An Educational and Entertaining Senior Capstone Design

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Abstract

The renovation of Lucas County's Winter Wonderland Christmas exhibit presented a unique opportunity for students to become involved and use their knowledge to design new displays. The project presented herein represents an ideal learning experience. It was an occasion for students to have fun, while demonstrating their technical knowledge. At the same time, students experienced some of the more gratifying aspects of community service. Instead of demonstrating an abstract model that served no purpose after project completion, students worked on something that had a viable purpose. The idea here was to design, build and troubleshoot a fully functional, interactive robotic exhibit intended to become part of a permanent display in a community holiday venue to be visited by several thousand children annually. To achieve this goal, students created an animated, life-sized, friendly "monster" that surprised his visitors after pulling aside a huge tree. Servos, controlled by a basic stamp, were used to operate the snowman. To make these movements look realistic to observers, a serial servo controller, with built in ramping functions was used in combination with the stamp. The entire operation is triggered by a motion sensor implanted in the tree. To project his voice, a sound card combined with an audio amplifier was used in conjunction with powerful speakers placed inside the monster's body. The project was completed successfully and gained a great deal of attention at the University of Toledo, 2004 college of engineering expo. The display also opened to rave reviews at the Children's Wonderland Exhibit, its permanent home. A sample of these reviews is presented in this paper.

I. Introduction

The principal purpose of a Capstone project is to give graduating senior students the opportunity to demonstrate their understanding of the concepts they have learned during the course of their studies. It is supposed to give students the chance to "put it all together", to make applicable use of conceptual information. A successful Capstone project should help students develop the resources they will need to make the transition from college to career. Students are required to design, build, troubleshoot and finally present their project in a professional manner. The most notable significance of this project should be to give the students self-confidence in their abilities to utilize their education to succeed in the job market. The project described in this paper not only achieves these objectives amply, but allows them to have fun doing it.

The snowman project is unlike others in that it is both a senior design project and a community service endeavor. Beyond being an arbitrary school assignment, this project accomplished an actual purpose. Community service is an important aspiration for people in any profession**.** When the Lucas County Recreation Center expressed a need for new animated exhibits for the community's annual holiday winter wonderland display, my students were presented with a unique opportunity to utilize their technical expertise to complete a senior design project, while at the same time serving the community's need. Children's Wonderland is an annual community holiday exhibition, which is visited by thousands of children each year.

Students taking the Capstone course are expected to use the knowledge acquired through their years of study, to develop a Capstone project. The abominable snowman project achieved this purpose. Students taking the Automatic controls course[1] learn about control systems, their basic components and how to interface these components. Also, through the course of their studies, students learn computer programming skills using different languages such as BASIC, Assembly and C[2]. In Electronics courses[3], students learn about audio amplifiers and electronic switches. In Digital System Design[4], students are taught how to interface digital components and how to connect them together. The knowledge the students accrued in these classes proved invaluable in achieving their Capstone goals. This project allowed students to gain a certain degree of realistic experience, by integrating all of their educational experience into a valid, practical and business-like endeavor. This kind of technical and functional experience prior to graduation, serves to give students a valuable opportunity to put academic principles into practice. They develop self-confidence in their capability to function and be successful in a competitive job market.

It is vital that technology students learn the value and necessity of teamwork. Being able to function well as part of a team is essential in any technological field. Therefore, in the technology program at The University of Toledo, each major course has a laboratory attached to it. Students in these courses gain the experience of working with a team to achieve the lab objectives. That experience proved to be a valuable asset when it came to accomplishing the Capstone project. Students were required to function as a team in a proficient manner in order to execute each and every aspect of this project. This allowed them to share ideas and skills and to examine each others strengths and weaknesses as well as the importance of delegating responsibility accordingly. Students shared responsibility for everything from establishing the parameters of the project, through the completion and public unveiling of their work. They created the animated display conforming to project specifications. It had to be cost effective and completed on time in a proficient manner. Students were required to give periodic reports and presentations on their progress just as they might be in the real job world. Students were accountable to their advisors, their clients and their colleagues just as they would be in their professions. This experience helps to boost the students' confidence in their professional abilities.

