Design and Manufacture of an EAP-activated Microscalpel System: An Interdisciplinary Capstone Project

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Abstract

This paper presents an interdisciplinary capstone project in which students expand their academic knowledge and research experience to other disciplines. Throughout this capstone project, the students realize the importance of interdisciplinary work, as well as explore fields of study that are not included in their regular curriculum. Faculty worked with students to develop a streamlined approach to their problem so that the students could swiftly achieve their educational goals and efficiently accomplish better outcomes in their design. In addition, the students were expected to obtain interdisciplinary research experiences, including new emerging technologies in electronics, materials, and micro/nano areas. The main objective of this project was the design and fabrication of a microsurgery device that allows surgeons to remotely remove diseased cells. A microscalpel device in conjunction with electroactive polymer (EAP) has been implemented as a case study. Students learned and practiced their knowledge and skills: to identify design constraints; to implement software and hardware components in their design; and finally to integrate, test and optimize their design. Students also demonstrated their design and shared their experiences with students in other teams. Unlike traditional robotic projects, students investigated various topics that they have not been exposed to before. Their research and design work was closely advised and reviewed by faculty until they successfully completed the project. The goal of this paper is to discuss the EAP project and its results.

Introduction

Electroactive polymers (EAP) are polymers whose shape can be manipulated when a voltage is applied. EAPs [1] have been around since the early 1990's but the concept was introduced in the early 1880's by Wilhelm Roentgen, who observed a length change in a loaded rubber band by applying an electric field. Since then, it has been discovered that EAPs can be used as an actuators where the shape of the device can be deformed and sustained. Research on EAPs as biometric actuators [2] has been increasing over the past fifteen years. One application that is actively being researched is the use of EAPs to create a microscalpel for cutting microsamples.

The current processes for cutting microscopic samples are long and tedious, often resulting in poor quality samples. Any small mistake in the cutting procedure can result in the loss of several hours of work. Researchers are currently looking for methods to improve this process. With the

EAP microscalpel, this lengthy process can be greatly reduced, resulting in technological breakthroughs that can also have benefits in the area of microsurgery.

A potential solution to this problem was proposed as a capstone senior design project. Students, under the guidance of faculty, designed, implemented and demonstrated an EAP-based scalpel. The solution included a small EAP scalpel interfaced to a joystick that could be used for three-dimensional movement and cutting action control. As a safety feature in the system, sensors, including a strain gauge, were integrated to protect the delicate cutting device. A field-programmable gate array (FPGA) [3] was employed to rapidly implement necessary circuitry for the precise operation of the entire system. This flexible FPGA-based implementation is also beneficial because it provides for simple, continuous upgrade of the current system. The remote EAP microscalpel system, therefore, provides accuracy and speed in operation, as well as offering the opportunity for rapid modification, so that researchers can create different applications on the system with minor changes.

Background and impact of this capstone project are briefly described. Additional EAP related information, that includes EAP terminology, different kinds of EAPS, and potential EAP applications, is also given. Other subjects, such as FPGA and sensors, are also discussed in order to explain the research carried out in this project. The students' interdisciplinary experience is presented with outcomes of their design and implementation. In addition, the students' verification work and their evaluation results are explained with detail results collected throughout the project. Conclusions and future directions for this work including a plan for the continuing upgrade of the remote EAP microscalpel system are addressed.

Electroactive Polymer (EAP)

EAPs are a type of polymer that reacts to electrical stimulation. They are usually created in strips of polymer about a centimeter wide and a couple of centimeters in length. The most recent EAP technology now allows for the production of larger size EAPs. An EAP device can be used as a mechanical actuator or as a sensor. If the device responds to an electrical signal through deformation it is considered a mechanical actuator. An EAP sensor generates an electrical signal based on mechanical deformation [4]. EAPs are being researched for use as artificial muscles for medical applications. One area of National Aeronautics and Space Administration (NASA) research on EAPs is as a replacement for heavy, high-power actuators being used on the space shuttles [5]. EAP sensors are also used as Braille readers, and strain and pressure sensors.

EAPs are usually classified as electronic or ionic EAPs. An electronic EAP is deformed by supplying electrostatic forces generated with a large actuation voltage. Electronic EAPs retain their deformation once the actuation voltage is removed. In contrast, an ionic EAP is operated by moving ions in the EAP. Because this ionic EAP movement is caused by motion and concentration of hydroxide ions, efficient operation requires a high humidity environment. In addition, the polymer should be wet. The EAP deformation, including bending and linear dilation such as stretching and compression, depends on the molecular arrangement during fabrication. Figure 1 illustrates examples of the EAP deformation.

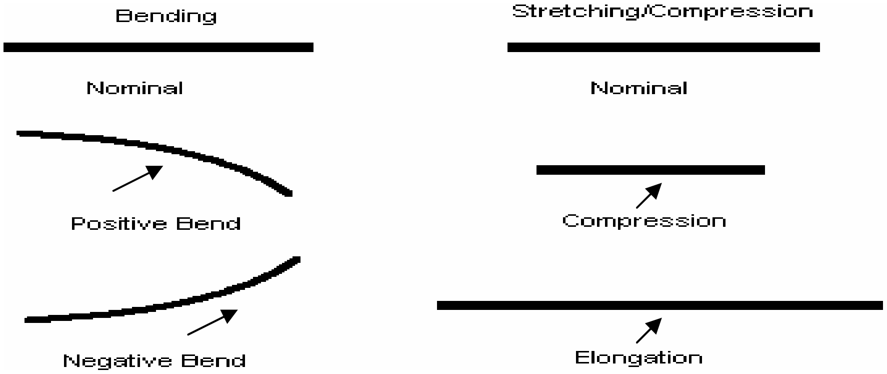

Figure 1 – EAP Deformation Examples: Bending (positive and negative) and Stretching (Elongation)/Compression

