DISTRIBUTED CONTROL OF A SEGMENTED AND SHAPE MEMORY ALLOY ACTUATED BIOLOGICALLY INSPIRED ROBOT

by

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ABSTRACT

Today's robots are limited in mobility, flexibility, and scalability. Their rigid bodies prevent operation in many environments and often restrict movement to a two-dimensional space. Most robotic vehicles cannot operate in a confined space or unstructured terrain and are incapable of climbing surfaces a fraction of their size. Their stiff bodies significantly reduce their performance and present a major weakness. The next-generation robot must be highly adaptable, flexible and capable of operating in many environments. A possible solution is to create a flexible and scalable segmented snake robot incorporating smart material for actuation. This project, in partnership with The Idaho National Laboratories (INL), plans to implement a snake-eel-worm (SEW) design to meet the needs of the next-generation robot as a part the Visual Inspection Platform for Exploration and Research (VIPER) project. Snake-eel-worm platforms have the dexterity to traverse highly unstructured amphibious and land-based terrain. To create this flexible and scalable structure this work proposes the implementation of Shape Memory Alloy (SMA) as the actuation device under distributed control of several embedded computer modules. This project found that a mechanical prototype can achieve snake-like locomotion while using SMAs under distributed control. A three-segment SMA-actuated structure moves in an inchworm motion under a distributed control network consisting of several PowerPC single board computers (SBC).

CHAPTER 1

INTRODUCTION

Imagine for a moment a wheeled-robot with state-of-the-art sensors and high-tech equipment patrolling the perimeter of a military base. The robot autonomously combs the fence line to detect threats and alert human operators. This scenario runs smoothly under ideal circumstances. However, consider if the robot's path is obstructed with a fallen tree, a flooded road, or another obstacle. It is possible the wheeled robot becomes useless and cannot accomplish its goal.

While wheeled and tracked robot platforms are very common, they often become useless in a dynamic environment. If the environment is unfamiliar, these robots struggle to adapt. An effective robot must have precise knowledge of its environment. It is often physically built with a particular environment in mind. Therefore, it always functions properly when interacting with the "expected" surroundings whereas actual field environments are not predictable; countless obstacles and changing terrain create a treacherous atmosphere rendering many robotic devices useless.

Wheeled and tracked robots lack mechanical flexibility since the rigid structures are incapable of adapting to unexpected terrain. The overall dimensions of typical robots dictate the surface on which they can travel. For instance, it is difficult for any wheeled robot to travel across a surface that is a fraction of its own size; the body simply does not have the ability to grip and provide the necessary traction for movement. A reduction in size could permit the robot to perform a specific task or navigate a particular environment but the functionality, capabilities, and the payload of the device also decrease, limiting its usefulness.

This brings about the second major weakness of rigid wheeled robots: scalability. In many cases, it is not feasible to change the size of these robots. The locomotion and other technologies may not function on different scales. Such is the problem with many electromechanical and mechanical devices. The miniaturization of these parts becomes prohibitively complex and expensive.

In essence, a flexible and scalable structure is required to navigate an unstructured environment. What structure allows for this diverse adaptive operation? The SEW. Advantages of a SEW robot include both the flexibility to accommodate difficult terrain and the scalability of size. Biological snakes prove scalable by ranging from a small garter to a large python; all move with similar methods. Perhaps the greatest advantage of SEW-like design is the ability to move with several different forms of locomotion, such as lateral undulation, concertina, side-winding, and caterpillar which are easily identified in biological snakes.

The VIPER Project

The Idaho National Laboratory (INL) is actively constructing a biologically inspired snake-eel-worm (SEW) robot within its Visualization Integration Platform for Exploration and Research (VIPER) project. The VIPER project focuses on developing serpentine robots for diverse tasks such as search and rescue as well as exploration and reconnaissance. Snake-like robots would have several advantages in the areas of reconnaissance and exploration. Typically, wheeled robots are restricted to relatively smooth terrains lacking confined spaces. On the contrary, a SEW design can free robots from these restrictions and conform to a dynamic contour, including significantly small spaces, all while allowing continual maneuverability.

VIPER Project Goals

The goal of the VIPER project is to develop a SEW robot that is light enough for a single individual to deploy, guide, and easily reconfigure. These requirements stem directly from the project's primary goal of reconnaissance missions in highly unstructured environments, such as collapsed structures within earthquake zones. The design will ultimately permit the replacement of modules or segments for added functionality such as sensor packages and computing power. Future project goals will include remote operations within hazardous environments and cooperative observation and manipulation tasks. Much of the advanced visualization requirements for complete implementation of the VIPER program reconnaissance missions are under parallel development [1-7]

CHAPTER 2

PROJECT OVERVIEW

The mobility and flexibility of a SEW structure requires a multi-segments design under a distributed control architecture. The control architectural goal is to manipulate the mechanical body into forms of SEW locomotion. By basing the initial SEW design on smart material actuators it will achieve a high degree of miniaturization possibilities, perhaps to the nanoscale size. Further, with the consideration of future technology, a solar-fuel cell system can replace the batteries which will vastly increase the operation lifetime with sunning cycles. To achieve these ends, the SEW robot requires several special design considerations covered in the remaining sections of this paper.

Problem Statement

This thesis addresses the problem of incorporating a mechanical structure and control methods into a modular autonomous platform capable of SEW locomotion. The intent of this thesis work is to construct and control a biologically-inspired SEW-like robot utilizing shape memory alloy (SMA) actuators. A segmented SEW design provides the desired mobility and flexibility while SMA actuators provide a method of scaling without major redesigns. The objective is to effectively coordinate the actions of each segment into a "global" locomotion or gait. This requires control strategies for both the individual actuators and multiple segments to obtain inchworm motion under a distributed control system consisting on PowerPC single board computers.

Project Objectives

The aim of this research is to build an autonomous robot capable of SEW locomotion that meets the VIPER project requirements: modular, and scalable. We intend to make a SEW structure that is both flexible, to conform to any terrain, and scalable, so that the control and actuation techniques function at any size without major redesigns. For instance, the diameter of the SEW design could increase or decrease to accommodate a particular task. A segmented structure will allow the SEW to change in length. This can also help accommodate certain tasks while increasing functionality through added processing power, the sensor package, or more physical power.

Specifically, the objectives are as follows: 1) Build a segmented structure capable of autonomous SEW locomotion, 2) Incorporate smart material actuation through the use of SMA pistons 3) Configure an embedded network of single board computers to control individual segments and 4) Create a distributed control algorithm to synchronize a four-segment structure into SEW locomotion, which allows the SEW to move without any commands from a “head” segment.

CHAPTER 3

LITERATURE REVIEW

Shape Memory Alloy

Future SEW robots will likely incorporate some type of artificial muscle, instead of hydraulics, pneumatics or motors. The VIPER project incorporates the “smart material” shape memory alloy as an actuation solution. The material is gaining use in engineering designs and applications as the demand for sophisticated actuation techniques continues to motivate SMA research [8].

Shape memory alloy metals belong to the class of “smart” materials since they respond to a stimulus; heat [9]. Discovered in 1932, SMA exhibits a large physical deformation when exposed to varying temperatures. Nickel-Titanium (Nitinol), developed in 1965 by the Naval Ordnance Laboratory, is the most common composition of SMAs. In this thesis the terms “shape memory alloy” and “Nitinol” are interchangeable.

The material can return to a specific geometry when exposed to heat. This “memorization” is known as the Shape Memory Effect (SME) [9] and creates a noticeable size change. The shape memory effect is the primary mechanism for the shape change which transforms the material’s microscopic structure. A phase change causes the crystalline structure to align, decreasing the size of the material. Martensite is the low temperature phase in which the unit cell of the material is a distorted cube. The austenite is the high temperature phase where the unit cell is almost a perfect cube. As the temperature of the material increases, the unit cell structure changes from a Martensite to Austenite phase. Figure 3-1 illustrates a phase transformation from Martensite to Austenite of a two-dimensional unit cell. At the low temperature Martensite phase, the SMA material has a great deal of flexibility. In this phase it can bend into many different shapes. Once heated to the Austenite phase the material deforms to its original shape and configuration.

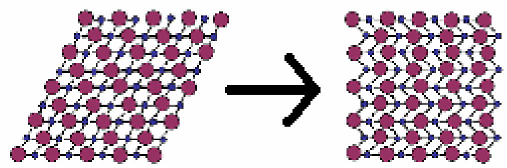


Figure 3-1: Shape Memory Alloy Phase Transition [9]

The shape change is recoverable as the material cools and returns to the Martinsite phase. This transformation results in a useful motion and force, which is often harnessed as an actuator useful to many applications.

Heating Methods

The most efficient method to induce the phase transition is joule heating, in which an electrical current passes through the material causing electrons collisions creating thermal vibration and heat. Researchers also use fluids to heat and cool the SMA material. Often cooling is done through convection with the ambient environment.

The physical size of SMA wire has several advantages as an actuator. First, SMAs have a very large power-to-weight ratio which traditional actuators cannot match [10]. Shape memory alloys are easily configured into many forms of actuation devices whether linear, rotary, or bundled making them applicable in many mechanical designs. Figure 3-2 highlights the comparison between SMA and other actuation methods [11].

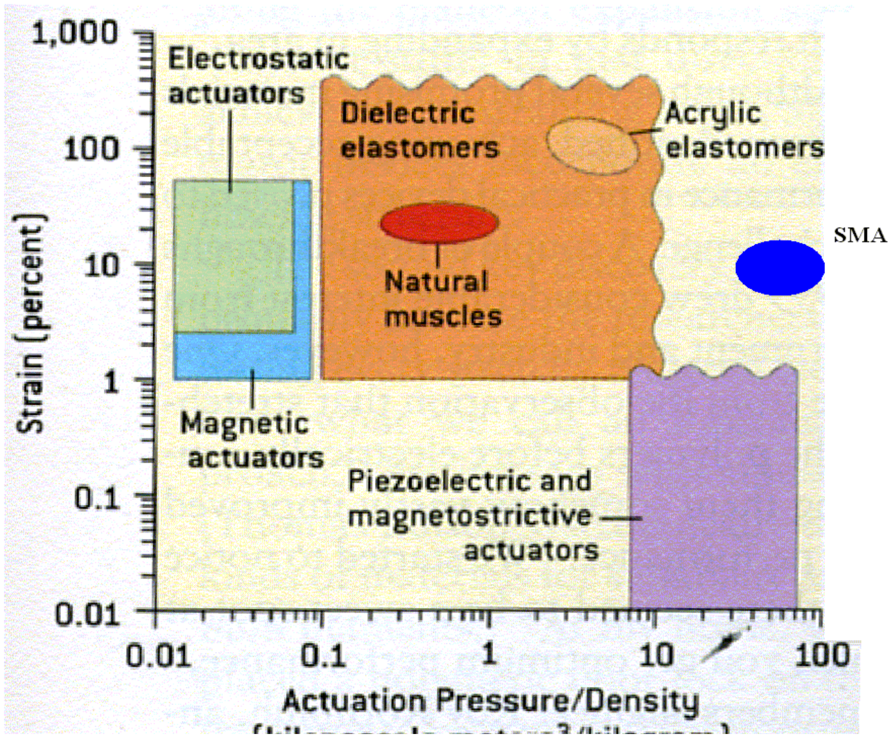


Figure 3-2: Actuator Comparison [11]

The size of the wire can scale to meet applications. Even SMAs with a smaller diameter maintain similar functionality. Figure 3-3 shows the relationship of an SMA's diameter and actuator force. Shape memory alloy wire can theoretically be miniaturized to the sub-micron scale; the miniaturization possibilities are optimal for small-space applications. Figure 3-3 and Table 3-1 illustrate the force properties of SMA wires.