II. The Abominable Snowman

The object of this project was to design and build an animatronics snowman to capture the attention of the kids visiting the Children's Wonderland. This was achieved by creating an animated, life-sized, friendly "monster" to surprise the visitors. The snowman had to be scary and amusing at the same time. Its behavior had to be established through a series of pre-designed functions. The first step in the design process was a brainstorming session to establish the scope of these functions. This phase was very important because it established the parameters for the project. Once the students decided that the snowman would incorporate both motion and speech, the next step was to determine the scope and logical order of these functions. First, when motion (a child approaching) is detected, the abominable snowman, who is hiding behind a large Christmas tree, pushes the tree aside, revealing himself and startling guests. Then, the scary creature looks around, ostensibly, seeking out the victim. Suddenly, he raises his arm in a threatening manner. Then, his demeanor changes and he waves. Simultaneously, the snowman speaks! He cheerfully greets his audience, transforming at once into a lovable friend. A complete flowchart of the scope of the project is given in Figure 1.

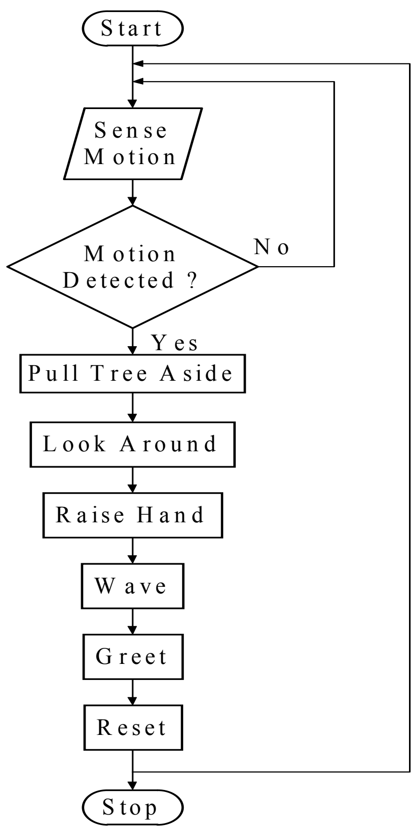

Figure 1. System Flowchart

Once the scope of the functions and their order was determined, the next step was implementation. To coordinate all the functions, a microcontroller was needed. This controller is the brain of the operation. It determines what functions are performed and when. In the automatic control course, students learned about control systems and their components. They learned about controllers, processes, servos and sensors and how they interact together to achieve a desired outcome. Using their knowledge from this course, students had to design a block diagram representing the entire system. This block diagram had to show all of the different functions and how they were achieved. A block diagram representing the proposed project is given in Figure 2.

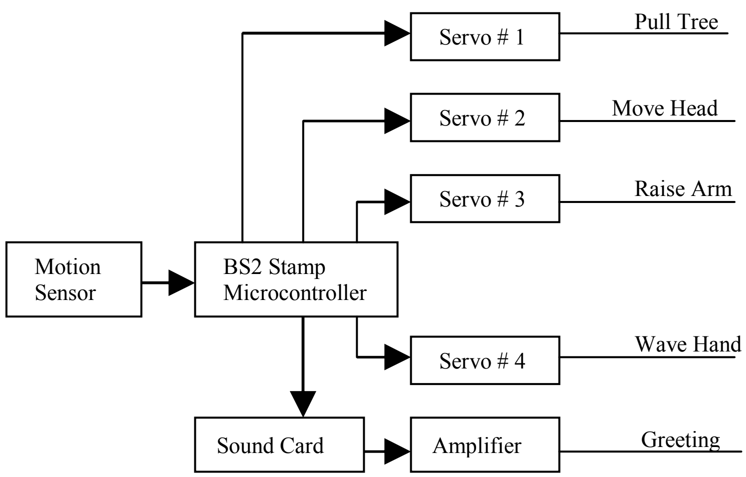

Figure 2. System Block Diagram

Students were to select, design and build each of these components based on the required specifications. They then assembled the components to form the entire system as shown in Figure 2. Implementation of the proposed project was to be carried out in two parts, hardware and software. The team was divided into two groups. The first group was responsible for the hardware implementation which included building the snowman. The second group was responsible for creating the software needed to program the snowman. The project was completed as follows:

