# UNDERGRADUATE REPORT

## Snake Inspired Robots with a Rectilinear Gait

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**Background**

Bio-inspired robotics is an emerging field at the forefront of robotic technology. Basing robots off the movement of living organisms is giving humans a better understanding of all biological species. One particular area of interest has been in snake-inspired robotics. There are many uses for snake robotics which have led to a large amount of interest in the field of research. Replication of a snake gait along with designing a robot that is compact and cost efficient is now a major area of research.

The main movement that we focused on involved rectilinear gait motion. This motion was studied in depth in Brent W. Spranklin's Masters Thesis. This motion uses a single degree of freedom to translate a wave along a horizontal axis from the back of the robot to the front of the robot. In doing this the robot is able to move forward. The rate that the robot moves forward will vary depending on the surface in which the robot is placed along with the material the robot is made with. It has been determined that the robot should move a distance of $2*l-2*l*\cos(\theta)$ [Merino, Tosunoglu; 2004]. This distance uses the length of $l$ as the length of a lever arm and the value of $\theta$ being the maximum angle reached by the lever arm.

The movement that was created in our tests involved a five joint, six link robot. The motion of the robot begins with the sixth link moving to an angle of -40°, simultaneously the fifth link is moved parallel to the ground but is raised up as the fourth link is moved to an angle of 40°. The motion is then translated forward through the robot so that the sixth link is then on the ground with the fifth link at -40°, fourth link parallel to the ground and the third link is at 40°. This process continues until all pieces of the robot have been raised and lowed. This cycle is repeated many times to get snake motion.

**Motivation**

The potential uses for snake inspired robots range far and wide. One of the major benefits to having a snake inspired robot would be its possible uses for reconnaissance missions and such activities. Situations often arise where it is not possible, or too dangerous to send a human in. Such situations are collapsed buildings, pipelines, and tanks, among other things. Using the snake robots we can go into areas that would previously be impossible to access and determine if there is a person in need of aid. These robots can be used in situations where a human would not normally be able to investigate. Snake Robots can go into pipe lines and determine if there is a blockage. These robots can be used by the military as a way to see if an area is safe for troops. If we lose a robot it is far better than if we lose a soldier. The other use which has been noted is in the medical field. With much advancement we can use these robots for surgical procedures.

The problem with these robots is their cost. Many of the situations in which the robots have a proposed purpose are areas in which the robot will likely be in danger. If the robot is not going to be able to survive then we need to have it be at a low cost. This criterion can be attained by making the robot modular. A modular robot is created by having all of the sections of the robot joined together at the joints and having each piece being completely separate from the prior piece. This can also help in if the robot becomes trapped in a situation. The robot is then able to separate the free pieces from the trapped pieces and finish the mission. Once the robot is recovered, new modules can be added to make the robot the same as when it was new.

The task I was given was to design a robot that would demonstrate rectilinear motion while being completely free from external power and control. Using this model we can then determine the best program to demonstrate rectilinear motion. With this known we can then find the motion that will provide the most efficient use of power. The robot will be running off batteries when it is being used in the future so battery life span will be an important part of design. The robot will need to be able to go for as long as possible. While speed of the robot is important it is sacrificed for longevity.

The next task I was given was to design a modular robot that would be created using injection molding. This task involved creating a design in Pro-Engineer and then making molds that would be able to house all of the components of the robot. This would allow for the determination of the effects that hot, molten plastic has on the different components of the circuit board, servo motor and the battery. This knowledge will better prepare us for later versions of such a robot. We need to ensure that when a large scale model of the robot is created that everything is going to work correctly and that heat exposed to the circuit in the molding process will not cause damage to the components. This task also allows for us to experiment with the modular concept for the robot and determine how to build a completely modular robot. Should the robot be a success we will then know a possibility for future versions of the robot to based on, a failure would give a new direction for the project.