An ionic EAP was chosen for the remote EAP microscalpel capstone project. The ionic EAP is constructed by a conductive polymer, such as polypyrrole or polyanaline. It is encased in an ionic polymer metal composite (IPMC) protective coating like sodium dodecyl benzene sulfonate [6, 7]. Figure 2 shows an EAP deformation example where an initial EAP configuration is changed by supplying voltage. The supplied electricity flows from the anode (+) to the cathode (-) on the opposite side of the conductive coating. As a result, a deformation is created by moving ions in the polymer. To understand this, one must consider that the polymer contains positively charged Sodium or Lithium ions with water (H_2O) initially. Diffusing the positive ions in the EAP towards the negative cathode causes the EAP to locally be swollen. The stationary negative ions are pulled towards the anode. This reaction results in the EAP deformation. This bending movement can be similar to the slicing motion of a scalpel if a blade is attached to the other side of the polymer. Consequently, the cutting motion can be controlled by applying different the voltages to the EAP.

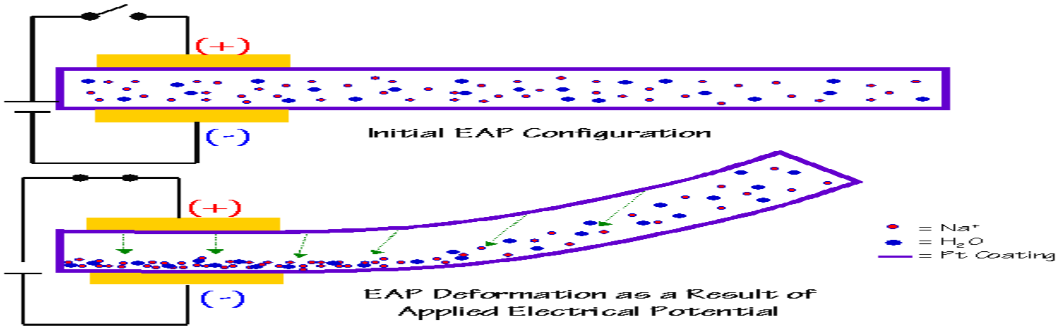

Figure 1– EAP Voltage Reaction: The conductive layer was coated along the entire EAP sample [8]

EAP Deflection and Response Time

The EAP samples used in this project were supplied by Environmental Robots Inc. [9]. The sample EAPs were deformed by supplying voltages from approximately 1 V to 3.5 V. Deflection varies linearly at low applied voltages less than 1 V. Nonlinear EAP deflection, however, was observed at higher voltages. As seen in Figure 3, the sample EAP was less deflected if the EAPs were immersed in water rather than in air, however, the EAP deflection in water was more consistent than in air. For example, the electromechanical response did not significantly change over a twenty to thirty minute period. In contrast, the EAP performance in air decreased over that same period of time. In order to achieve constancy in the research, the EAP was re-wetted every three to five minutes.

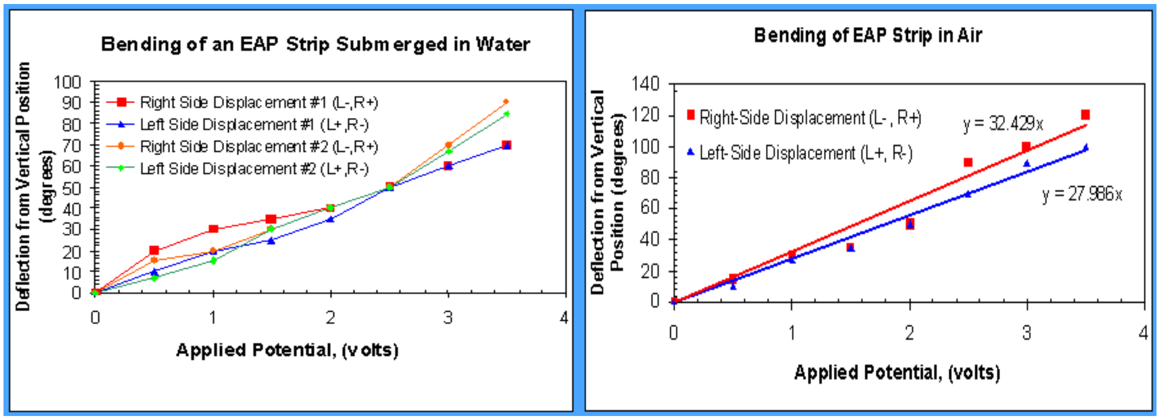

Figure 2 – EAP Bending Reactions (Deflection and Response Time) in Water and Air with Different Voltages [8]

The EAP response time [10] was measured as the time difference between the time an EAP strip started to deform and the time the EAP deformation was saturated. From this, the speed (or rate) of deformation was evaluated in terms of degrees of deflection/second. The EAP deformation is controlled by attracting the positive counter ions to the negative electrode (cathode). Because this attractive force increases with increasing applied voltage, the EAP strip bending speed increased with increasing voltage. For the EAP strip measured in Figure 3, the deformation speed increased with the applied voltage up to about 7 degrees per second; however, the deflection speed increase was progressively less as the applied voltage increased above 1.5 V.