III. Hardware

3.1 The Snowman

The snowman's body had to be built sturdily, but also had to permit easy movement at the joints. It had to be realistic looking. He would be something of a cross between Sully from the movie "Monsters Inc." and Bumble from the Christmas special "Rudolph the red nose reindeer". The outside shell was built using paper machete and chicken wire. It was built in two pieces, a front and a back to allow easy access to the inside. This body was mounted onto a metal skeleton made from metal corner brackets. The corner brackets were strong enough to be used as a simple, easily assembled, alternative to a welded frame. After the internal framing was complete, the two body pieces were stapled together. To avoid placing excess weight on the servo, the head was mounted on a ball bearing plate. The servo was then bolted to the metal frame and linked to the ball bearing plate. The remaining servos, one enabling the left arm to pull the tree over, a second to raise and lower the right arm and a third to produce the hand waving motion, were physically powerful enough to avoid the need for additional hardware. Therefore, they were attached directly to the frame and to the components. After assembly, which left all servos exposed to permit future repair access, the body was covered with blue fur to give it a "realistic" look. The fur was attached to the body with hot glue and stitching. Extra care was taken around the moving joints to make sure servos were concealed, but also to avoid hindering joint movements.

The snowman was bolted to the rear of a 4x8 plywood platform equipped with caster wheels. This allowed the entire display to be transported and stored in one piece. To block the snowman from view, an 8ft tall white, artificial Christmas tree was then mounted to the platform in front of the snowman. A hinge was used to allow the snowman to move the tree aside. The weight of the tree was counterbalanced with a spring to allow its return to a standing position with ease.

Figure 3. Snowman's Body

3.2. Tree Servo

The Christmas tree was bolted to the snowman's left hand and a servo was used to connect the left arm to the body. The servo moves the left arm which in turn, pulls the tree aside revealing the snowman. Due to the combined weight of the arm and the tree, a strong servo with a high starting torque was necessary. Also, this display would be required to run 12 hours a day for a month, so the selected servo had to be tough enough to handle the intense usage. After doing some research on the internet, the students decided to use the heavy duty SSPS-105 servo made by Tonagawa Seiko. This is a precision, electro-mechanical servo designed for industrial and special effects robotics. It is well-built and ruggedly designed with an aluminum case, heavy duty gears and stainless steel shaft for performance critical applications. This allows it to function for long hours of intense usage. The servo's compact size allows it to be hidden inside the shoulder performing the task while remaining unseen. Its starting torque of 27.5 ft-lb will easily allow movement of the tree repeatedly without hesitation. It has a range of 180 degrees which is enough to pull the tree aside and back with room to spare. It is a fast acting servo with little delay time, which allows for a quick response once motion is detected. A picture showing the actual servo implementation is show in Figure 4. A complete data sheet of the servo is available on this website[5].

3.3. Arm Raising Servo

A second servo was needed to enable the snowman to raise his right arm to greet people. Due to the heavy weight of the arm, frequent use and durability requirements, another SSPS-105 was used. The high torque of the SSPS-105 was needed to counter the weight of the arm and produce a realistic movement consistently. Another smaller, cheaper servo was tested for the arm, but could not perform reliably over a long period of time. The actual servo is shown in Figure 4.