**Problem Statement**

The problem that I was working on was trying to create a robot to successfully demonstrate rectilinear snake motion, try to create the quickest gait possible for the robot, and then work to create a modular robot. We were currently without a model that has no external constraints to test gaits on.  Creation of the modular robot was being used to determine the effects of injection molding on robotic components and to see the effects that they would have on such parts. This would also help in the long term goal of creating a fully modular robotic snake. In accomplishing these goals I would need to create two separate robots. The first being a simple robot that would demonstrate rectilinear motion, the second robot would be modular and made from the injection molding. The two robots would have nothing to do with each other.

**Research Issues**

The research issues that I faced on the project ranged far and wide. The robot that needed to be built in the beginning had many constraining factors that needed to be considered. The robot was only allowed to have five servo motors and needed to only have a single degree of freedom for motion. Rectilinear motion occurs only in a single dimension so creating a robot with a single degree of motion was imperative. All of the components needed to be on the robot and everything needed to be balanced to prevent problems from arising with the weight distribution on the robot. All of the components need to be able to withstand the motion of the robot, which can cause sudden stopping and dismantle attached components easily. The robot needed to have all of the lever arms to be exactly the same length in order for the robot to be useable for gait testing. Finally the robot needed to look aesthetically pleasing. This meant creating the robot so that all of the wires and any other components other than the batteries or the circuit board would be imbedded inside a casing of the robot and would therefore not be visible to any viewers of the robot.

The problems with the imbedded module robot were a little more diverse. The first problem was trying to determine how to imbed everything in plastic given the constraints of the Babyplast hot injection molding machine that was needed for embedding. This problem was not a hard thing to solve, but rather a small annoyance as the creation of molds was being done. The next problem was creating the molds so that all of the components would not interfere with each other. There needed to be a method for the switch on the circuit board along with the gearing on the servo to remain free of plastic and also have enough of an opening around them so that they would be useable. This task was made harder by the awkward shape of the motor along with the shape of the circuit board.

**Research approach**

The design of the robot that was made to demonstrate rectilinear motion was fairly straightforward. The robot needed to have only a single degree of freedom so it was determined that there needed to be five different joints with hinges along with six links that will help to balance the robot. This task was solved by creating a design that used parts from a robotic company called Lynx motion. The robot was created from pieces which were made to hold a servo motor which then attached to an aluminum bar that attached to the next servo. The bar was hollow which allowed for the wires to be easily concealed and for the robot to have a good aesthetic appeal. The robot was also designed to be fairly long so that the motion of the robot could be more easily determined. I originally worked with a model that contained external constraints (a power supply and external control board). This robot was very small and determining the distance that the robot had traveled was difficult. The new robot was to be much longer so the distance traveled would be clearer.

As with all designs, problems arose along the way and it was necessary to design a solution. One major design flaw that was overlooked was the instability of the robot. It was necessary to create sides to the robot that would help with the stability of the robot. The sides needed to be machined from Plexiglas to create a more stable robot that would be able to move without falling over. It was also important that the batteries and circuit board be attached to the robot. This was done by creating a Plexiglas stand for the pieces and from there working to attach them by creating a mounting bracket from a piece of sheet aluminum. The final task involved placing the brackets on the aluminum bar and making sure it was securely mounted.

The approach for the embedded module involved creating a design which would house all of the pieces and working to put that together. Molds needed to be created for the injection molding machine that would be able to house all of the pieces. Everything needed to fit together perfectly for the robot to work properly. Once the molds were created a program needed to be written for the microcontrollers and then inserted into the control board. From here the majority of the work was simply milling the various molds needed for the injection molding and then actually completing the injection molding process. Six modules would be created to demonstrate the motion and would all need to be attached using a fixed arm system.