EAP Electrical Resistance and Lift/Strength

Measuring the electrical resistance of the EAP strip is typically performed in the middle and near the edges of the EPA strip. As described, evaporating water from the EAP strip causes a slowing down of the electro-mechanical response. In other words, the electrical resistance of the EAP is increased until the strip is wetted again. Because the water in the region held by the electrodes in the EAP is “squeezed” out when it is exposed to air, the EAP resistance increases. Subsequent water evaporation from the electrode area, already depleted of water, eventually causes an EAP resistance “disruption,” because of loss of mobile water. Consequently, the mobility of counter ions inside the strip, near the electrodes, is virtually eliminated. As time progresses, the water squeezed away from the compressed electrode region diffuses back to the region. This phenomenon is explained in Figure 4 (a). This restoration process of the counter ions bring an increase in the mobility of the water explaining the slight decline of the EAP resistance observed after the resistance disruption.

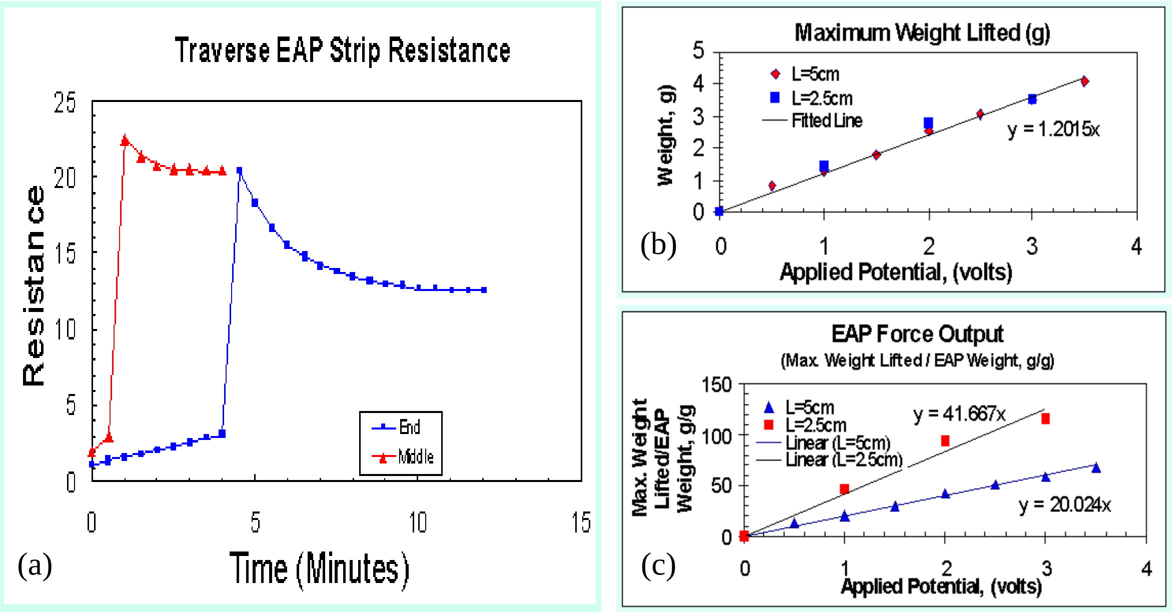

Figure 4 - Traverse EAP Strip Resistance (a) and EAP Force Output (b) and (c) [8]

The mechanical performance of an EAP strip is an important factor for robotics, artificial muscles and actuator applications [11, 12]. In general, the maximum lifting ability of an EAP strip is linearly proportional to the applied voltage for the same weight lifted. Figure 4 (b) shows a rate of about 1.2 gram per volt. If the EAP strip length is shorten by half, the supply voltage must be doubled in order to maintain the same maximum weight lifting capability. Thus, the flexural strength of a shorter strip is greater, although the extent of deflection is smaller, as seen in Figure 4 (c).

A Capstone Project: Design and Manufacture of an EAP Microscalpel System

The capstone design course, ENTC 420, requires students to design and implement a system that effectively reflects on students' research, design and implementation experiences throughout their academic career. The course typically involves teams of three to four students who have previously developed a project proposal, a tracking plan, and a preliminary design through the semester-long project management course, ENTC 419. The students then submit their final proposal at the beginning of the ENTC 420 course. If the final proposal is approved, the team proceeds with implementation and present weekly project status reports and discuss their progress and challenges. Finally, students are required to complete a final report and project demonstration. At the final presentation, they present their project experience to the faculty and industrial advisory board members and other students. The capstone project, "Design and Manufacture of an EAP Microscalpel System" was performed during the Fall of 2005 and the Spring of 2006 academic periods consecutively.

In this project, three students in the Electronics and Telecommunications Engineering Technology programs researched subjects related to electronics, mechanical and manufacturing engineering under the supervision of a faculty project advisor and a faculty project sponsor. In addition, the students were advised about issues on their design, implementation, and verification including the analysis of their outcomes by both the project advisor and the project sponsor. The project team also received valuable feedback and comments on their design and presentation.

Design of an EAP Microscalpel System

The design process for the EAP microscalpel system consists of two main sections. The first deals with both the manufacturing of the final housing. The second is the electronic design related to the microscalpel, which includes the sensor circuits design, digital logic design with FPGA, voltage control interface, and printed-circuit board (PCB) board layout. The overall system block diagram is illustrated in Figure 5. Each block will be discussed in detail in the next sections.