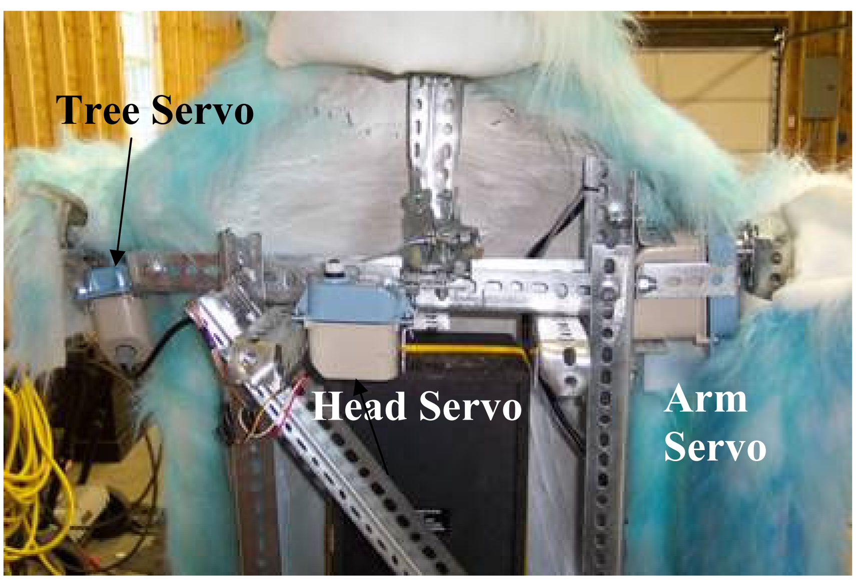

Figure 4. Actual servos placement

3.4. Head Servo

To allow the snowman to look around, a third servo was needed. Because the head was very heavy, it was mounted on a ball-bearing plate to allow free rotation. The servo was then attached through a linkage to move the head as desired. For reliability and performance, a heavy duty PS-050 servo made by Tonegawa Seiko was used. This servo is smaller than the SSPS-105 and was selected because less torque was required to move the head around. This servo is also ruggedly designed and built using an aluminum case and heavy duty gears to provide good performance, over an extended period of time. The SSPS-105 servo has a starting torque of 907 oz-in., which is more than needed to rotate the head. A smaller, cheaper servo could suffice here, but the key again, is durability. The smaller servo would not be able to perform reliably over the long hours for years to come. The actual servo placement is shown in Figure 4 and a detailed specification sheet is available on this website[5].

3.5. Waving Servo

A fourth servo was used to provide the snowman's hand movement. Since the hand was very light, a smaller servo could be used. The hand was connected through a linkage to the shaft of the servo, which was bolted to the frame of the arm. The HS-800BB robotic ball bearing servo offered by Jameco Electronics could be effectively used here. This servo has a starting torque of 161oz–in which was strong enough to wave the hand. Also, it has a range of 180 degrees which was more than adequate to produce the waving motion. Additionally, the servo is small enough to be embedded in the wrist and easily concealed. A complete specification sheet for this servo is offered on the Jameco website[6].

3.6. Pyroelectric Sensor

To give the snowman the ability to see, a pyroelectric sensor module was used. The KC7783 is a complete passive infra-red movement detector module (PIR) which features a pyroelectric detector combined with an infrared fresnal lens and an analog IC, the KC778B, for signal processing. This sensor was developed for human body detection. Its compact size made it ideal for this application because it could be easily hidden in the top of the Christmas tree, giving the snowman "eyes" without being detected. Also, its wide range of 3m enables the snowman to detect approaching people. Another likable feature of this sensor was the ease of implementation. The output could be directly connected to the stamp controller. If needed, output pulse could be easily adjusted by the students to satisfy the specifications of the controller. The sensor can be easily operated from a DC voltage of 5V which was already available for other parts of the project. A detailed specification sheet of this sensor can be found on this website[7].

3.7. Stamp Controller

To coordinate all of the pre-selected functions, a controller was needed. The controller receives a signal from the motion sensors and initiates the series of movements, ending with the greeting, and then resets the snowman to the original position. There are various microcontrollers available on the market which could serve this purpose. The Basic Stamp 2 controller, developed by Parallax, was selected because it was one of the simplest in terms of connecting and programming. It can easily be programmed using a simplified form of the BASIC programming language called PBASIC and servos can be directly connected. Basic Stamp 2 comes with a BASIC interpreter chip, internal memory (RAM and EEPROM), a 5V regulator, a 16 general purpose I/O pins (TTL-Level 0-5V) and a set of built-in commands for Math and I/O operations. The BASIC stamp is fast and capable of running a few thousand instructions per second. The PBASIC program could be written on a laptop or a PC using a Windows editor and then transferred to the Basic Stamp using a serial cable. Once it is in the stamp, the program is stored in the EEPROM. A complete documentation on the stamp is offered on Parallax web site[8].