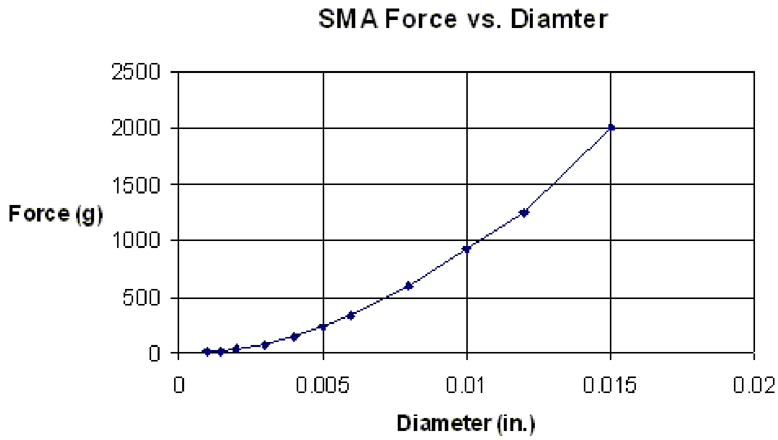


Figure 3-3: SMA Force and Diameter Relationship [12]

Wire Diamter (inch)	Reisistance (ohms)	Max Pull Force (g)	Acutation Current (mA)	Strain (%)	Contraction Time (sec)	Off Time (sec)
0.001	45	7	20	4	1	0.1
0.0015	21	17	30	4	1	0.25
0.002	12	35	50	4	1	0.3
0.003	5	80	100	4	1	0.5
0.004	3	150	180	4	1	0.8
0.005	1.8	230	250	4	1	1.6
0.006	1.3	330	400	4	1	2
0.008	0.8	590	610	4	1	3.5
0.01	0.5	930	1000	4	1	5.5
0.012	0.33	1250	1750	4	1	8
0.015	0.2	2000	2750	4	1	13

Table 3-1: Characteristics of SMA Wires [12]

Further, SMA actuators can simplify mechanical structures reducing the need for additional components in applications [13]. Wire actuators are also noiseless and do not suffer from vibration disturbances associated with many motor actuation methods.

The drawback of SMA actuation is the inefficient power consumption. The amount of current required for joule heading depends on the size, see Table 3-1. For wires with larger diameter than those of Table 3-1 the resistance is very small and requires an impractical amount of current to create the necessary heat. The larger diameter creates less resistance in the wire while adding more material heat.

Shape memory alloy material suffers from hysteresis. Hysteresis occurs when a system does not react to applied forces or inputs. Instead the performance depends heavily on the heat transfer with the ambient environment. When the actuation heat is removed the wire does not immediately regain its shape. Figure 3-4 shows a typical heating and cooling cycle of a SMA wire.

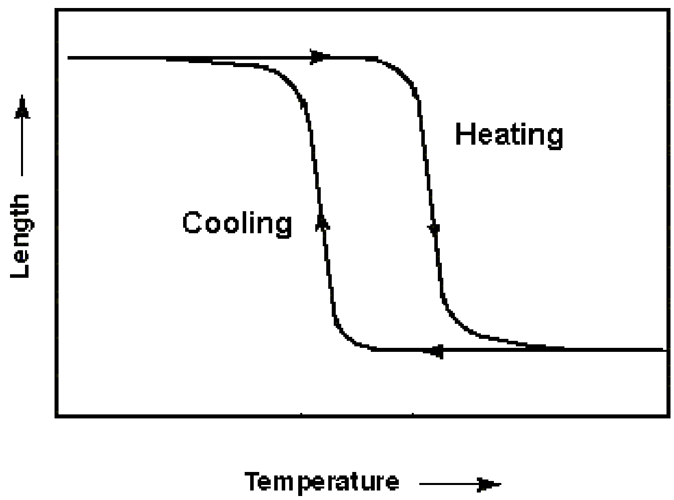


Table 3-4: Hysteresis Property of Shape Memory Alloy

<u>Modeling</u>

Development of a mathematical model which incorporates the nonlinear behavior of SMA as it undergoes temperature, stress, strain, and phase changes is difficult task. Researchers continue to study how to model and control these materials [14].

Ikuta developed a variable sub layer model in which the percentages of the SMA phases are described mathematically with respect to time [14]. The strain is calculated for a given load by weighting the strain from the different phases. This work is the basis for many nonlinear models including Madill and Wang’s differential equation where the temperature-current relationship is used to capture the dynamics of a SMA actuator [15]. This model is well-suited for position control systems since electric current is the input and source of heat.

$$\rho c V \frac{dT}{dt} = R i^2(t) - hA\left[T(t) - T_\infty\right] \qquad (3.1)$$

Previous Work

Despite the difficulties to model and control SMAs are incorporated into many applications with a variety of control methods. This literature review concentrates on SMA wires as opposed to other shapes such as a tube or bar.

Barooah and Rey, of the United Technologies Center, investigate the use of SMA wires for a variable area fan nozzle (VAN) which compares to the VIPER project’s actuation techniques [16]. The size of SMA wire in the VAN is of comparable size so control methods are also useful to study. They experiment with several different controllers starting with a proportional (P). Figure 3-5 shows the nozzle flap controlled with SMA actuators. The initial assumptions were that linear control strategies, such as proportional, do not function well due to the strong nonlinearities of the SMA actuation process.

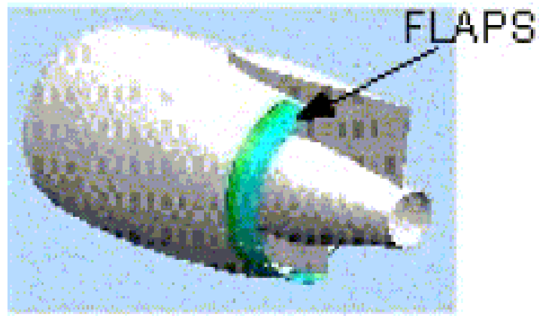


Figure 3-5: Variable Area Fan Nozzle [16]

Their results indicate the proportional-integral-derivative (PID) controller has the best performance. In the PID controller the supplied voltage, Vc(t) is a weighted sum of the error (e), the integral of the error, and the derivative of the error. The weighting factors or gains are represented by K_p and K_d in the following differential equation.

$$V_C(t) = K_P e + \int edt + K_d \frac{de}{dt} \qquad (3.2)$$

The derivative term reduces an overshoot of the position while the integral compensates for the steady-state error. In the experiments the PID controller is suitable if the SMA wires are small and have a low thermal inertia; the ability to store heat. Barooah and Rey also state that an inverse hysteresis model can perform quite well but was too complex for real-time control. The main actuation objective is to avoid an overshoot since it takes more time for the wire to cool then it does to heat. A simple control algorithm in implemented:

1. If the measured error is large, the best action is to supply the maximum power possible. If the error is negative no power is supplied.
2. When the position is close to the desired one, the current is reduced intelligently, and cut off before the target is reached.
3. When (1) and (2) are not satisfied (the measured position is close to the target) voltage is continuously controlled.

Figure 3-6 shows the position control of the fan nozzle under proportional control with three different gains. An overshoot in position is avoided by incorporating a controller which is sufficiently overdamped.

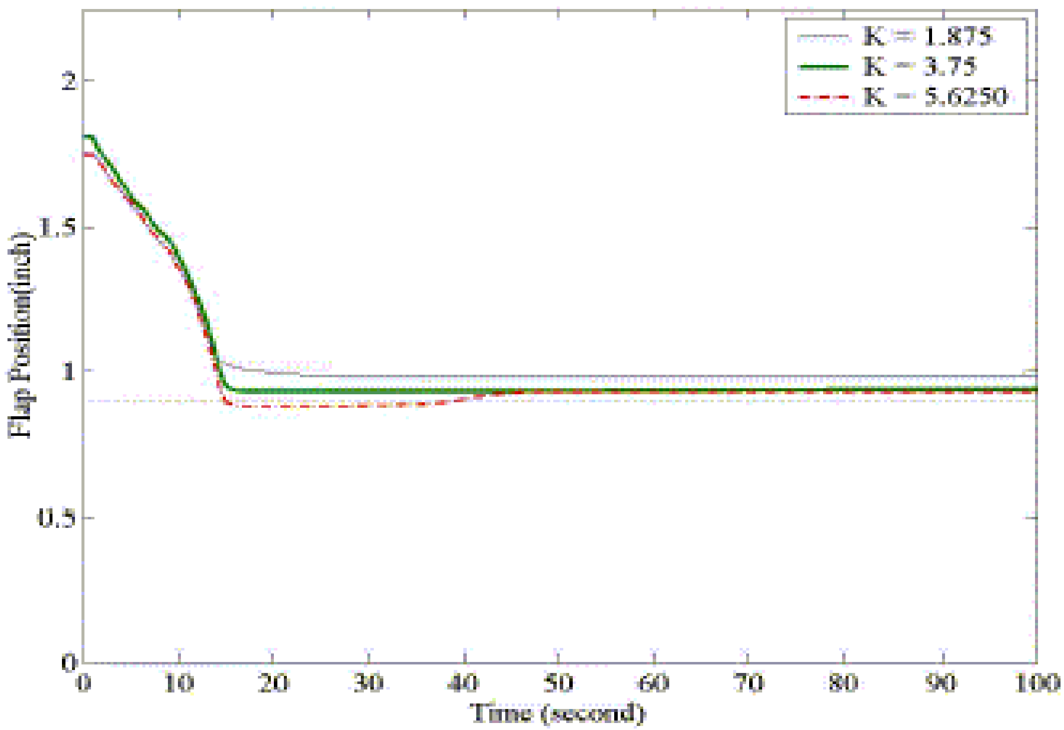


Figure 3-6: Position Control of VAN [16]

Researchers at Texas A&M incorporate SMAs into a biomimetic hydrofoil, Figure 3-7 [17]. Each segment of the hydrofoil is actuated by a SMA wire through joule heating and forced cooling using fluids. Their objective was to incorporate an adaptive hysteresis model and proportional-integral (PI) controllers.