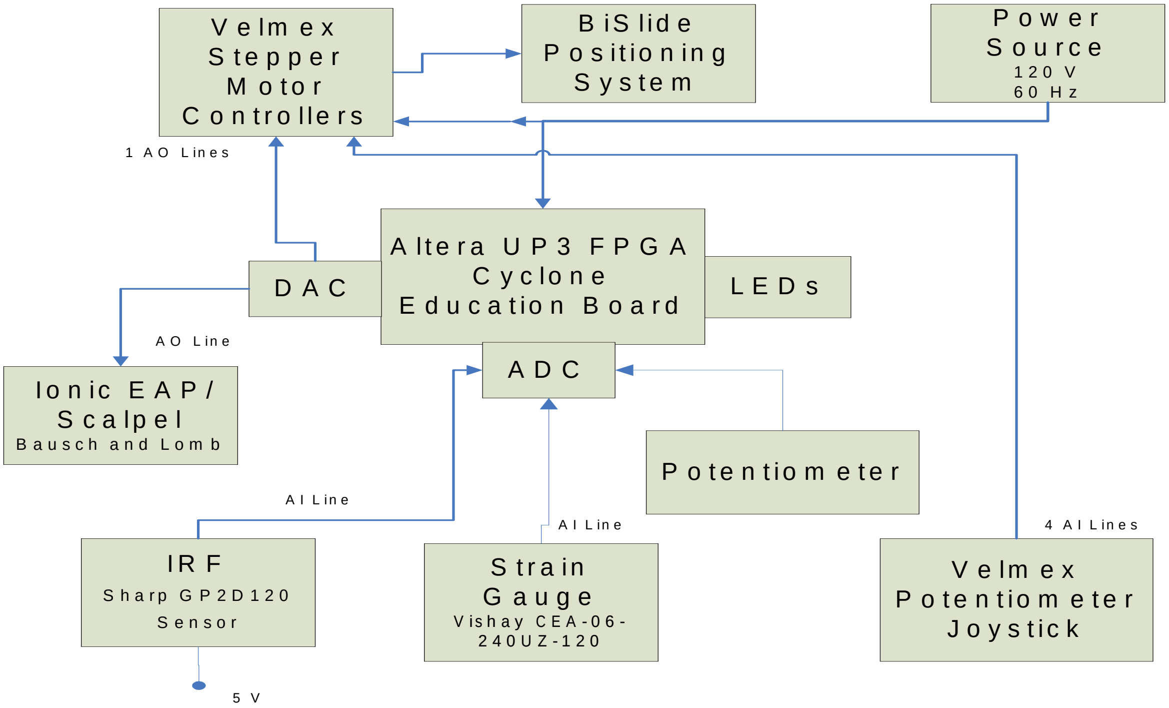

Figure 5 – System Block Diagram of the EAP Microscalpel System [21]

Electronics System Design

The hardware design and implementation of the system is addressed. A rapid hardware system design methodology [13] taught in a previous course (ENTC 249) was used throughout the project. First, the hardware was partitioned based on available hardware resources and time/cost requirements of the system being developed. The hardware development focused on rapid and integration-oriented design [14, 15] using programmable logic arrays. To perform the rapid hardware development, the Verilog hardware description language (HDL) [16] and an educational FPGA board are used as the fundamental building blocks. The hardware blocks were developed according to the system block diagram shown in Figure 5 Those hardware blocks are: (1) data processing, (2) sensor logic and control, and (3) interface blocks. Another important design consideration was the flexibility of the hardware for continuous upgrade and rapid modification for the new applications.

Data Processing

A few design options were reviewed for the data processing block and two were chosen and compared to produce the final design. Those design options were: (1) microcontroller- and (2) FPGA-based designs. While the microcontroller-based design was originally preferred because the students had previous experience with Freescale MC68332 [17], an FPGA-based approach was suggested by the faculty advisor. This was because an FPGA had the resources necessary to handle the required processing operations. In addition, it provided other advantages such as the flexibility to support frequent design changes and a design tool to facilitate prototyping. A final benefit of the FPGA-based design was the support for continuous design upgrade and modification without the need to change physical design components. One disadvantage to the FPGA-based approach was that the FPGA available for the project dealt with only digital signals while most microcontrollers are capable of dealing with both the analog and digital signals necessary for the data processing block. This was easily solved using an analog-to-digital converter (ADC) and a digital-to-analog converter (DAC). Although the students were less familiar with FPGAs than with microcontrollers, they quickly saw the benefits of the FPGA approach and decided to work in that direction. The Altera UP3 Cyclone FPGA [18] shown in Figure 6 was chosen for this project due to the following features: data processing power (Cyclone on-board memory (e.g., Flash/SRAM)), various interfaces (e.g., serial/parallel ports, digital signal connectors), and ease-of-use (e.g., power supply - 3.3 and 5 volts, Quartus II simulation/programming).

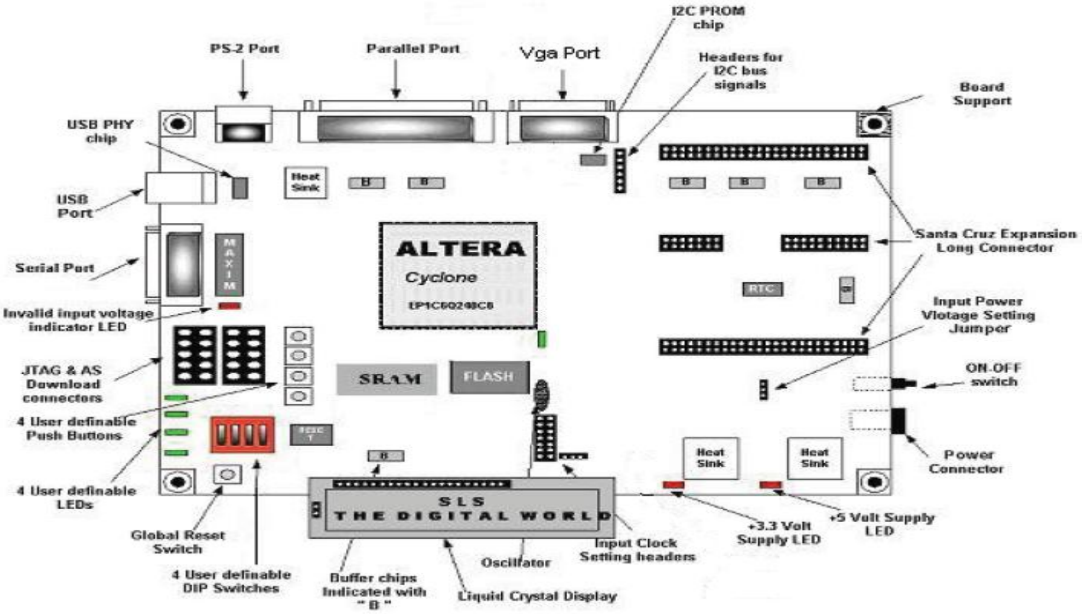

Figure 6 - Altera Cyclone FPGA Education Board [18]