3.8. Board of Education (BOE)

When used in conjunction with the stamp controller, the BOE can provide the students with an easy way to program and connect the controller. The BOE features a BS2 IC socket, a DB9 programming connector, four servo connectors, 9V battery clips, a barrel connector, a 5V regulator, a power LED and a three position power switch to provide power to the board only, or to the board and the servos. The DB9 connector provides the students with an easy way to communicate with and program the Basic Stamp. The BOE also includes a small breadboard for connecting simple circuits such as the motion sensor switching circuit and LED indicator circuits. To simplify connections, I/O pins P0-P15, and supply pins have connectors adjacent to the bread board. A female 10-pin connector is also available for optional modules which students used to connect the sound AppMod. The combination of the BS2IC and BOE makes it easier for students to program and connect servos and other devices. A complete documentation on the board is offered on Parallax web site[8]

3.9. Servo Controller

Using the combination of the stamp and the BOE, students can control up to four servos. When a servo receives a signal from the controller it moves rapidly from one position to another. In the snowman's case, this would result in unrealistic jerking motions. The snowman's motions should be much more smooth and animal-like. To provide the necessary fine-tuning to the movements a Parallax Servo controller (PSC) was used. The PSC provides the servos with ramping inputs. Students can use one of 63 ramp rates to set the speed for each servo. With PSC ramping, you can tell the servo where to go and how fast to get there. Using the servo controller, up to 16 servos can be controlled simultaneously. When connecting two together, up to 32 servos can be driven at the same time. Also, with the PSC, it was simpler to program the home position of each servo and the return to it. Abundant examples of connecting and programming the PSC are available on the Parallax web site. A complete documentation on the controller is offered on Parallax web site[8]

3.10. Sound Module AppMod

To provide the snowman with speech capability, a sound module was implemented. The sound module AppMod could be easily used in conjunction with BOE and the BS2 IC. The BOE has a 10 pin row connector reserved for the AppMod. Using the stamp, the module could be serially programmed to manually record up to 60 seconds of sound. This could be done as one long message or as several smaller ones to be played together or at different times. Recording of messages could be done locally, using a push button switch, from a microphone or a line in. The sound module has a 1W audio amplifier, a volume control and a speaker on board. The volume provided by the AppMod was not high enough to provide the monster with the desired thunderous sound, so an external amplifier was used to intensify the output of the sound module. A line-out connection on the sound module could be used once the onboard speaker is disconnected. A 30W amplifier kit made by Vellman and supplied by Jameco Electronics could be used to provide a quality stereo sound. This amplifier provided excellent sound quality with low noise and low distortion. This amplifier is a simple circuit designed around a TDA1521 amplifier and comes complete with a rectifier and a smoothing capacitor. A complete specification sheet is given on the Jameco website[7]. A Kenwood speaker was embedded inside the body of the snowman. The combination of the sound module, the amplifier and the speaker provided the snowman with a voice fit for a monster. A complete documentation on the module is offered on Parallax web site[8]

3.11. Power Supply

To satisfy the high current requirement of the strong servos and other devices, a high power, DC supply was needed. The S-320 switching power supply made by Meanwell and distributed by Jameco Electronics was an ideal choice. The power supply which is rated at 12V, 25A and 320 watts was good enough to meet the demands of all of the different parts of the project. The low cost, ruggedly constructed, enclosed power supply, designed with overload protection, auto recovery and cooling fans will perform reliably for long hours and years to come. A complete specification sheet of this power supply is offered on the Jameco website[7].
Another power supply was needed to supply power to the combination of the BOE and sound module. A low current rating power supply can be used here. A regulated table-top 5V DC supply, offered by the local Radio Shack was a good choice.

3.12. Complete System

To start with, the BS2 IC was placed into the stamp socket of the Board of Education. Then, the output of the motion sensor was connected to Pin 0 of the board. Using a three conductor cable, the Parallax Servo Controller was connected to slot 15 on the board as shown in Figure 5. Paying attention to polarity, the 12 V power supply was connected to the servo controller. Next, the four different servos were connected to different channels on the servo controller. The tree servo was connected to channel 1, the arm servo to channel 2, the head servo to channel 14 and the hand servo to channel 15.

Next, the sound module was plugged into the special connector on the board. The line out on the module was connected to the input of the audio amplifier, which was then connected to the speaker. A complete circuit and actual implementation are given in Figure 5 and 6 respectively.