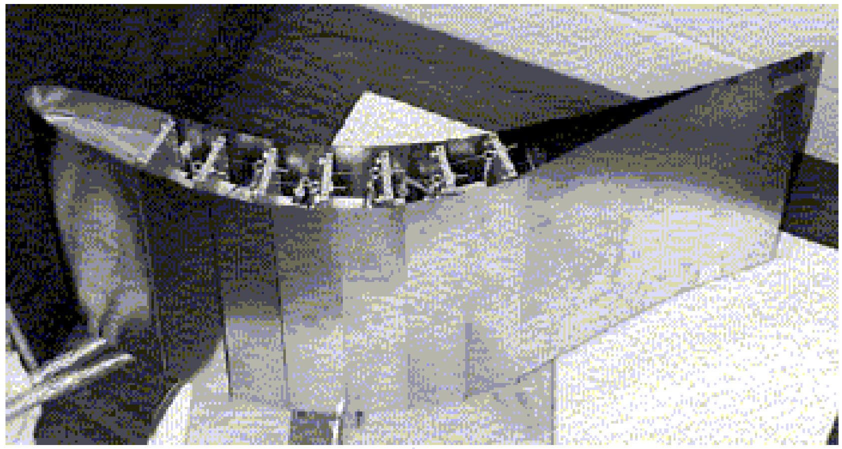


Figure 3-7: SMA Actuated Biomimetic Hydrofoil [17]

They conclude that the adaptive hysteresis model is too complex for a six-segment hydrofoil, each segment with two SMA wires, and concentrate on the PI controller. Results indicate good performance with a linear control strategy if the wires are small and have a low thermal inertia. Ikuta's literature also suggests similar results [8].

In other work Dickinson and Wen [18] do not directly compensate for hysteresis with and inverse model but use proportional closed-loop feedback to control the position of a flexible beam. Their work shows that SMA position stability is possible with a linear control strategy. The controller is shown in the following equation. The input current, u, is zero when the position, x, is greater then the desired position, $x_{d.}$ When the position is below the set point the input current is proportion to the error by a gain factor k.

$$\begin{aligned} u^2 &= 0, & x > x_d \\ &= k(x_d - x), & x < x_d \end{aligned} \quad (3.3)$$

Dickinson and Wen also use this controller with a fictitious desired position instead of a fixed value. The fictitious set point is mapped from a table which is updated through an adaptation law. The mapping of a different set point helps reduce the steady-state error. The control strategy functions well with both fixed and mapped set points and results in an actuation bandwidth of 1-2 Hz.

Still other research uses varying control schemes from P to adaptive variable sub-layer models [19] [20]. Most control methods focus on either position feedback or reverse models to control the position of an SMA actuator. It is often the case that open-loop control is very difficult since the hysteresis model is usually changing depending on stress and life cycle [9].

Snake Motion

A snake's adaptability stems from its physical body type as well as its several methods of locomotion. To move between land and marine environments a snake may simply use a different gait. To realize the advantages of SEW locomotion; one must study how these organisms accomplish biological movement.

A SEW organism moves by shifting its body in a cyclic pattern or gait and by pressing on the surrounding environment. Several SEW gaits are discussed in Hirose's extensive study [21]. The most common modes of locomotion are undulation, concertina, side-winding, and rectilinear or caterpillar. The most identifiable type of locomotion is undulation or serpentine motion in which an S-shaped curve propagates through the body of the SEW organism creating friction with the environment causing forward motion.

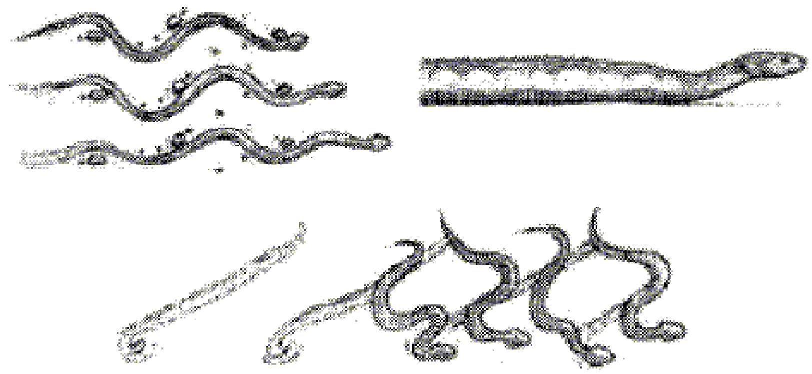


Figure 3-8: Snake Motion [22]

Biological snakes move in a side-winding motion by lifting their body off the ground and placing it in the direction of motion. When side-winding, the snake's body has only several points of contact with the ground. As a snake lifts one part of its body, another part serves as a base. The snake then pushes off this base and moves latterly.

Caterpillar motion resembles a ripple traveling vertically through the snake. In this case, the scales push on the ground as a curve is created vertically in the snake. This motion is the same as undulation except restricted to the vertical plane of motion where friction is created on the bottom of the SEW organism.

Concertina is another valuable form of locomotion which snakes use to navigate difficult terrain. With concertina the snake uses half of its body as a base and extends the other half. If a snake encounters a difficult obstacle it may bunch its back half and extend its front half forward over or onto the obstacle. When the front half reaches a surface it can then provide traction and bring the back half forward. This type of motion allows a snake to adapt to an unstructured terrain and is often used inside holes as seen in Figure 3-9.

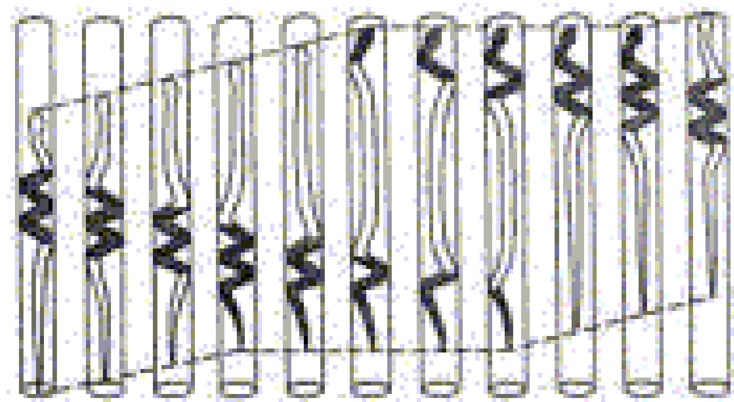


Figure 3-9: Concertina [23]

The few gaits discussed here show the adaptability of SEW organisms to move through various environments. This trait of the SEW locomotion is ideal for many robot platforms.

Snake Robots

Today's mobile robots perform work too difficult or dangerous for humans. However, their inability to adapt to different environments leaves a significant void which the SEW robots will help fill.

Snake-Eel-Worm designs aim to capitalize on the robust and dynamic locomotion of real SEW organisms. SEW locomotion is applicable to areas such as search and rescue, military reconnaissance, pipe and bridge inspection, hazardous environment operation, as well as the medical field for active endoscope and catheters [24].

In general, SEW robots can access environments and perform tasks wheeled robots and humans cannot. A SEW robot, has the potential to traverse objects many times its own size. To illustrate this, consider how a snake can climb a tree or swim across a lake while the Mars rovers Freedom and Independence, two of the most sophisticated robots to date, probably cannot climb a boulder a fraction of its own height.

The snake's ability to traverse unstructured environments makes them ideal to many industries, organizations, and professions. A primary goal in developing several snake robot platforms is search and rescue. Erkmen, illustrates how many local governments are not equipped and lack an appropriate immediate response to natural or manmade disasters [25]. Current rescue efforts still need a sophisticated and highly capable robotic search tool. This is the primary objective of Choset at Carnegie Mellon University [26]. Choset is developing several robots for use in urban search and rescue (USAR). One of Choset's robots is seen in Figure 3-10.

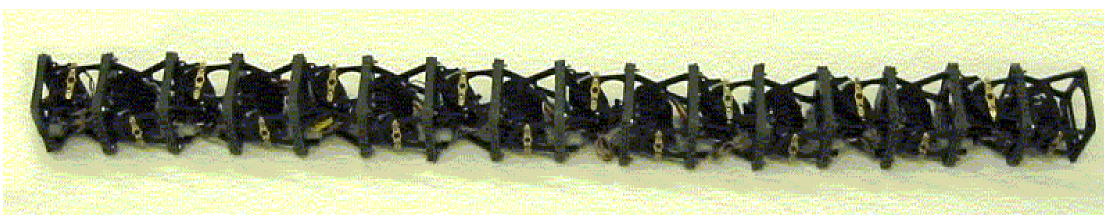


Figure 3-10: Choset's Robot

Choset's earlier research included work for NASA's JPL and focuses on a snake which probed through rubble.

In addition to Choset, other researchers combine snake-like features with traditional robots. An example of this hybrid approach is the OmniTread robot [27] developed by engineers at the University of Michigan, Figure 3-11.

Figure 3-11: The OmniTread Robot

Figure 3-12: Hirose's Hybris Robot

The OmniTread is controlled by a human operator through a tethered cable. It is able to climb objects twice its size. The Hybris robot, seen in Figure 3-12, from the Hirose and Yonedia Lab uses a similar design [21].

A good overview of actuation techniques is Downling's doctoral thesis [38]. The DC motor is the most common actuator in robotic applications, included in many SEW platforms such as Hirose's 20-segment active cord mechanism (ACM) [38]. SEW designers often consider artificial muscles such as "smart materials" too experimental or impractical and revert to the DC motor.

The newest actuator method involves Electroactive polymers (EAPs) [11]. EAP actuators exhibit a fast response time and a large actuation force. However, the large voltage required and the high temperature transition point often yields EAPs inadequate for low temperature and robotic applications.

Snake Motion Control

The coordination of a highly articulated body in three dimensions is a difficult motion control problem. Centralized control is the most common control scheme in which each movement is the result of a command sent from some central processing unit. Decentralized or distributed control is the result of decision making and control commands from several processing units. Yim [29] uses a centralized control protocol to control his Polypod robot.

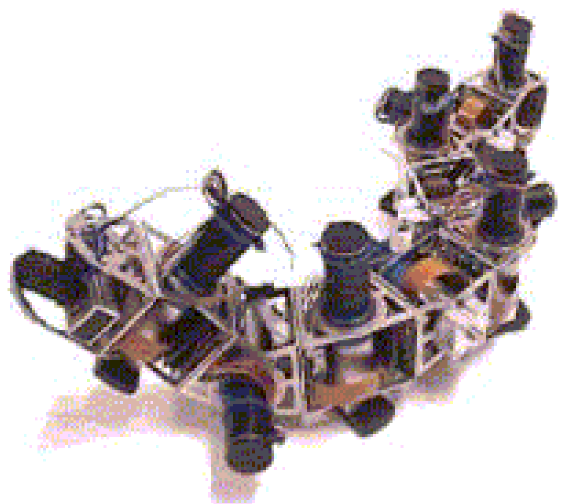
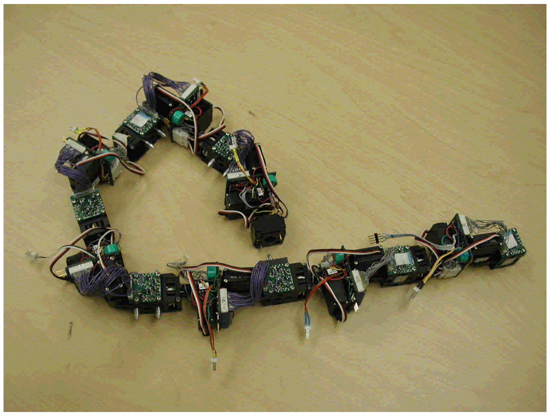


Figure 3-13: Yim's Polybot

In this application the locomotion gait is represented in a control table. Each column of the table is a sequence of actions. A Polybot module will transition from one sequence to the next coordinated by the central controller. Yim suggests the results of this method are versatile, scalable, and that the complexity is manageable. Shen and Stoy [30] employ what they call "hormonal" signaling in their CONRO robot. In this method a signal propagates through the length of the snake causing different actions in segments. With this method of control their snake achieves a motion of approximately 5 cm/s.