Sensors and Signal Conversions

Different kinds of sensors were used in the EAP microscalpel system. To start, the design requirements for the sensors were determined. One of the requirements was to sense a very short distance, on the order of millimeters. Several different sensor technologies including sonar range finders (SRF), infrared range finders (IRF), and laser range finders (LRF), were reviewed as potential solutions. Due to students' previous experience, they originally chose to use a sonar sensor. However, based on range of their measurements, they eventually migrated to an IRF sensor (Sharp, GP2D120). Also, in order to create a precise incision, a second requirement was to measure the force on the microscalpel. This measurement would also prevent damage to the delicate microscalpel during implementation and testing. For this sensor, the students chose to use a strain gauge (Vishay, CEA-06-240UZ-120).

Because an integrated solution for the IRF range finder was used, it did not need to be signal conditioned. Its signal was sent directly to the ADC0804 [19] to be digitized. The signal conditioning circuit for the strain gauge consisted of several phases which included a voltage divider, a buffer, a Wheatstone bridge, and an instrumentation amplifier with a gain of 100. The final stage of the strain gauge circuit required the use of another amplifier with a gain of 46 in order to meet the signal range of the ADC. The voltage leading to the EAP was controlled through a voltage divider, using on fixed resistor and a potentiometer. When the potentiometer was turned the voltage divider adjusted the input 5 V to a smaller voltage value which was processed through the ADC and sent to the FPGA. This in turn controlled the output to the DAC and finally to the EAP. This voltage created the necessary bend in the EAP to create the cutting motion.

Mechanical and Manufacturing System Design

Stepper motors that allow multiple degrees of freedom were used to control and position the end-effector of the system. BiSlide positioning stepper motors (Figure 7-a) were available for this project, driven by a Velmex motor controller (Figure 7-b). An analog three-axis joystick (Figure 7-c) was used with the Velmex motor controller to provide user control of the BiSlide positioning system.

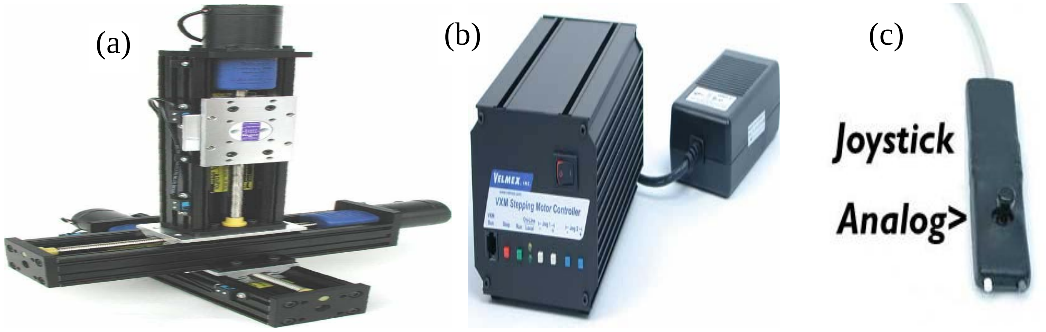

Figure 7 - BiSlide Positioning System (a), Velmex Stepper Motor Controller (b), and Three Axis Analog Joystick (c) [21]

Housing/Attachments

A variety of ideas were brainstormed for the attachment and housing portions of the EAP microscalpel. An attachment holder was designed and fabricated using a rapid prototyping machine. Students used the Inventor software to create 3-D solid model and generated a stereo-lithography file for fabrication. As for the housing of the EAP microscalpel, several different designs were developed. The enclosure needed to house the FPGA, the PCB and all signal conditioning circuitry. The final design involved an 8” x 6” x 2” project box. The housing, PCB, and FPGA were connected with mechanical fasteners. Plastic spacers were used between the components to reduce the chance of unintentional connections or circuits be created. The housing and its integration are illustrated in Figure 8.

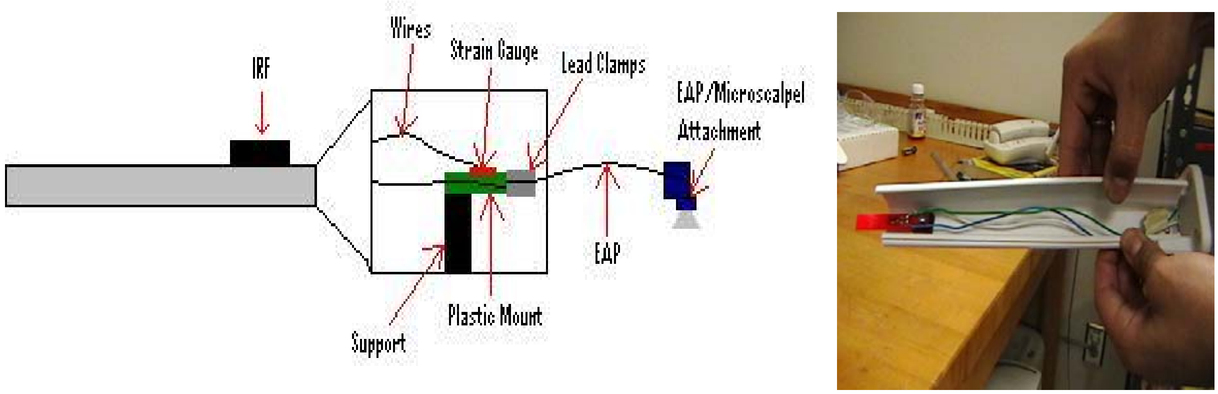

Figure 8 - Housing and its Integration [21]