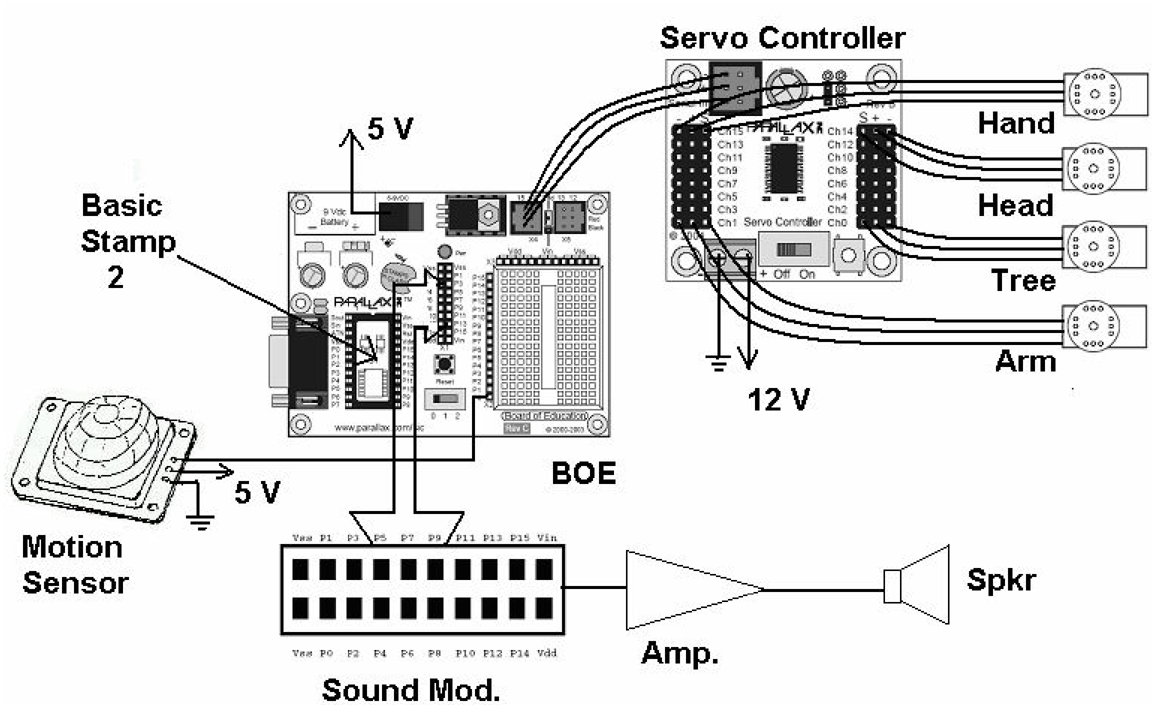

Figure 5. System Circuit

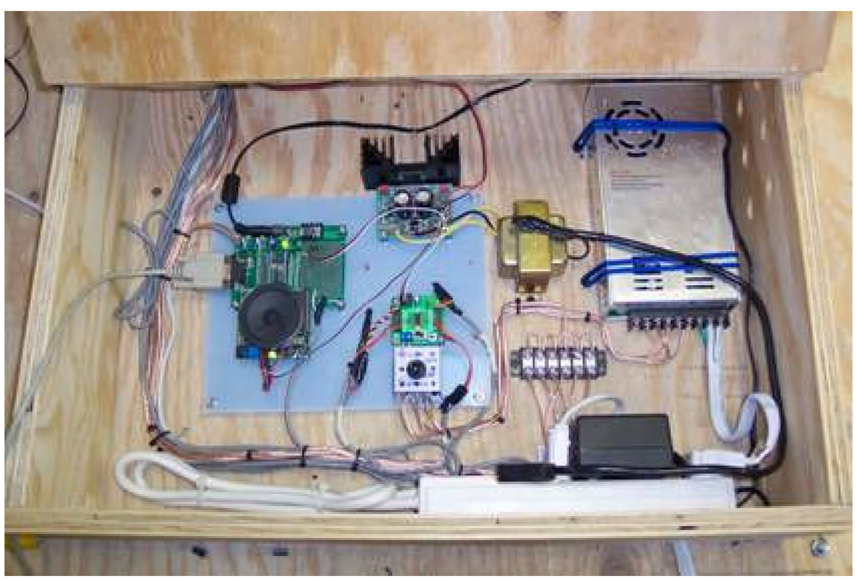

Figure 6. Actual circuit

IV. Software

After all the different parts of the project were assembled, the second phase was to program the stamp controller to perform the diverse functions. This could be done easily by utilizing the stamp editor, which was downloaded free, from the Parallax web site. Using the stamp editor, a PBASIC program could be written on a PC or laptop. After the program was written, it was downloaded to the stamp EEPROM using a serial cable between the computer and the BOE. After loading the program into the stamp memory, it begins execution any time the power is turned on. The stamp memory is a non-volatile one, which keeps the program intact even when power is turned off. The program can be easily changed by changing the code. The stamp memory has 2K bytes of program storage, which is enough for 500 to 600 lines of PBASIC code which was more than enough for this project. The PBASIC language is a simplified version of the BASIC programming language, easy to use and developed especially for the Basic Stamp. It includes the main instructions of the BASIC language (GOTO, FOR…. NEXT, IF…THEN….ELSE) as well as specialized instructions (PAUSE, PULSOUT, SEROUT, DEBUG) which makes it easy to program the stamp controller to perform the desired functions. The output of the motion sensor is connected to I/O pin 0. If a pulse is sensed at pin 0, then the controller performs a series of timed servo movements. First, the tree is pulled aside revealing the monster, then the head is programmed to turn left, then right twice as though looking around. Next, the controller sends a signal to raise the right arm suddenly, as though to strike someone. Then, a signal is sent to start the sound bits. Several messages were programmed to welcome the children to the Children's Wonderland exhibit. While he speaks, the monster's head continues to move. Also, at the same time, the controller sends a signal to begin the hand wave. A note here, is that each of these servos is connected to a separate channel, so that the speed of movements and repeatability can be as simple as changing a number in the program. After the greeting is done the hand, arm, head and tree return to home positions and monster is again hiding behind the tree, lurking in wait for his next victim.