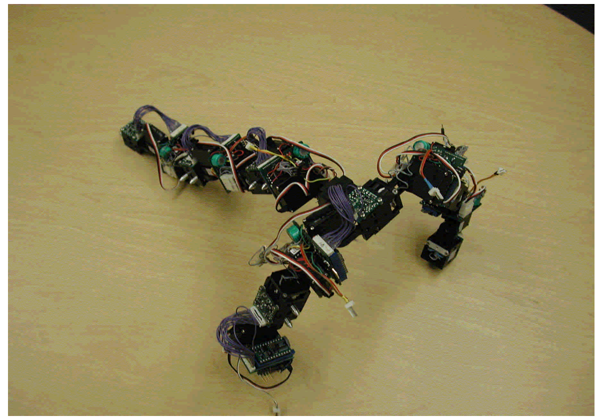


Figure 3-14: CONRO

Several studies also investigate path planning of snake motion. Choset and Henning have developed a path planning simulation [26]. Choset attempts to exploit the geometric snake structure to accomplish accurate path planning for snake motion. The geometry and kinematics of the snake determine the “road map” and thus the path the snake follows. Their work is divided into three aspects: accessibility, connectivity, and deportability. Accessibility is the study of a snake finding a path that will bring it close to a desired point. Connectivity is the traversing of the path to reach the point. Deportability is leaving the path to reach the actual point. Currently Choset and Henning’s work is purely in simulation.

Bentley [31] uses an evolutionally algorithm for adaptive control and creates a damage-resistant snake. The snake is able to learn which sequences of movement provide the best locomotion. His results show recoverable motion when an actuator is damaged. Bentley incorporates SMA actuators in his snake design and concludes that hysteresis in negligible when the wires are small (i.e. 0.15mm).

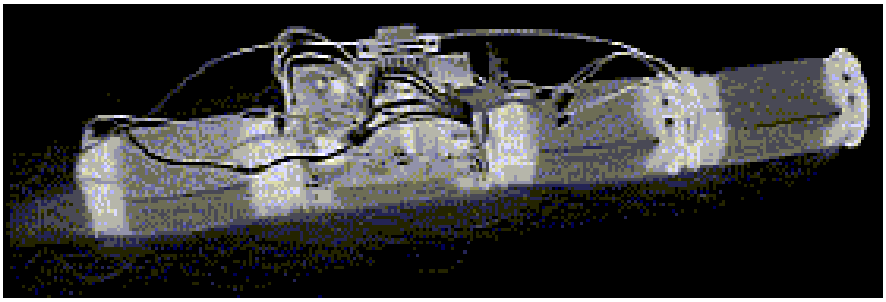


Figure 3-15: Bentley's Robot.

Hirose [21] is a standard reference for the study of snake kinematics. Several researchers go farther then just controlling the snake and also adaptively discover the network topology. Researchers use a centralized controller for snake motion and also for discovering the network topology [32]. Hirose also incorporates distributed control in his ACM-RC, Figure 3-15, in which segments listen for their neighbor's angular position.

Figure 3-16: Hirose's ACM-R3 [23]

Embedded Systems

The platforms discussed in the Snake Robots background section are advancing several SEW technologies such as locomotion, actuation, and mechanics. Most rely on tethered cabling for power and control. Others still lack the on-board processing necessary for autonomous operations such as image recognition. A truly useful SEW platform must operate autonomously on some level, such as locomotion or navigation. The autonomous platform must possess several capabilities such as motion control, image recognition, path planning, and communication. These functions, among others, are extremely difficult for a small microcontroller or embedded computer. It is likely a cluster of computers will meet the needs of these autonomous functions. Eight and 16-bit microcontrollers generally lack the processing power and network support for use in a cluster. Therefore a cluster computer is usually a 32-bit processor or greater running an operating system (OS). The VIPER project uses the Embedded Linux operating system since it is well suited for embedded computing and contains many desired networking features.

While there are several embedded operating systems such as VxWorks, NetBSD, Windows XP, Linux has several advantages. Linux is freely distributed and free to download which has created a large community of support. Linux allows an embedded system to be highly configurable in both hardware and software. The ability to multitask and enable multi users is also an advantage. Usually Linux is platform independent enabling it to run on a number of processor architectures. Thus little or no software changes are needed for new hardware.

Linux has vast networking capabilities which allows for easy exchange of information with other embedded devices or systems. It also allows for many embedded systems to be updated easily. This networking also permits distributed processing and clustering. For this reason several of the world’s supercomputers are Linux or UNIX based. The most common network interface for embedded systems is Ethernet since it is well documented and inexpensive.

Linux further supports a variety of other bus and I/O interfaces allowing the embedded systems to interact with the environment. There are numerous types of busses and interfaces to choose from or develop into any embedded system. Linux has varying levels of support for many of the most common busses and interfaces including ISA, PCI, PCMCIA, PC/104, VME, CompactPCI, Parallel Port, SCSI, USB, GPIB, I2C, I/0, Serial Port.

Toolchain

Embedded Linux and other embedded operating systems generally lack the resources to create the programs and applications they will eventually run. Most embedded applications are created on a larger more powerful computer known as the “host” and then are transferred to the platform which runs the application, the “target.” Often the computer building the application is not the same processor architecture as the embedded system. Therefore the application must be built with the embedded system architecture in mind with a toolchain. A typical toolchain consists of an editor for writing code, a compiler and a linker to transform the code into an executable. More specifically the toolchain consists of gcc, glibc, and binutils.

CHAPTER 4

APPROACH

This chapter discusses the methods to realize the research objectives of Chapter 2. Ideally the overall device will help implement and test a variety of mechanical, electrical, computer processing, and networking solutions. This chapter presents the mechanical, electrical, and computer processing tactics for building a robot capable of SEW locomotion.

Mechanical Design

The mechanical design maintains the VIPER project goals by providing a skeletal structure which supports various types of SEW locomotion. It further enables the use of SMA actuation techniques and the associated electronics and control hardware. The mechanical framework must also accommodate the additional components required for autonomous SEW locomotion.

Segmented Structure

A segmented SEW structure creates a flexible and scalable mechanical device. It makes the body physically and functionally flexible. Adding segments could conceivably add processing power and sensing capabilities or to scale the physical size to adapt to a particular application. In all, the segmented structure allows the SEW to adapt to many situations.

Actuation

Another objective of VIPER project, and this research, is to integrate smart material actuation devices. Shape memory alloy is one of the most viable smart materials. Several companies provide brand-name SMA wire such as Dyallonyol's Flexinol which must be incorporated into an actuator. This project selects an SMA wire already in actuator form. The Electric Piston from Raychem is an SMA wire enclosed in a piston configuration [33].

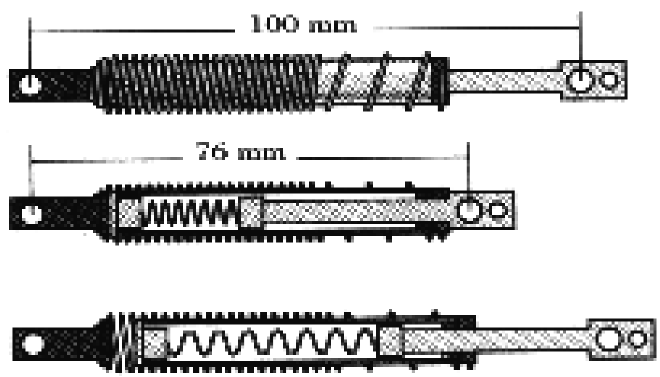


Figure 4-1: Shape Memory Alloy Actuator

When heated, the SMA wire pulls the plunger inside the metal casing. This design has an overextension spring which helps protect the wire from excess strain.

The actuator is not necessarily optimal in this application but the piston configuration is easily integrated into the mechanical structure. These pistons require four amperes of current supplied by Lithium Polymer batteries.

Construction

The SEW segment is sufficiently large to house a variety of electronic and mechanical components. The diameter of the end plate is the primary dimension which dictates the usable space inside the segment. Consequently, the endplates, which act as the ribs of the SEW supporting the weight of the structure, have a diameter of 4.5 inches. The endplates are in the shape of a hexagon to prevent a multi-segment structure from rolling.

A center post connects the two endplates. A telescoping double-ended universal joint originally connected each end plate to the center post but this configuration was under-constrained causing a segment to collapse. The segment was then constrained to 3-Degrees of freedom by removing one universal joint and fastening one end of the center post directly to an endplate. This configuration allows one endplate to swivel and providing rigidity in a segment.

Actuators attach in parallel to the end plates with swivel joints permitting a wide range of motion. A mounting plate attaches to the center post and serves as an area for electronic components.

Below in Figures 4-2 and 4-3 are CAD drawings of a SEW segment [34]. Figures 4-4 and 4-5 show a Pro-E representation of the mechanical design [35].