The potentiometer and LED's were mounted on the lid of the housing for easy access and visibility and the entire housing apparatus attached to the BiSlide positioning system. This allowed the user to move the scalpel to the desired position with the use of a joystick interface. The joystick allowed up to four-axis movement and was controlled by a push button to switch between the motors. The housing was made up of a hollow plastic tube, which held the wires, infrared range finder, and the strain gauge. The EAP attached to a plastic strip mounted to the plastic tube. The plastic strip had the strain gauge on it to determine if too much pressure was being put on the microscalpel. The plastic strip had clamps at the end of it that held the positive and negative terminals which delivered the voltage to manipulate the cutting motion of EAP.

Design of the EAP Microscalpel System: Integration

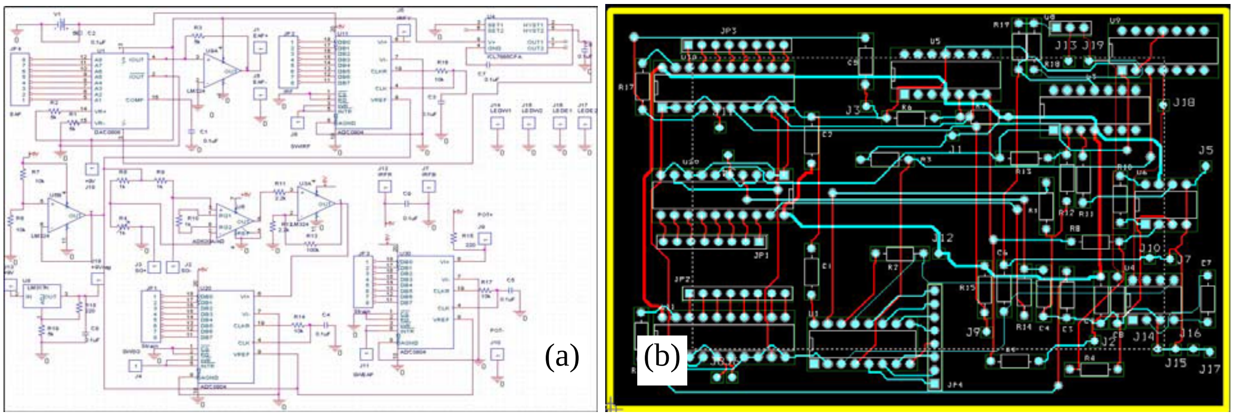

Figure 9 - PCB Schematic (a) and Layout (b) [21]

The prototype board, as seen in Figure 9, was designed using a combination of Orcade Capture and Layout. The software portion of the project dealt primarily with the hardware specification created in Verilog HDL and programmed into the FPGA. Each input signal was assigned a specific pin on the UP3 education board. The input signals held the values from the ADC which digitized the voltages sent from the sensors and from the potentiometer input. Each digital signal corresponded to a specific analog voltage. The FPGA outputs were used to drive the EAP control DAC, the warning and danger LEDs, the start-of-conversion pulse for the ADCs and the stop signal for the positioning system.

Rapid Hardware Prototyping with Verilog HDL

The actual coding process first dealt with declaring all ports used on FPGA. Next, each port had to be declared as an input or output. Several registers needed to be declared in order to process specific values. There were several assignments made in the beginning of the code to initialize output pins. The value of the "RFWarn" output was then set based on the distance between the EAP and sample substrate. The "SGwarn" output worked the same way except the values corresponded to a warning value from the strain gauge. The "RFWarn" output also automatically stops the motion of the EAP.

Table 1 - Voltage Mapping for FPGA Implementation

Digitized Voltage Inputs	**Output Voltage to EAP (V)**	**Digitized Voltage Inputs**	**Output Voltage to EAP (V)**
0000	**0**	**1000**	**4**
0010	**1**	**1001**	**4.5**
0011	**1.5**	**1010**	**5**
0100	**2**	**1011**	**5.5**
0101	**2.5**	**1111**	**6**
0110	**3**	**others**	**Undefined**

Several output signals were assigned to values in registers since these values were continuously changed, including the output signals to the EAP and an initial start-of-conversion pulse to the ADCs. The data processing was executed on the positive clock edge. Initial values to ADCs were sent by setting a flag. Then, the movement of EAP was controlled based on the position sensed. Finally, the input voltages from the voltage dial were mapped to specific values for the EAP. There were 10 set positions on the voltage dial. Each change in position incremented the voltage. The mapping of the input voltage of the dial to the output voltage to the EAP is seen in Table 1.

EAP/Scalpel Interfaces

The project required a blade to be attached to the EAP for performing the cutting motion. Several possible ideas were developed for this attachment. The three dimensional rendering of the final design is shown in Figure 10 (a). The design allowed for replication of the drawing with exact dimensions using a rapid prototyping machine. The two pieces were constructed; a top and a bottom, and both were built from bottom to top. The final object was very similar to the initial drawing and was made with sufficient resolution/tolerance. Figure 10 (b) and (c) show the final prototype attached to the scalpel and to the EAP.