**Problems and Solutions**

There were many problems that came along the process of building the robot, some from design flaws, some from bad luck. One of the first problems I encountered was with trying to put the entire robot together. The robot was full of several components that needed to be put together without any instructional guidance. The robot was finally put together with one of the next problems coming in the size of the pieces. The piping that connected all of the pieces of the robot together had a very small diameter which led to some problems in getting the wires into the pipes. The solution that we came up with was to use 30 gauge wires which were small enough that several stands could be run through a pipe at the same time. The next problem came in trying to attach the batteries to the servo motors. The connectors that were on the two pieces were different so we needed to create a connector ourselves. After many different trials of connectors I found that using a switch which was soldered right from the servo motor to the battery was the best method since it was then not possible to have a broken wire. This solution was not as simple as it may have seemed. The switches broke on two separate instances causing a large delay in the building process as the problem with the robot was trying to be determined.

One of the next problems that needed to be worked out was the orientation of the motors. The program that I first tested on the robot was written for a robot with alternating motors (the first motor faced the right side, second the left, third the right and so on); however the one I built did not have this feature. I then worked to make all the motors be alternating. Once the robot was finally all together then the biggest problem was discovered. The robot was unstable because of its size and was tipping over easily because of this. The solution that was decided upon was to create sides at all the joints and at the end of the robot that were made of Plexiglas. These sides would give the robot stability at all stages of movement and keep it from falling over. The sides needed to be the same size and have an exact center for this to work correctly. I decided it would be best to mill them in a CNC machine which turned out to be far from the best decision. The Plexiglas was cracking when the end mill came in contact with it and it did not want to allow holes to be made in it. This process was fixed by drilling the Plexiglas very slowly and slowly increasing the size of the holes until they were of the correct diameter.

The next stage was to try and see how fast of a gait I could program for the robot. This was done by studying the rectilinear movement of a snake and from there working to replicate the motion in as few stages as possible. I created several different programs and worked to test the programs. Once the programs were tested I was able to see a difference in the speed of the robot from the original program for rectilinear motion I was given. The final program that was written does not perfectly replicate the motion, but satisfies the requirement of moving as fast as possible.

The second part of my project involved working with injection molding to create a fully embedded module. The problems with this process were much greater than the prior project. The module must be a small enough size to be contained in the injection molding machine. This meant that a module must be approximately an inch and a half square and be less than 2 inches long. Considering the control board, servo motor and battery must be contained inside of the plastic meant the complexity of this project was very great. The design needed to include a way for the user to turn the robot on and off via the switch on the control board. Along with the switch there also needed to be a way for the servo gears to be free to move. The gears needed to have no plastic around them so the robot would be able to move. The other major problem that was encountered came in that the injection molding machine (Babyplast) was only able to insert about a half of a cubic inch of plastic into the mold in a singe shot. With a robot that was to be approximately 4.6 cubic inches it was going to take several shots to be able to properly fill the molds and ensure that everything was going to be held together.

A mold design was created to easily put everything that was needed for the module together. This design was a several stage mold that would work by first creating a cavity in which the circuit was to be put in. The circuit was to have all the wires soldered into the different ports to ensure a good connection when the plastic was injected into the mold. The top half of the mold contained cut outs for the circuit to fit into along with cut outs for the wiring to fit into. This would allow a tight fit for the wires along with the switch to ensure that there was no plastic blocking loose wires or getting into the switch and preventing operation of that piece. The first stage would build a mold for the servo to fit in by creating a three sided cradle. To get to this point the four shots will be needed to get enough plastic to truly create a cradle for the servo. From there the servo will be placed into a mold that will have a piece that will fit over the gearing to prevent plastic from getting into the gears. The servo is offset (moved over about 1.5 cm from the center of the circuit board) to allow the robot to be able to move easily since it is then ensured that the robot will not interfere with the servo gear motion. Once the servo is in place there is another shot which is injected to create a space for the battery to go into the module. The battery is then placed into the piece and a final shot is used to encapsulate the entire module.