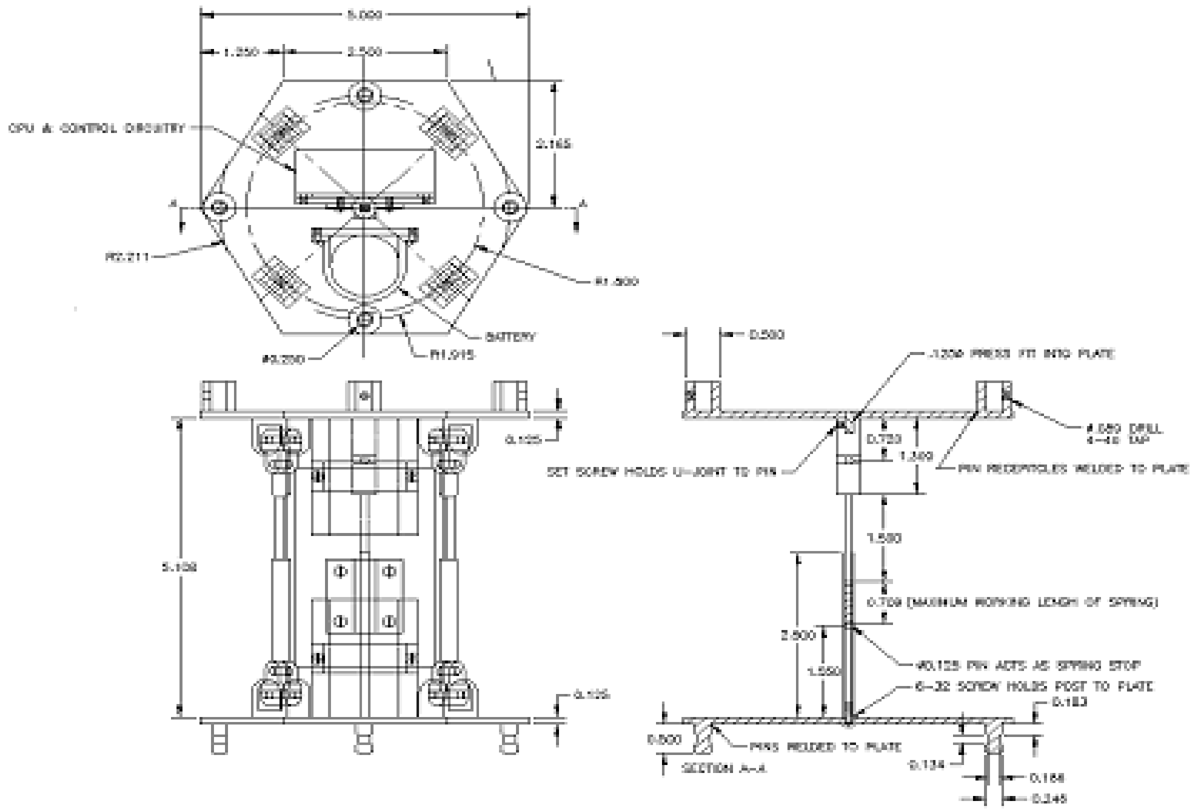


Figure 4-2: CAD Drawing of Segment

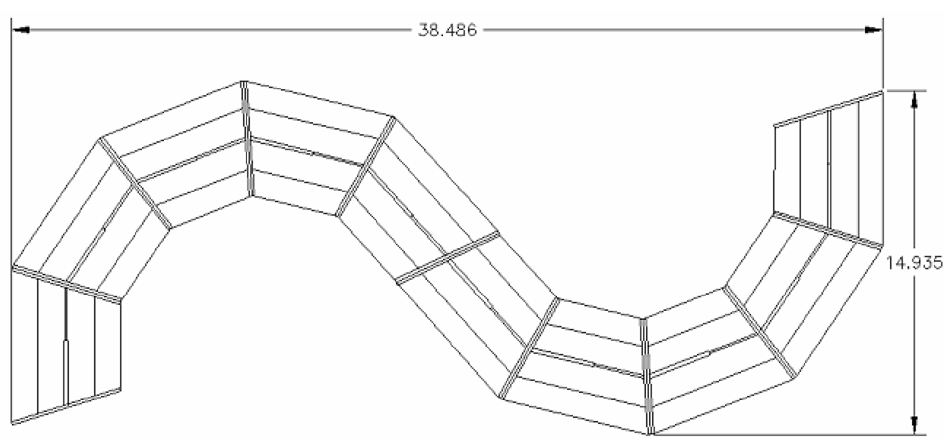


Figure 4-3: Multi-Segment CAD Drawing

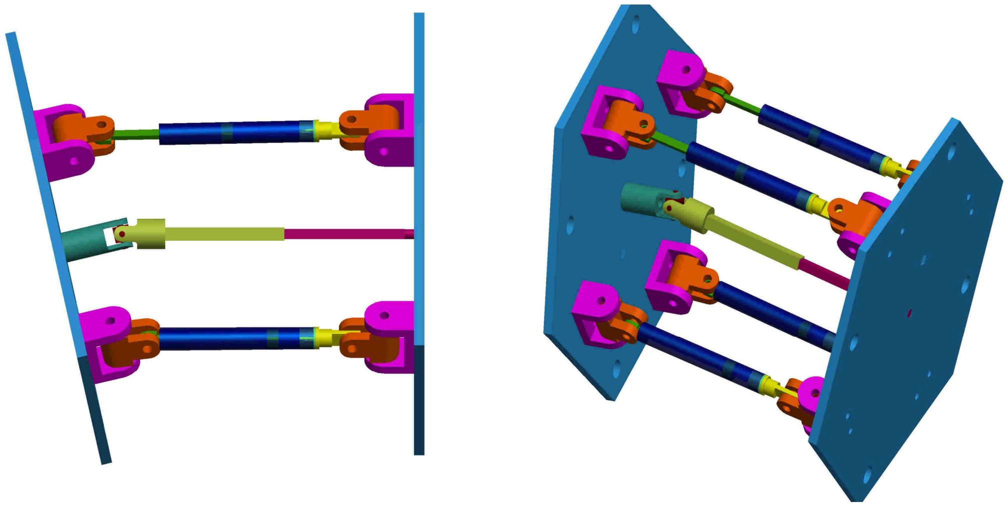


Figure 4-4: Pro-E Drawing of Segment

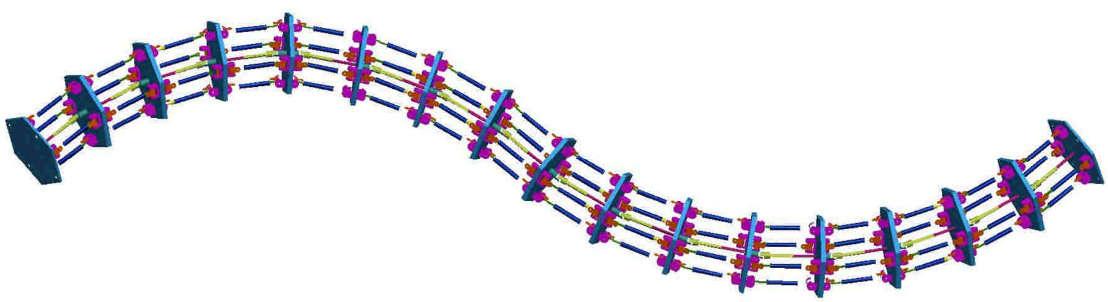


Figure 4-5: Multi-Segment Pro-E Drawing

Aluminum was chosen for rigidity. A single-segment and a four-segment aluminum SEW structures are seen in Figure 4-6.

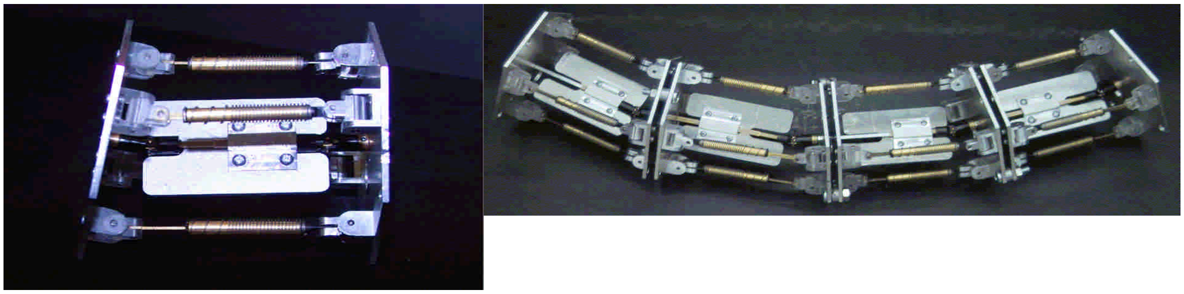


Figure 4-6: Machined Aluminum Segments

Machining took place on an Emco CNC milling machine. Eventually all the parts were built out of Lexan because of weight concerns. Cross country ski skins act as the scales creating a high amount of friction in one direction and very little in the other, Figure 4-7.

Figure 4-7: Cross-Country Ski Skins

SMA Heating

As described earlier any heating method can cause the shape change in SMAs. The VIPER project uses joule heating to actuate the SMA position.

The custom current controller meets several requirements specific to this application. To fit inside the constrained space of a single segment the circuit board must have a small area. The weight of a typical controller is often negligible; however, consideration is still given to it, since weight is critical to this project. The current controller pulses the maximum current allowed by the battery, which is rated at 5 Amps.

To vary the SMA temperature, and thus the piston length, the current controller provides a variable amount of current through the use of a pulse-width-modulation (PWM) chip. A typical PWM signal is seen in below.

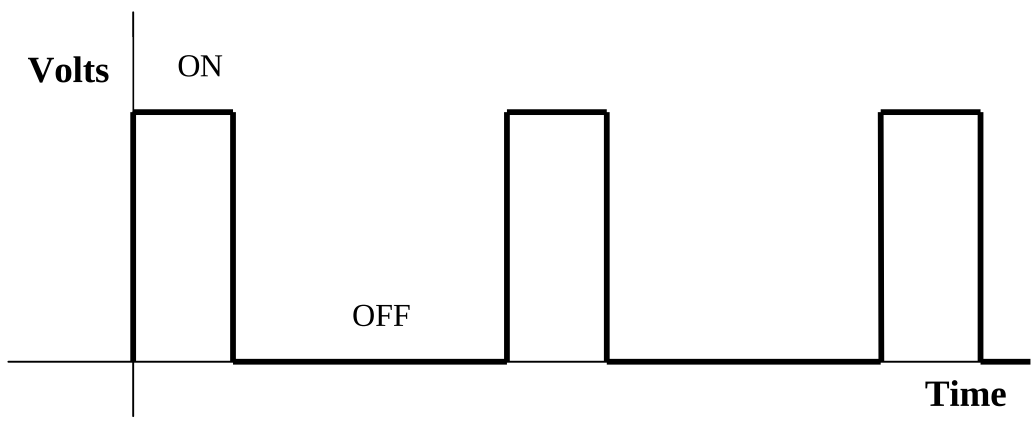


Figure 4-8: PWM Signal

When the PWM signal is high, the current is ON and flows through the SMA, otherwise when the PWM signal is low the current is OFF. The high voltage level causes current flow by activating a HEXFET transistor. These transistors turns ON (i.e. completes the circuit) when a 5 V signal is placed on the input terminal. The percent of time the PWM signal is high is known as the duty cycle. If the signal is high for 10 microseconds and low for 90 microseconds the duty cycle is 10%. The duty cycle of the PWM is set by control commands received on the I2C communication bus. Pulsing current at a high frequency (kilohertz) creates slight temperature variations by changing the duty cycle which allows for greater control. Additionally, a PWM current is one of the most efficient heating methods.

The current controller board also incorporates additional components such as an analog-to-digital (A/D) converter for the SMA position feedback and an input-output I/O expander for future needs. The current controller board is seen below.

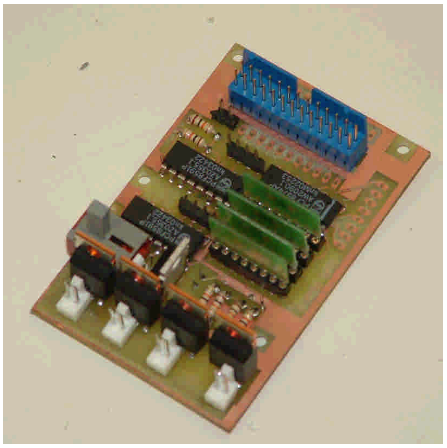


Figure 4-9: PWM Circuit Board

Position Control

The SMA actuation is currently under two-position or bang-bang control in which the actuator has only two desired positions. The equations below describe the controller output signal, m(t), and the error signal e(t). Typically in two-position control m(t) remains at either a maximum or minimum value as described by to following equations.

$$\begin{aligned} m(t) &= M_1 \qquad e(t) > 0 \\ &= M_2 \qquad e(t) < 0 \end{aligned} \tag{4.1}$$

The values of M_1 and M_2 relate to the electric current duty cycles of 15% and 0% respectively. Figure 4-10 shows the block diagram for the two-position controller. A differential gap causes the controller output to maintain the present value until the error signal has moved beyond a certain threshold. This method control the actuator between two positions. The Spider module supplies the reference input signal as well as calculates the position error. Figure 4-11 illustrates the system with a block diagram.