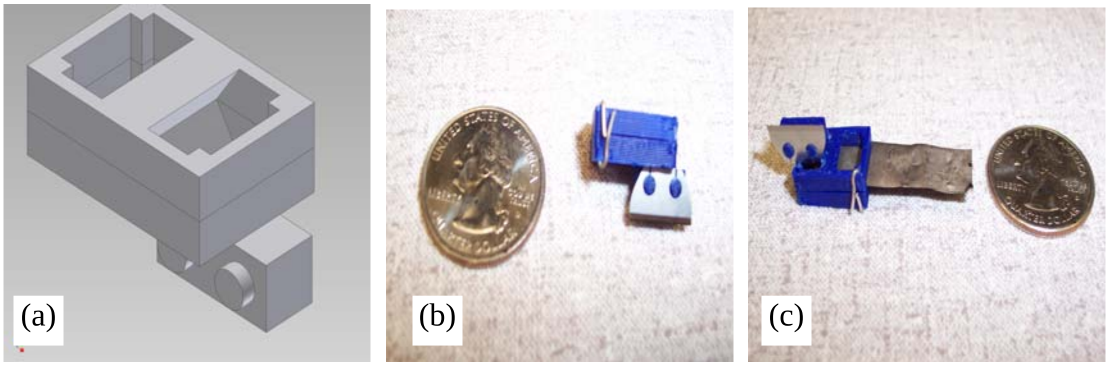

Figure 10 - 3D Model for Scalpel Adaptor (a), Microscalpel Attachment Prototype (b) and Microscalpel Attachment Prototype with EAP (c) [21]

The EAP strip was then connected to lead clamps as shown in Figure 11 (a). These clamps had a conductive metal which provided the voltages sent from the DAC. A DAC 0808 [20] was used in this project to convert the digital signal from the FPGA to an analog voltage that actuated the movement of the EAP for a cutting motion. The output of the DAC was sent to a current-to-voltage converter. Figure 11 (b) shows the DAC circuit.

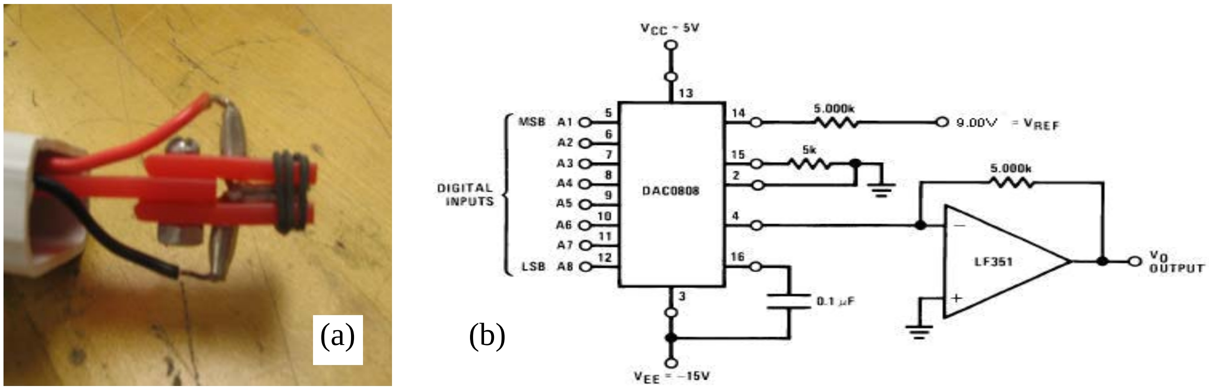

Figure 11 - Lead Clamps (a) and DAC Layout (b) [21]

System Verification and Outcome Evaluation

The overall system testing of the EAP microscalpel was done using food samples that resembled human tissues. This included the use of sugar-free Jell-o and Vienna sausages. Each article was placed on a platform under the microscope while the EAP material was soaked in water. First, testing of the positioning system was completed through the use of the analog joystick; all motors were tested on each axis to make sure desired movement was achieved. The infrared range finder was incorporated into the test to make sure that both the warning level and danger level could be detected. The next testing aspect of the EAP microscalpel was the actual cutting of the tissue-like material. The set voltage for the EAP was controlled through the use of a voltage dial and then the EAP was controlled by the FPGA/DAC to cut the material. If too much force was exerted on the EAP, the strain gauge detected this and shutoff the EAP controlling voltage.

The testing phase was a very in-depth process due to the nature of the application and the EAP characterization was one of the main objectives of this project. There were also a number of components that had to be integrated together requiring functionality, characterization and durability testing. The functionality of the EAP was another main concern for the project, and as such, the EAP voltage to degree-of-deformation characterization was a critical component. Other tests were created to evaluate the performance of the entire system. Repeatability and accuracy were also verified with overall system testing by iterating the test procedures with different inputs.

EAP Characterization and Results

The EAP needs to produce a repeatable movement each time a given voltage is applied. The team needed to characterize the EAP in order to understand what level of movement accuracy was possible. The characterization test involved soaking the EAP in water for a set time and then connecting it to 0 – 3 V signal. Voltages were applied at 5-minute intervals to test how long the EAP could function without rewetting. The different types of water (e.g., salt water, distilled water, and tap water) were also tested to see if it had a noticeable effect on the EAP movement. Salt water and distilled water appeared to have the worst results, only allowing 1 mm of movement when 3 Volts were applied. The tap water had the best results. The actual data from the tap water-based EAP characterization are summarized in Table 2.