The next step involves connecting all of the wires and putting a final coating on all of the components and wires to make sure there are no loose pieces in the end. The wires are all going to be free during the first stages of injection molding allowing the leads from the control board to be inserted into the servo. The battery will be run into the control board to power everything. The one problem that will need to be overcome will be recharging the robot. The wires will need to be run to the outside of the robots final coating to make sure it is possible for the robot to easily be recharged. Wires also need to be run to the outside so that all of the modules will start and stop at the same time. A control wire must be run throughout all of the modules to accomplish this. Once all the wires are connected then the module is placed back into the mold where a final two shots are injected over all of the wires to encapsulate everything, except the recharging wires and the control wires. There is a cap that is placed over the switch along with the cap that was used before on the servo gearing to make sure that there is no leaking of plastic that will impede motion.

Once all of this is done the modules will need to be connected together to create a robot. The modules will be connected using a simple joint method. Each module will have an arm running from the servo to the next module which will allow for the movement of the module. On the exact opposite side of the robot will be a rigidly attached bar that will connect the module to the prior module. This method will allow for rectilinear motion of the snake to be seen.

**Parts Used**

There were several different parts that were needed for these robots. The first robot was comprised of many pieces ordered from Lynx-motion. The servo motors that we used were Hi-Tec HS 645MG (Figure 1) motors which provided the most torque of any standard servo motor.

Servo motor holders (Figure 2) were ordered to allow for an easy connection of the servos to the robot. L brackets (Figure 3) and C brackets (Figure 4) were ordered to attach to the servo and the servo holder to give a spot for the links to join to one another. The joints were held together using 6 inch aluminum tubing (Figure 5) that was purchased from lynx-motion. Along with the tubing we needed to purchase fittings (Figure 6) for the ends of the tubing to allow the tubing to attach to the L and C brackets.

**Figure 1: Servo Motor**

**Figure 2: Servo Holder**

**Figure 3: L Brackets**

**Figure 4: C Brackets**

**Figure 5: Al Tubing**

**Figure 6: Tubing Hubs**

The batteries that were chosen were 4.8V 280mAh NiMH batteries (Figure 7). These batteries fulfilled all of the criteria that was needed in that they were small and weighed little while still being within the range of 4.8 – 6 V. Most of the other batteries that were found to be in this

**Figure 7: Battery Used**

range had the downfall of being heavy and having far more Amp-hours than were necessary for our use. The battery that was used for the circuit was a 7.4V 145mAh Kokam Li-ion battery. This battery was extremely light and reliable. The circuit (Figure 8) that was used was custom made for use on a robot of this type. It contained 6 outputs for servo motors, and supplied the motors with a constant 5 V pulse. The program was placed on the circuit using a microcontroller (PIC16F877A-I/P) which was programmed on an external board that attaches to a computer through a USB port. The program was written in Microsoft Visual Basic. The wiring that was chosen for this robot was 30 gauge casing wire. The 30 gauge was chosen since several strands of the wire could fit inside to tubing without problem. The switches that were used with 3 way mini switches from Radio Shack which allowed for an easy on/off for the motors while allowing a way to recharge the batteries.

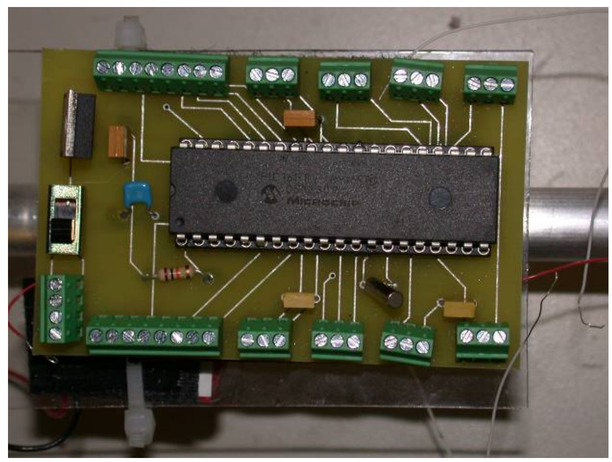

**Figure 8: Control Circuit with Microcontroller**

The embedded robot again needed new parts and materials. The circuit board (Figure 9) that was used was again custom made for the type of motion needed. There was an output for 2 servo motors along with a power output for both motors. The voltage