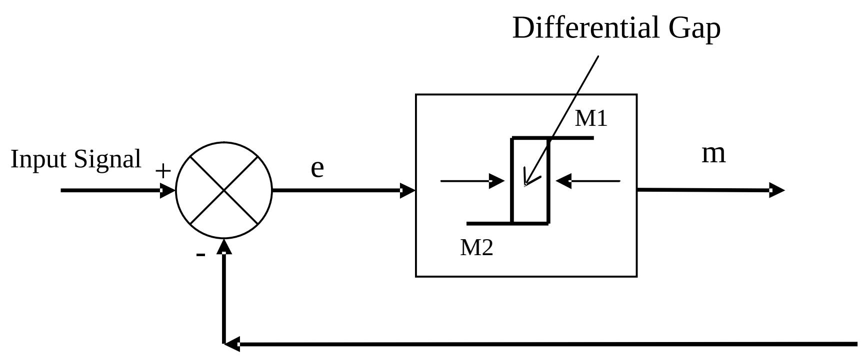


Figure 4-10: SMA Controller Block Diagram

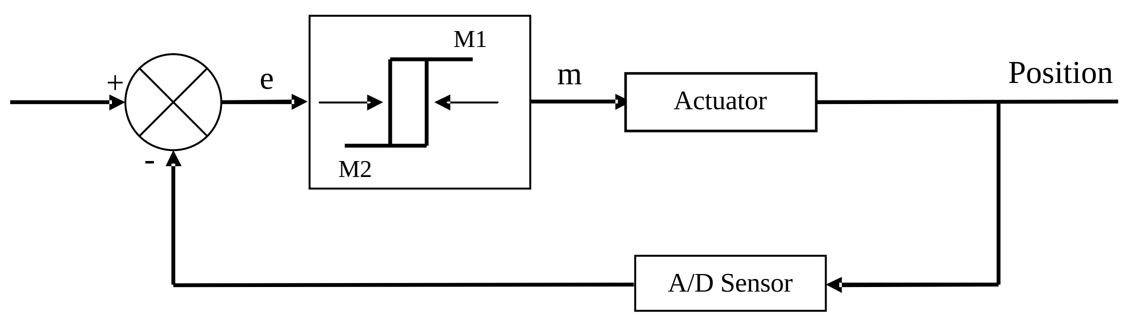


Figure 4-11: System Block Diagram

Embedded System Development

Computer clustering will provide the anticipated processing and control for SEW operation. This section describes the embedded Linux system which will enable distributed control in the VIPER project. Chapter 5 describes the implementation of a simple distributed controller.

In this SEW design, each segment contains a P501 Spider single board computer (SBC) with a PowerPC 440GX processor [36] [37]. The Spider module, Figure 4-12, is ideal for embedded applications with a small area (1.9” x 2.8”) and large amounts of RAM and ROM. The Spider’s two Ethernet ports further enable a variety on network configurations. In the VIPER project the Spider’s are connected in a daisy-chain network topology which supports a SEW segmented design. Figure 4-13 shows how each SBC and segment are nodes of the network. Below is a discussion on how to create and configure applications for the Spider modules.

Figure 4-12: P501 Spider Single Board Computer

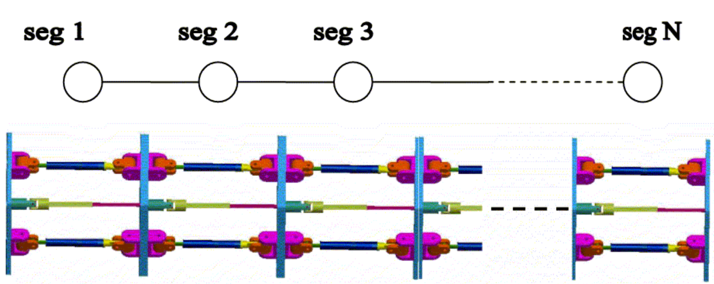


Figure 4-13: Daisy-Chain Network

Network Topology

The spider modules are physically connected in a daisy-chained network configuration in which the computers are in series. In actuality each link functions as its own network allowing a Spider module to only communicate with its immediate neighbors. Both of a Spider's Ethernet ports have identical internet protocol (IP) address. A routing table on each spider contains the IP address of neighboring computers. Figure 4-14 is a diagram of the VIPER network topology with corresponding IP address for each segment.

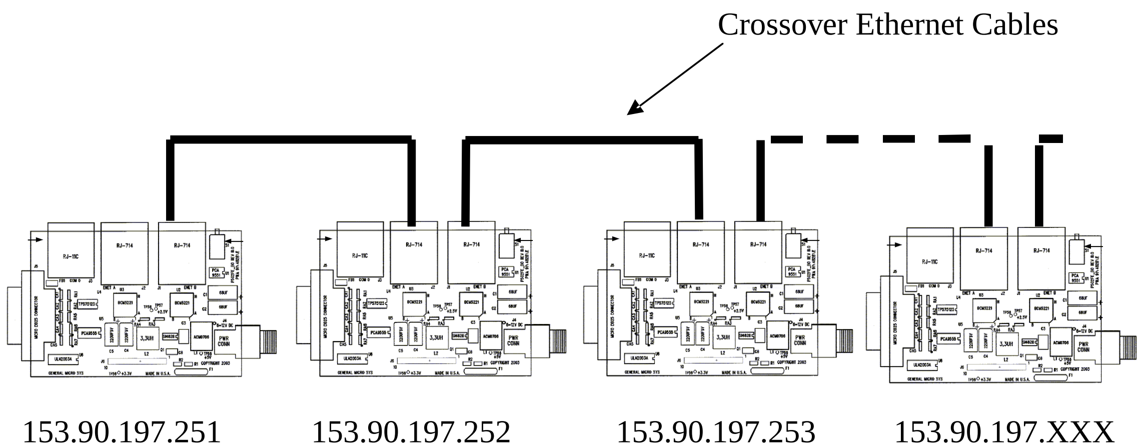


Figure 4-14: Daisy-Chain Computers

Toolchain Build

The toolchain creates the embedded application for the Spider. The SBC vendor, General Microsystems (GMS), cannot legally supply the toolchain and its utilities under the GNU Licensing Agreement but can provide directions of how to obtain the same toolchain which they used for development. The toolchain is downloaded from the Denx website [38]. See Appendix A for detailed steps to setting up the toolchain.

The toolchain image is configured for a specific host/target environment. In this instance the toolchain is configured to produce applications for a PowerPC target from an i686 host to create executable applications for the Spider.

Root Filesystem

The Embedded Linux command line interface is very similar to its desktop counterpart. Both permit users to move through the filesystem folders (i.e. /usr /bin /proc /mnt) which contain various documents and programs. The Spider's root image; which is a block of memory which the embedded system uses like a disk. GMS provides a RAM disk image which is modified to meet the needs of the VIPER application. See Appendix B for more details.

To modify the root filesystem, the RAM disk is first extracted, uncompressed and mounted as a temporary device on the host system. Now anything can be added or removed such as files, directories, Linux commands, device files, etc. Once properly configured the image is unmounted and compressed. The toolchain command *mkimage* creates the actual image used by the Spider. Appendix D describes to steps to load an image to the Spider.

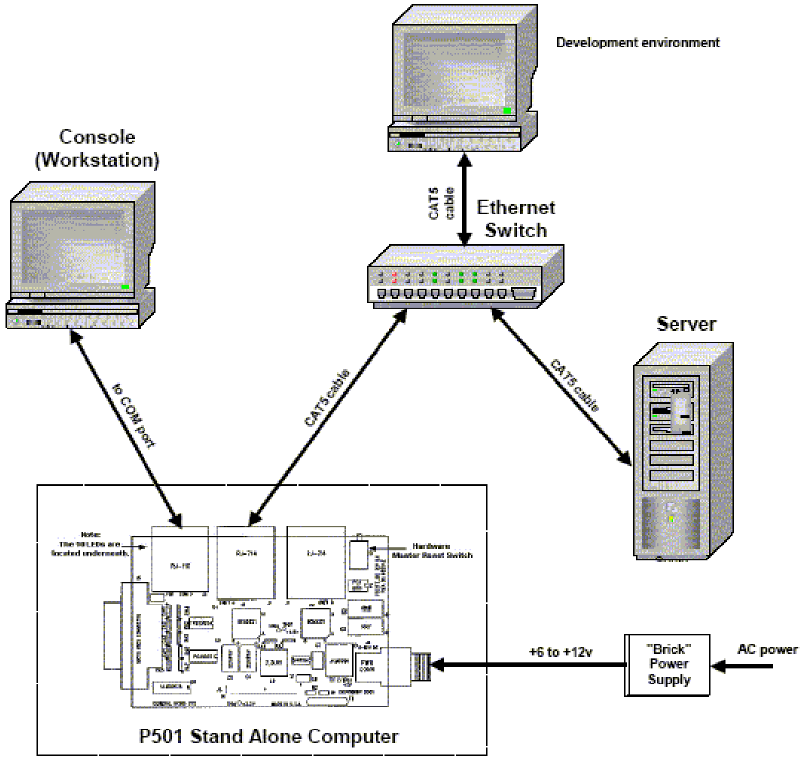


Figure 4-15: P501 Development Setup [38]

<u>Busybox</u>

Included in the root filesystem is the Busybox executable [40]. Often considered a cornerstone of embedded Linux systems, Busybox is a single executable which contains the functionality of most Linux commands such as *cd*, *ls*, *ifconfig*, etc. When a command is typed at the command prompt of the embedded system it is linked to the Busybox executable which runs as that command. Busybox is widely used in embedded applications because of its small size (roughly 200 KB) and familiar functionality. Developers can easily obtain the source code and build the Busybox executable with the desired functionality. It is simply built like another Linux application but with the toolchain for the desired platform. Using the *make menuconfig* command it is easy to select the desired commands. This is useful in development as well as running applications on the embedded system.

Application Transfer

Minicom is a common terminal emulator which allows developers to issue commands and initiate file transfers to the target system. Minicom uses the RS-232 serial link to communicate with the Spider module.

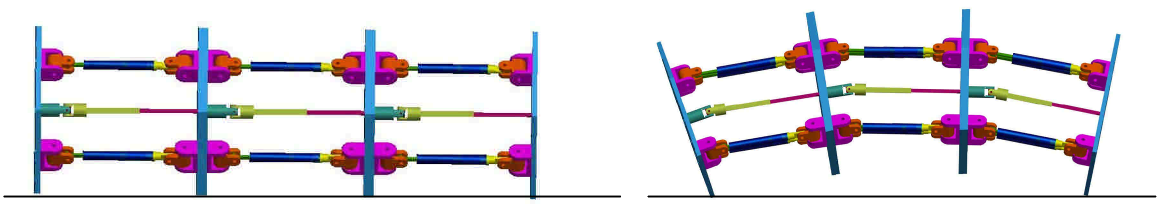
When the Spider is powered the bootloader prompt appears in the Minicom terminal window. The bootloader is a target application which conducts low-level hardware initialization and ultimately starts the operating system [39]. The VIPER project uses the U-boot bootloader, provided by GMS, to load application images to the Spider. See Appendix D for the steps to load the U-boot to the Spider. The U-boot "Flash" command uses TFTP to retrieve RAM disk image from the development workstation. It then places the RAM disk into the user-specified memory location on the Spider. For details of this installation see Appendix D. The kernel and RAM disk images contain the complete Spider application.