Table 2 - EAP Characterization Results

	4/4/2006	Timeout = 5:37:37		4/6/2005	Timeout = 2:55:45	
EAP Samples	**#1**	**#2**	**#3**	**#1**	**#2**	**#3**
Voltage Range 0-3V	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
Time	3:54:45	3:55:45	3:56:45	2:57:25	2:59:35	3:00:20
Movement	2mm	3mm	2mm	2mm	3mm	2mm
Time (10 min)	4:00:00	4:01:00	4:02:00	3:05:07	3:06:15	3:07:10
Movement	4mm	3mm	5mm	3mm	3mm	3mm
Time (20 min)	4:10:35	4:11:35	4:12:35	3:15:30	3:16:05	3:16:40
Movement	2mm	2mm	2mm	2mm	3mm	2mm
Time (30 min)	4:20:35	4:21:35	4:22:35	3:25:25	3:25:50	3:26:10
Movement	2mm	1mm	2mm	2mm	1mm	1mm

Three EAP samples were characterized under the same test condition. The test process consists of first soaking EAP in tap water for an extended period of time, from 15 minutes to a few hours. The EAP was removed from the water and allowed to dry. The EAP was placed into the lead clamps after dried. A voltage varying between 0 – 3 Volts was applied to it. The EAP movement was measured from the tip of the EAP to a point below the initial position. This displacement was recorded for several trials at different times. The trials were repeated 10, 20, and 30 minutes after the EAP was initially taken out of the water. This test was repeated for three days. The best response from the EAP was found to be after it was removed from the water for 10 minutes. The displacement averaged 3.2 mm of movement when 3 Volts were applied. As seen in Figure 12, evaluation was based on the fact that the 10 minute data most closely related 1mm of movement to 1V increment.

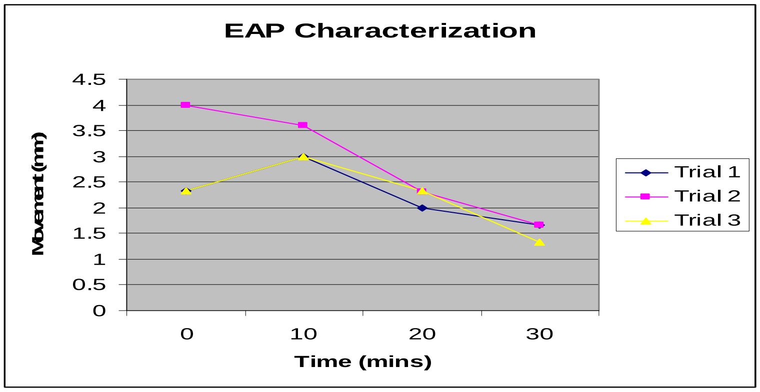

Figure 12 - EAP Characterization [21]

Simulation and Verification of Hardware

Verilog code was developed and compiled with Altera Quartus. The first test was to make sure the FPGA was properly initialized with the other circuitry. The next test was to verify functionality between input and output signals. For example, a warning level was posted on the rangefinder inputs and the value of the output port was examined. The danger level was then tested by collecting signals from the positioning system. Figure 13 illustrates the simulation result of these tests.

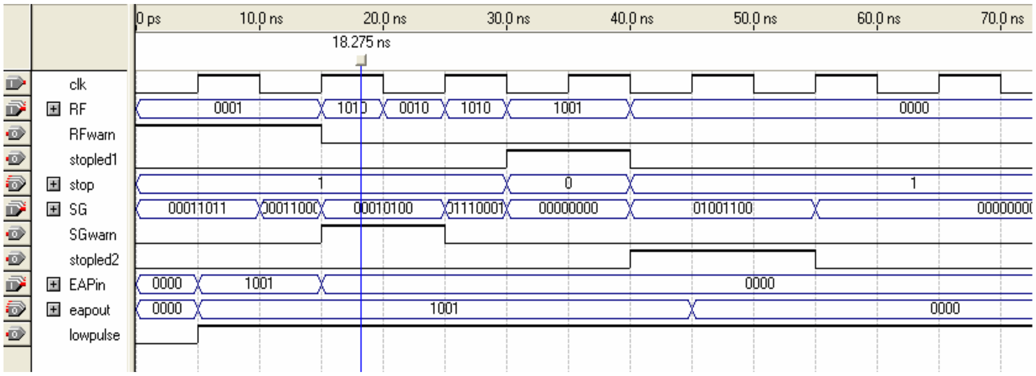

Figure 13 – Simulation of Hardware in FPGA [21]

Next, individual hardware components were tested. Interface of the FPGA was verified by using external LEDs and Verilog testbenches. The infrared range finder was tested for functionality by measuring the voltage from the sensor as the distance between a test surface and the range finder was changed. To test and characterize the ADC and DAC, National Instruments LabView and an EAQ6251 DAQ data acquisition board was used. Eight-bit data was input to the DAC and the output voltage was measured. To characterize the ADC, analog voltages were sent from the data acquisition board to the ADC and the device transfer function was measured. Finally, the voltage dial was tested by taking voltage readings for different resistance values of the potentiometer.

Conclusion

The EAP Microscalpel project was a very interesting, interdisciplinary project. All aspects originally defined in the scope of the project were successfully completed by the student team. This project required that the students use all of the knowledge they had acquired through the Electronics/Telecommunications curriculum while expanding the students' knowledge of mechanical and manufacturing engineering. The students also had opportunities to interact with other students and faculty in other departments throughout the project period. A better understanding of new technologies was also gained from working with a fairly new application of the electro-active polymer. The team also gained valuable experience in teamwork and communications skills. A closer relationship between faculty in the Electronics and Mechanical/Manufacturing Engineering Technology programs was also developed. Being able to provide intricate electrical schematics and design, as well as building physical attachments for the EAP is a perfect example of this relationship. Finally, as mentioned previously, significant assistance was provided by faculty and staff in each program creating future opportunities to integrate the different curricula.

Acknowledgement

This project was done by three electronics and telecommunications engineering technology students, Daniel McReynolds, Sarah Perez, and Jack Culberson. The authors would like to thank the Mechanical Engineering Department at Texas A&M University for use of their rapid prototyping system and the student team for the diligent efforts required to successfully complete this project.

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