In general, programming servos is an easy task. A servo has three connectors. One is usually connected to 5V, the second is for ground and the third is the control connector. Direction of rotations and speed of the servo depend on the pulse width of the signal, which the controller sends to the servo through the control connector. If the pulse is 1.5ms wide, the servo will not move. If the pulse is 1.7ms wide, the servo will run at full speed in a counterclockwise direction. Finally, if the pulse is 1.3ms wide, the servo will run at full speed in a clockwise direction. To change the speed, send a pulse at between 1.3 and 1.5 for clockwise and between 1.5 and 1.7 for counterclockwise.

Controlling servos using Basic Stamps is very easy because the stamp has a PULSOUT command which sends out a pulse of specified width. When using a serial controller in conjunction with the stamp, the command is SEROUT. A simple PBASIC program was written using these commands to control the motion and speed of the different servos.

Using the SEROUT command, a pulse can be sent out to configure the sound module. Usually, the command contains the address of the sound data and the type of operation to be performed by the module. A simple PBASIC code was easily written to enable recording and then playing back the different recordings at different times.

V. System test

To test the performance of the proposed project, the system was put together and a program was written to perform the required functions and downloaded to the stamp. When the power was turned on, the snowman acted erratically moving to undesired positions. After further checking, it was discovered that the servo controller had been initialized to some home positions from the factory, which caused the snowman to move to the wrong positions when powered up. This was solved by initializing the servo controller, to the desired home positions at the beginning of the program. After fine tuning, the snowman moved exactly as desired.

Another problem the students faced was the noise projected by the speaker every time the head servo moved, while the sound module was powered to talk. The students attempted to use different sized capacitors to filter the noise out, but they were unsuccessful. The problem was finally resolved by using a separate 5V power supply for the sound module.

With these problems behind them, the students were able to effectively control all the snowman's functions flawlessly as shown in Figure 7.

Figure 7. The snowman revealed

VI. Cost Analysis

The idea here was to build a very dependable, reliable display which is to function for many years to come. That necessity was taken into account when students were selecting all of the different components for the project. The Lucas County Commissioners sponsored the project and covered all of the costs. A breakdown of the cost of all components is given in Table 1