Motion Control

This section describes the distributed controller. The control scheme is important to realizing the goals of the modular SEW design. The embedded system described previously will apply distributive control to the SEW assembly to create an inchworm motion. In this control system each segment contains a Spider computer module to control the actuators as well as communicate with neighboring segments.

Overview

The inchworm type motion is accomplished by the SEW structure curving its body into a C-shape and returning to a flat position, as in Figure 4-16. With the use of the snake skins mentioned in section 3-1 this cyclical shape change will result in forward motion.



(a) (b)

Figure 4-16: Positions of Inchworm Motion

To keep the system modular, segments do not issue commands to other segments. No "head" segment functions as a centralized controller. Segments base their movements on the environment which indicates the overall shape of the SEW. As a result the control protocol must allow all segments to assess environmental data and make an informed decision based upon the information from neighboring segments. Segments will assess the environment data and determine the action. Sharing this information through the high speed communication network the segments can actuate concurrently creating the smooth inchworm motion.

Detailed Operation

The system-level overview is best described with a state diagram and logic equations. The objective is for the segments to collectively curve into the orientation seen in Figure 4-16. If the segments move to these positions at the same time the coordinated movement will move the structure forward.

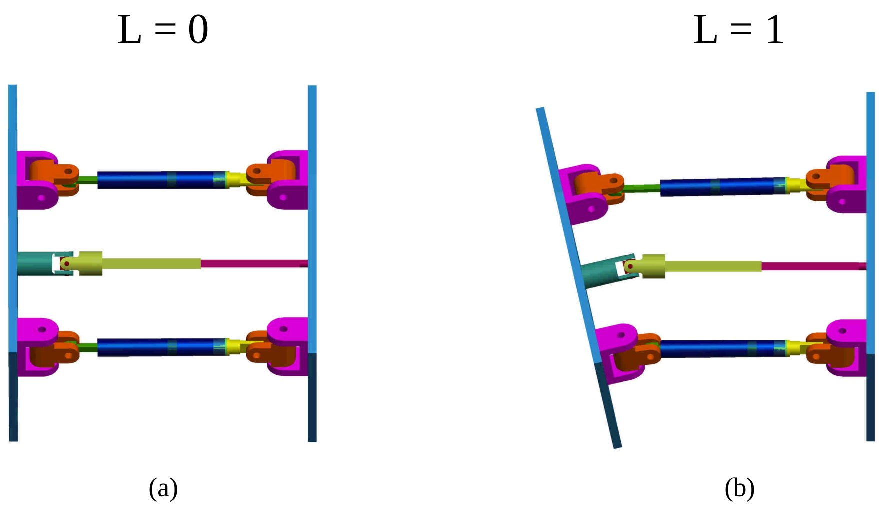


Figure 4-17: Single-segment Positions for Inchworm Motion

Single segment position control is accomplished with the heating control hardware discussed earlier. Actuating the segments at the same time is the crucial factor. This coordination relies on the data exchanged over the Ethernet links. Segments must exchange information describing the position of the end plate. Position feedback from the sliding resistor is the source of all environmental information. For this study when the plates of a segment are parallel as in Figure 4-17(a) it has a local state, L, of zero, (0). Conversely when the bottom pistons are actuated, as in Figure 4-17 (b) it has a local state of one, (1). Likewise when the entire structure is in the form of Figures 4-17 (a) and 4-17 (b), the Global states, G, are A and B respectively. Figure 4-18 shows the state diagram of the control protocol.

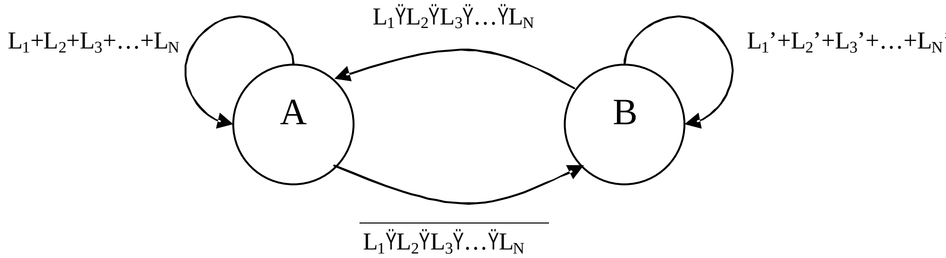


Figure 4-18: State Diagram of Inchworm Motion Control

Each segment will use the local information of other segments to determine the global state and select the appropriate action. For instance, if the global state is A, segments will wait for all local states to become zero and then transition to global state B. A transition corresponds to a state of actuation whereas global states A and B corresponds to states of rest. All segments then wait for the global state to become B before it actuates towards a local state of 1.

To exchange information each segment first determines its own local state by reading the A/D. If the reading is above or below certain threshold values the state is determined to be either a 1 or 0. For this work a local state of 1 corresponds to an A/D reading of 80 or higher and a local state of 0 corresponds to 20 or lower.

Transmission Control Protocol

Once known the local state is exchanged with its neighboring segments using the Transmission Control Protocol (TCP). The segment will make its local state available by functioning as a TCP server. To receive that information the neighboring segments must request this document and read the data. Transmission Control Protocol is a connection-oriented communication service. It is also a byte-stream service; a sequence of bytes is sent from the source to the destination [39]. The bytes are “buffered” since they are placed into blocks which then go to the IP layer. The communications link is duplex since it can send and receive data concurrently. Netcat is the specific TCP utility used to transmit data across the Ethernet connections. Netcat is as a reliable backend tool which can easily interact with programs and scripts and can handle both inbound and outbound connection using either TCP or UDP [41]. This utility comes on most distributions of Linux and UNIX operating systems. With these systems netcat is a feature-rich utility which is highly configurable for almost any type of connection. The Busybox netcat can function as a server or client. As a server it listens for inbound connections and provides the requested file. When a client it can request data from a server or can pipe data to another connection.

With each segment functioning as a server information propagates to all the segments. Middle segments have the additional responsibility of passing multiple local state values to other segments. All segments will operate under the same algorithm and test the global data equally. As a result, they should all observe the completion of a global state and independently decide to move toward the correct state.

Example Operation

To further illustrate the control protocol a simple example is presented. To start out the structure is lying flat on the ground. Segment #1 reads the A/D and determines the local state is 0 and stores it in the global document which neighboring segments request. The global document which Segment 1 requests from Segment 2 is seen in Figure 4-19.

```
Seg1: 0
Seg2: 0
Seg3: 0
Seg4: 0
```

Figure 4-19: Example Global Document

By reading these values Segment #1 determines that the structure is lying flat on the ground. Thus to create motion it must actuate towards a local of 1. The next time it requests information it receives the following document:

```
Seg1: 0
Seg2: 1
Seg3: 0
Seg4: 0
```

Figure 4-20: Example Global Document

It decides that it needs to keep actuating its pistons. The next time it observes the environment document it sees:

```
Seg1: 1
Seg2: 1
Seg3: 1
Seg4: 1
```

Figure 4-21: Example Global Document

It decides a global state has been reached and actuates its pistons towards a local state of 0. This process is a continuous loop. Ideally, the position of each segment will be identical to all of its neighbors. The optimal positions, with respect to time, of the individual segments in a three-segment structure could be represented graphically as a sine wave. If data transmission was instantaneous all segments would observe the global state at exactly the same time allowing them to all actuate between states in unison.

Important Issues

Communications delay is one concern to this network and the control scheme. It will take longer for the outer segment to acquire the state of the entire system. If a segment oscillates around a local state it will write corresponding values to the global document. This may cause distance segments to see a false local state. This could result in the observation of different global states. In this case a segment could actuate in different directions making the system highly unstable. The combination of the high speed Ethernet network and the low cycle-time of the actuators will help stabilize this problem. It is conceivable that in a 4 or 8-segment structure, all environment data could reach end to end within one second creating a communication rate of approximately 1 Hz. The cycle time for a piston is specified as once per minute or 1/60 Hz. For that reason the order of magnitude difference in cycle times allows segments to make well informed decisions.

Another main concern with distributed networks is synchronization. The observation of the global state allows segments to observe the same data and make informed decisions. As a result there is no need for a global clock to synchronize all segments.

Flexibility

This control approach can be flexible in that it can be applied to structures with varying number of segments and other gaits of locomotion. The challenge is properly defining the required states needed for different types of locomotion. In more complex schemes individual segments would need to achieve desired states of position, velocity, and acceleration. For instance, a serpentine type motion may require the velocity of the preceding segment as the environmental data. The segment would then try to move its end plate with the same velocity but slightly out of phase.

This distributed control protocol addresses the issues of communication delay of synchronization. Each segment will observe its current state as well as the state of the entire system and make a decision based upon both.

In the future, segments will observe more environmental information through sensors such as accelerometers, gimbals, and GPS. Additional capabilities of individual segments will minimize inter-segment communication and reduce the communication delay. With the current structure the described protocol is a way of allowing an individual segment to control its own functionality based on environmental observations. The segments will automatically operate in an inchworm type of motion. This type of motion could also be accessed from another “main” program if inchworm motion was the best solution.

CHAPTER 5

RESULTS

This chapter describes the integration of mechanical, electrical, and embedded control subsystems for inchworm movement. Discussed are several trials ranging from single-segment motion under manual control to three-segment motion under autonomous control. Each trial includes a discussion of the physical setup, performance of the structure, subsystems operation, and general notes and observations.

Manual Control

Single Segment

The first locomotion trial involves an aluminum single segment which includes the current controller and battery housed inside. A human operator controls the piston actuation by turning the current ON and OFF with a constant duty cycle of fifteen percent. The top and bottom actuators are controlled as pairs to produce the inching motion seen in Figure 5-1.

(a)

(b)

(c)

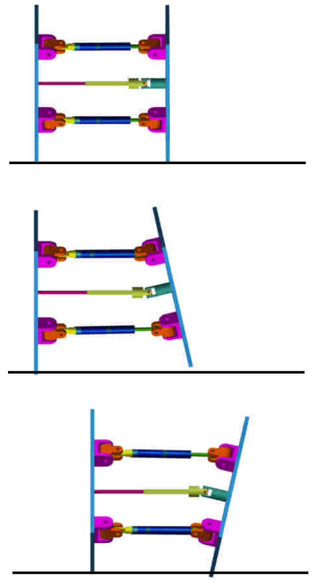


Figure 5-1: Single-segment Inching cycle.

For this motion trial the above figures are not associated with the local states described in Chapter 5. Instead the segment is controlled to the positions shown to produce forward motion.

As documented in [42] the segment moves approximately 0.5 inches per minute. Although slow, it demonstrates the mechanical design moving under its own power for a sustainable period of time. As a result of this trial the current controller board was redesigned with larger current traces and an A/D for position feedback. It was also evident that a position control system would improve performance. Often the piston was supplied with an incorrect amount of current. When too much current is supplied the SMA wire overheats and requires a longer cooling period. If too little is supplied the current must be turned ON again. Both situations reduce the cycle time and the overall speed of a segment.

<u>Three-Segment.</u>

The manual control of a Lexan three-segment assembly allows a human operator to control each segment with a desktop computer into the desired states. A simple circuit allows the computer's parallel port to function as an I2C bus which provides the actuation into the motion in Figure 5-2 where the associated local and global states are listed to the right. The circuit schematic is seen in Appendix I. The setup is also seen in Figure 5-3.

