hits even if he had not touched his opponent [38]. Cheating affects not only the contestants, but also the credibility of the system. For the system proposed by this project to be taken seriously by the Kendo community security will have to be considered and concerns addressed. For this project security risks are centered around the use of Bluetooth technology. Like most technologies related to computers this technology has a governing body that has developed a set of standards. In this case the body is called the Bluetooth special interest group. According to S. Sandhya and K. A. S. Devi "Bluetooth security works on the basis of authentication and encryption. There are four security modes in Bluetooth which are Security Mode 1, Security Mode 2, Security Mode 3 and Security Mode 4" [39]. These unimaginatively named modes have different concerns or criteria. Mode 1 dictates no security or encryption, 2 calls for encryption and authentication for local file transfers or synchronization, 3 dictates authentication prior to synchronization and all subsequent traffic is encrypted, mode 4 uses secure simple pairing to ensure service level security. This project employs level 4 for security. The establishment of a pairing code was described in section 3.3. For the prototype, the factory code was used; however it is possible to change the code for added security. It should also be noted that the modem used for this project has Bluetooth v2.0+EDR. This is not the latest version. Version 4.0 has been released and has a key difference. S. Sandhya and K. A. S. Devi's analysis of Bluetooth threats states "To maximize security, this process uses a 16 character PIN. The Bluetooth version 2.0 + EDR and earlier versions use a 4 character PIN or a fixed PIN Passive Eavesdropping Protection" [39] . The obvious advantage of a 16 character PIN is the increased difficulty of cracking the PIN. This is due to the greater number of permutations and combinations. This provides greater security against passive eavesdropping; however, it still leaves a system vulnerable to what is called a man in the middle (MITM) attack [39]. According to the authors:

> A man in the middle attack occurs when a user wants to connect two devices but instead of connecting with each other they unknowingly connect to a third device. The third device then relays the information between the two devices. [39]

The authors offer three different means of protection against this type of attack; Numeric Comparison, Out of band, and Passkey Entry. The final configuration of the project will decide which of these models is best suited for use. Regardless of which model is selected, it will be necessary to upgrade the Bluetooth device to this latest version.

4.7 Summary

Motivation for this project included the goal of investigating different configurations, or architectures, for the wireless electronic scoring of competition Kendo matches. While the primary goal was to provide consistent and accurate data, a secondary goal was to discover alternative configurations that may aid in areas that go beyond the martial arts. The use of the window comparator board as the controller for the pads will provide a more flexible or finely tuned instrument for use in areas such as patient rehabilitation (see Figure 25).

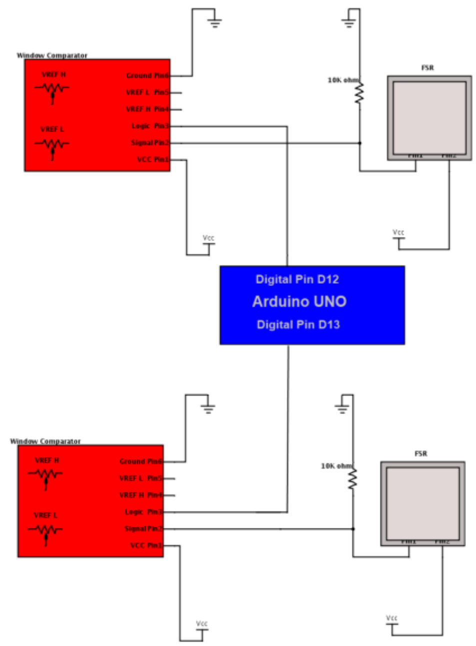

Figure 25 Project Diagram with Window Comparators and FSR Pads.

An alternative configuration, using the Texas Instrument's LM339 quad comparator chip was also constructed (see Figure 26). This provides a more compact architecture which should prove easier to fit to the combatant's armor. Part of the considerations of this project was to produce a system that would eventually be accepted by the Kendo community. The lower the profile of the system, the easier this task will be. Kendo is a very mobile martial art form. The combatants need to be able to move about the competition area with little impediment. The less they have to worry about wires and boxes on the armor the better.

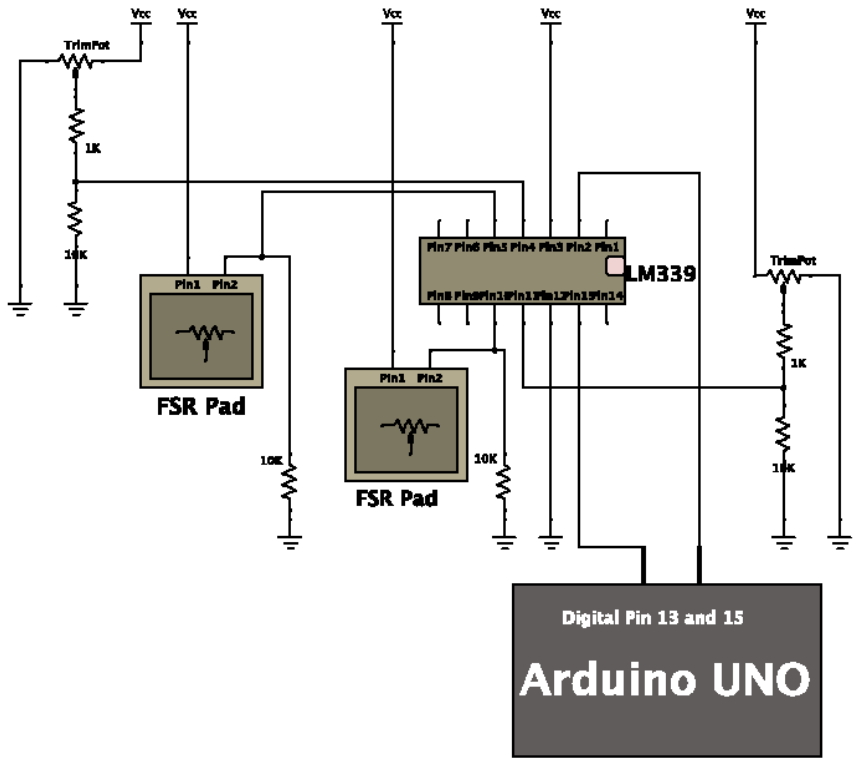

Figure 26 Project Diagram with LM339 Quad Comparator and FSR Pads.

Further consideration was given to Kendo etiquette and tradition. Tradition states that the head judge is the final word in the scoring and control of a competition Kendo match. The software part of the project was formulated with this in mind. No score is tallied and the match is not stopped until the head judge indicates his decision in the matter.

Finally, the consideration for future improvements explored different materials for use with the project system. Both materials discussed have both advantages and disadvantages. However, this consideration provides a direction for growth in both this project and other areas of computer related data sensing.

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Vita

Author: Edward B. Hogan

Place of Birth: Peekskill, New York

Undergraduate Schools Attended: Eastern Washington University

Degrees Awarded: Bachelor of Science, 2011, Eastern Washington University

Honors and Awards: Graduate Assistantship, Computer Science Department, Eastern Washington University, 2011-2013

Graduated Cum Laude, Eastern Washington University, 2011