Component	Quantity	Price	Total
BS2 IC	1	$49.0	$49.0
BOE	1	$65.0	$65.0
PSC	1	$37.05	$37.05
Sound Mod.	1	$84.55	$84.55
SSPS-105	2	$495.0	$990.0
PS-050	1	$190.0	$190.0
HS-800BB	1	$49.95	$49.95
Motion Sen.	1	$10.0	$10.0
Power Sup.	1	$124.95	$124.95
5 V Supply	1	$10.0	$10.0
Amplifier	1	$29.95	$29.95
Transformer	1	$10.0	$10.0
Speaker	1	$50.0	$50.0
Tree	1	$100.0	$100.0
Hardware	1	$150.0	$150.0
Fur	1	$25.0	$25.0
			1975.45

Table1. Cost Analysis

VII. Project Evaluation

“Welcome to The University of Toledo’s 2004 Engineering Expo”, the snowman’s debut performance opened to rave reviews. He and his creators were the stars of the show. The snowman functioned flawlessly, welcoming one and all to the exposition. The engineering exposition gives graduating seniors a chance to display their Capstone projects to their peers and perhaps more importantly, to the public. Students are required to be on hand to present their work Students are well aware of the importance of making a good impression. Because this exhibition is opened to the public and attended by local industry leaders, students are offered the chance to network with potential colleagues and employers. The Abominable Snowman project attracted both university and media attention. The student designers were interviewed by local media and the abominable snowman appeared both on television news and in the in the local newspaper. He was also selected for the cover of the University of Toledo’s Undergraduate

Research and Senior Design Engineering Project Exposition 2004 catalog. A picture of the snowman at the Expo is shown in Figure 8.

Figure 8. Snowman debut at the Expo

Following the 2004 Exposition the abominable snowman was transported to his new home at the Lucas County Recreation Center where he will reside for many years to come. As of November of 2004, the snowman has become a permanent part of the newly renovated Children's Winter Wonderland exhibit as shown in Figure 9.

Figure 9. Snowman's debut at the Children's Wonderland.

For the purpose of this paper, visitors were interviewed as they passed by the abominable snowman exhibit. Without fail, young children were enthralled by the snowman. To them, he seemed to be quite real and many were a little hesitant to approach him because of his sheer size (he is 8 feet tall on his platform). But the timidity vanished instantly and was replaced by squeals of delight when he began to wave and speak to them. Children really believed that he was talking to them personally. Parents were charmed by the effect he had on their children.

"He is so much better than we expected! Great job people! Thank you so much!", proclaimed Irene Petree, Project Coordinator of the Children's Wonderland.

In response to the question "What do you think of the snowman?", here are some sample answers from children and their parents attending the exhibit:

"He is awesome!"
"Wow! He looks so real!"
"Wow! He scared me! But just a little bit!
"Mom! Mom! Mom! Look! It's Sully!"
"He is so cool"
"He looks so real! Can he walk? Can I touch him?"
"Hi Sully! Can you come out of there?"
"I'm glad the monster isn't real, my kids are usually pretty shy, but I think they would gladly walk right out the door with him!!"
"My boys are just nuts about Monsters Inc. This is great!"

VIII. Conclusion

An educational and entertaining senior Capstone project is presented. Students were required to design, build and troubleshoot a fully functional, interactive robotic exhibit to be displayed at the Children's Wonderland Christmas exhibit. This project gave the students the chance to use their technical expertise and knowledge gained during years of study to serve their community and put a smile on thousands of children's faces. It charged the students with the responsibility of realizing every phase of the project from concept to reality and boosted their confidence in their professional abilities and achieving their goal. This was a fun project to work with. Students really enjoyed fine-tuning the snowman's movements and speech. They were very excited to see their creation come to life before their eyes. Students were satisfied with their learning experience and what it prepared them to accomplish. Another appealing aspect of the project is the ease of implementation and flexibility. It can be easily modified to perform different sequence of movements and different sounds. Additional servos can be easily added to perform additional moves. This snowman project was a success and attracted a lot of attention at the University of Toledo's 2004 Engineering Expo and at the Children's Wonderland. Sample of the children's reactions to the display was presented in the paper.
Finally, students have the pleasure of knowing that their senior design project, unlike some other types of projects, will be on public display for many years to come.

Acknowledgement

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Biography

AHMAD M. FARHOUD is currently an assistant professor in the Engineering Technology Department at the University of Toledo. He received his B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Toledo in 1985, 1987 and 1991 respectively. His research and teaching interests cover the areas of adaptive control of power systems, automatic control systems, Electronics, Analog and digital systems design and electric machines.