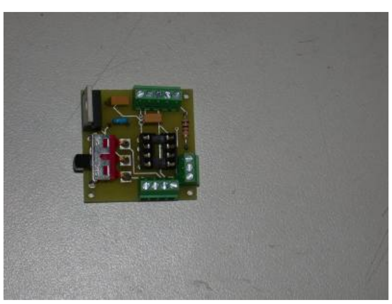

**Figure 9: Control Circuit for Embedded Robot**

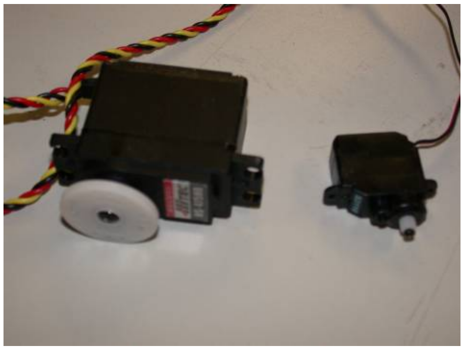

Figure 10: Mini Servo Used Compared to a Standard Servo Motor

regulator supplied a constant 5 V at all times to the motor. These circuits were controlled by a microcontroller (12F629 I/P) which was also programmed is Visual Basic. The servos that were chosen were Futaba mini servo motors (S3110, Figure 10). These motors provided the best torque to weight ratio for their size. The battery that was to be used was again the 7.4 V 145mAH Kokam Li-Ion battery (Figure 11). This battery would be used to power everything since the circuit controlled the motor and contained a voltage regulator.


**Figure 11: Battery**

**Results/ Discussion**

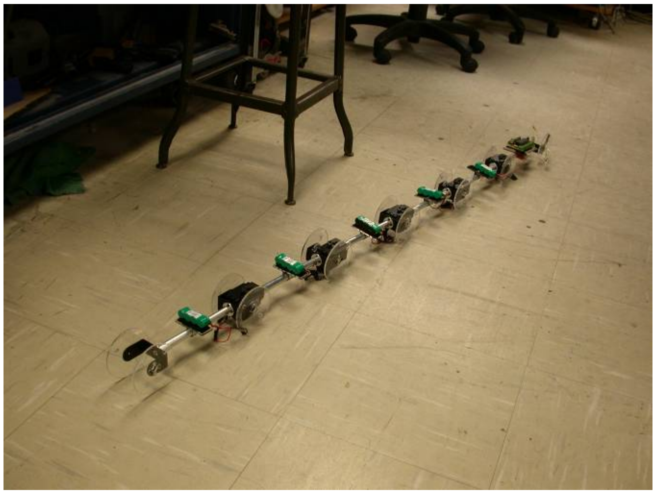

**Figure 12: The Completed Robot**

The first snake (Figure 12) which had all the components attached was very successful after several trials. The snake robot is now able to demonstrate rectilinear motion of a snake. The snake contains all of the pieces necessary for its motion including the circuit board and batteries. All of the wires are contained inside the robot giving an aesthetic appeal to all viewers and also greatly improving the functionality of the robot itself. A program was created to get the most movement out of the snake and get the snake to move as fast as possible. The snake was then able to move at approximately 7-8 ft/min. This was almost twice as fast as the top speed recorded by the original rectilinear gait program. Several variations of rectilinear gait programs were tried with several of these programs immediately showing no signs of improved speed. Some of the programs were transferring the motion to the front of the robot too fast and therefore the robot was not given a chance to have friction help it move along. Other programs were simply moving too slowly and the robot was moving the correct distance for each cycle, however it was taking a long time for each cycle to occur. Several different program variations along with studying the motion of the robots that were created, along with journals from others regarding rectilinear motion allowed me to gain a better understanding of the motion I was trying to achieve in this robot and finally create the quickest program. It should be noted that many of the programs that were written did not demonstrate perfect rectilinear motion. The program needed to be modified for speed and therefore was approximately rectilinear.

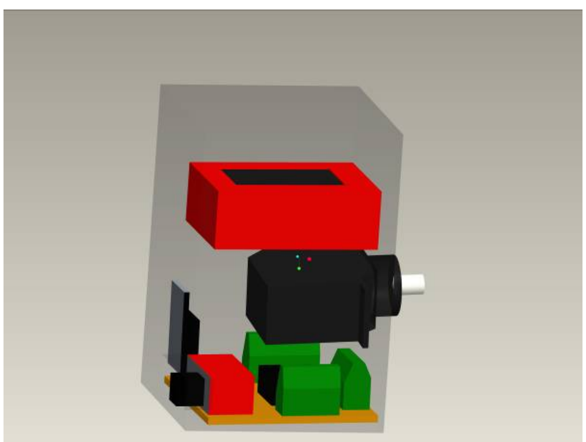

**Figure 13: Design for Embedded Module**

The final stage of the project was working on the fully embedded module robot (Figure 13). This step was one which never completely came to fruition. The robot was never able to be completed due to a mechanical failure of a CNC milling machine that was needed for the molds to be created.

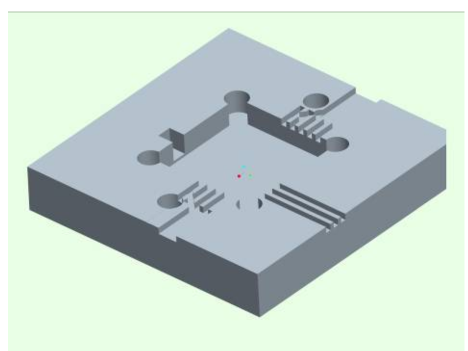

**Figure 14: A Sample Mold Designed for Holding the Circuit**

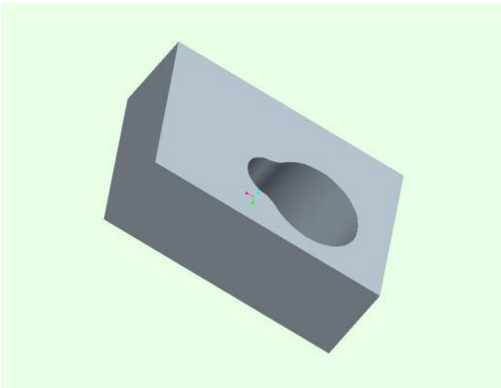

**Figure 15: Cover for Servo Gearing**

Molds (Figures 14, 15) were designed for all of the steps of the injection and from there an NC sequence was written to prepare the molds for milling. All of the programming is ready and as soon as the machine is up and running the molds can be made. All of the circuit boards have been soldered together and are ready to be tested with the microcontrollers. A program for the microcontrollers has yet to be written but once this is done we will simply have to place the microcontrollers into the circuit and then we will be ready for injection. This project is scheduled to be continued with the completion coming in about 5 months.

**Conclusion**

This project can be considered a success. We were able to replicate rectilinear motion of a snake robot using a robot with external power and controls and then translate that into a snake robot with everything self contained on the robot itself. We were successfully able to create a program in which the speed of the robot was nearly doubled as compared to the original program, though not using perfect rectilinear motion. Finally we were able to design a system of molds that will be able to create a module that will have the circuit, servo motor and battery all contained within the confines of the piece. This step of the project is one that will be continued over the next couple of months and will hopefully be completed in the upcoming winter.

**References**

[1] Master's Thesis of Brent W. Spranklin

[2] C.S. Merino and S. Tosunoglu. Design of a Crawling Gait for a Modular Robot. In the *Proc. of The 17th Florida Conf. on Recent Advances in Robotics, FCRAR 2004*, University of Central Florida, Orlando, Florida, May 6-7, 2004.

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