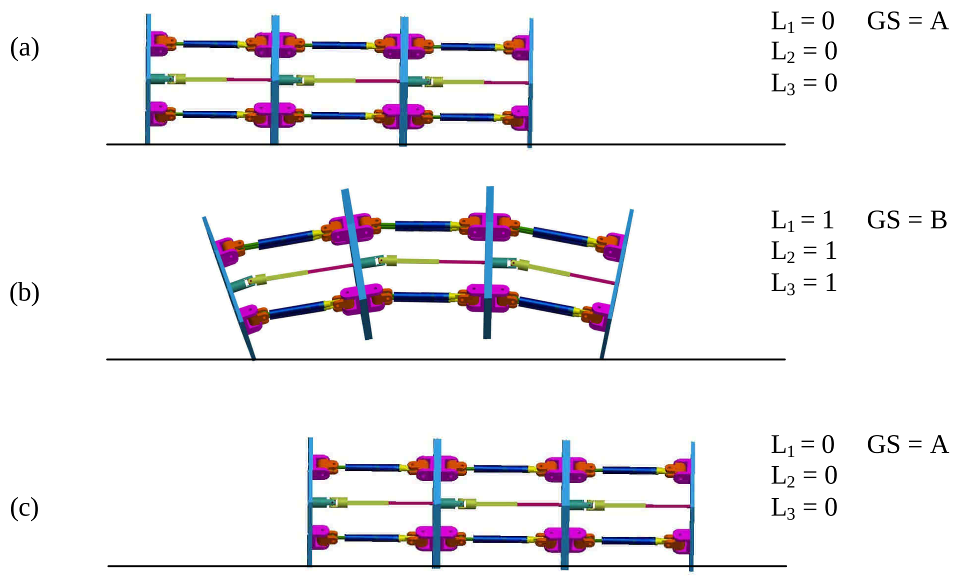


Figure 5-2: Three-Segment Inchworm Motion Cycle

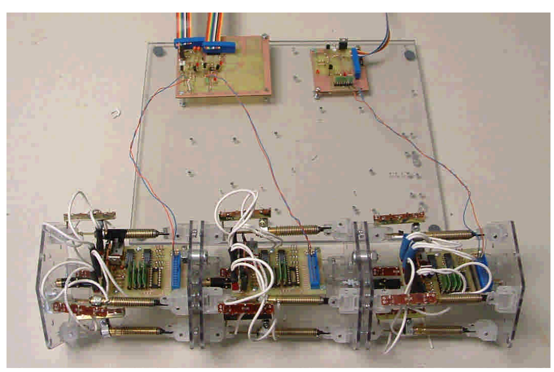


Figure 5-3: Three-Segment Manual Control Setup

Under the PC control the structure moves approximately 1.375 inches per minute. The 3-segment desktop control experiment reveals valuable insight to the mechanical design. The structure cannot achieve a noticeable body curvature with the current piston configuration. The telescoping universal joint provides no pivot point; actuation causes the endplates to move closer together while still remaining nearly parallel. This causes a decrease in the overall length of structure, with virtually no forward movement, instead of the desired C-curvature. A slight difference in the telescoping range possibly prohibits this motion in the Lexan segments. It is likely telescoping center post length is different than the aluminum single-segment test. By temporarily removing the telescoping aspect of the center post, a pivot point is created at the expense losing a degree of freedom. This does not greatly affect any of the common SEW gaits discussed in Chapter 3 but does eliminate the possibility of locomotion by the compression and expansion of each segment also known as accordion locomotion. Also, this modification most likely reduces the concertina motion slightly restricting the extension of the body.

In this test it was observed how the pistons are not optimal in this mechanical structure. Being spaced equally from the center post the bottom pistons cannot overcome the weight of the structure to create a C-curve. For this work the bottom pistons are temporarily repositioned directly underneath the center post to provide an increased moment around the pivot point. This configuration creates the necessary force to produce the desired curvature. This change does decrease the lateral or azimuth mobility of the structure since only the top pistons provide an actuation force in the horizontal directions. However, SEW gaits such as lateral undulation are still possible with optimal SMA wires

[33]. The top pistons remain in the original configuration since the force they provide, along with gravity, cause the structure to easily flatten against the surface. When an optimal piston is found they can easily be placed in the original configuration.

Overheating and under heating the SMA wires were again common problems resulting in reduced cycle times.

In this trial the 3-segment structure moves under its own power. Each segment included the battery and the current controller. Not included on the structure is any sort of processing device.

Autonomous Control

The SEW device must now intelligently control itself with the embedded system and protocol discussed in Chapter 3. Trials with one, two, and three segments are conducted.

Single-Segment

The single-segment trial utilizes the feedback sensor and Spider control to obtain inchworm locomotion as seen in Figure 5-1. The test setup is seen in Figure 5-4. The application program running on the Spider is a modified version of the protocol discussed in Chapter 3.

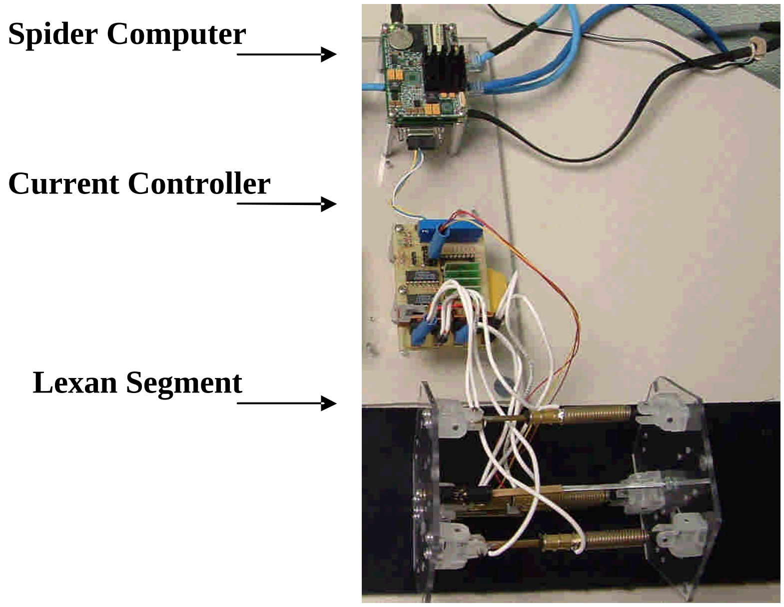


Figure 5-4: Single-Segment Autonomous Setup

The single-segment inches forward at approximately 1 inch per minute. All subsystems seem to operate properly. No modifications to the mechanical structure were made as a result of the tests. Results indicate the Spider module is able to move the end plate into the desired position and is ready to be synchronized with other segments.

Two-Segment Motion

The two-segment setup incorporates communication to synchronize the plate movement. The fixed plates of each segment are arbitrarily attached end-to-end. Actuating corresponding pistons on each segment will yield forward motion as in Figure 5-5. The Spider's onboard LEDs show the global and local states for observation and debug purposes. The physical setup is seen in Figure 5-6.

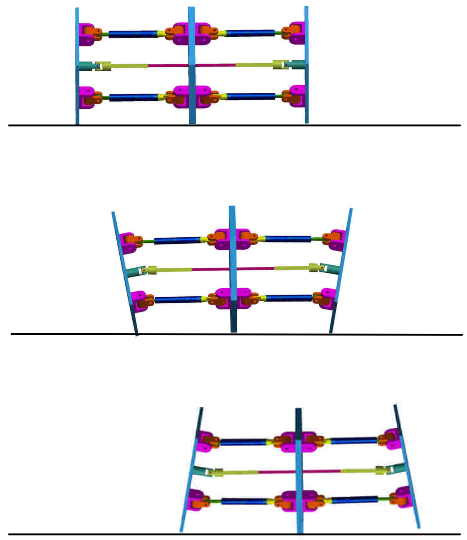


Figure 5-5: Two-Segment Inchworm Motion.

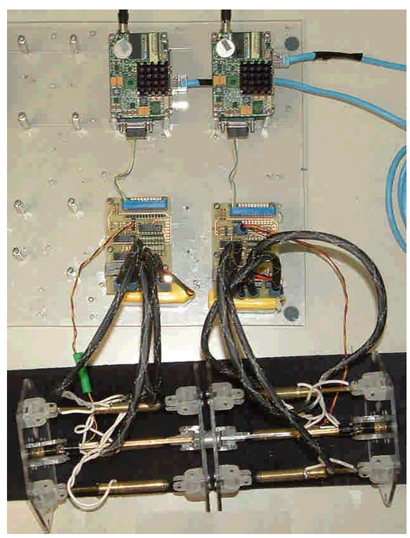


Figure 5-6: Two-Segment Autonomous Setup

Again, a slightly modified version of the protocol discussed in Chapter 3 controls the two-segment assembly. The control program does use the same communication techniques to determine the global state and control the pistons.

The two segment setup moves approximately 1.5 inches per minute. Although the application program observes a global state change nearly instantaneously, as seen on the LEDs, there is some lag in the mechanical response due to the SMAs pistons. A pair of pistons actuates pulling on the end plate and continues until a global state is observed causing the opposite pistons to actuate. However, the first pair has had little time to cool and resists any extension. The opposite pair induces no movement on the end plate until the pistons cool. This causes the segments to be temporally out of sync before reaching the same state. It appears the cycle time is too fast and the segments cannot instantaneously change between positions of Figures 5-5(b) and 5-5(c). When a state is reached time is needed for the SMAs to cool.

Three-Segment Motion

The three-segment setup incorporates the distributed control protocol of section 3-3. The Spider modules communicate in order to achieve a synchronized motion. In this test the segments are assembled in a homogenous fashion with each movable end plate attached to the next segment's fixed plate as seen in Figure 5-3.

The 3-segment structure achieves a speed of approximately 1.83 inches per minute. The overheating and cooling problem was observed in this test as well, however with a more debilitating effect. The sliding resistor does not take into account the length of the overextension spring. A piston can fully actuate and still cause no movement on the end plate but instead lengths the overextension spring. When this occurs the program will see the reading of the A/D and interpret a false position and state. A segment may then move towards the other state when it has not fully reached its original target re-actuating the pistons which have not cooled.

a) $L_1 = 0$, $L_2 = 0$, $L_3 = 0$ GS = A

b) $L_1 = 1$, $L_2 = 1$, $L_3 = 1$ GS = B

c) $L_1 = 0$, $L_2 = 0$, $L_3 = 0$ GS = A

Figure 5-7: Three-Segment Inchworm Motion

The mechanical design of the segments has a noticeable affect on movement. The segments appear to actuate one after another instead of concurrently even though all corresponding piston are actuating. The leftmost segment of Figure 5-7 has less force opposing the movement of its end plate and thus takes less current to change its position. The left segment creates more weight for the middle end plate and requires the middle segment’s pistons to actuate longer.

Figure 5-8 shows the segments actuating synchronously. The horizontal lines on each plot represent the threshold values which determine the local state. When all the all of the positions are above or below the horizontal lines a global state is reached and actuation begins towards the opposite state. The transition to a global state is denoted as a vertical dashed line in Figure 5-8. Segment 1 in these figures corresponds to the rightmost segment in the figures above.

Segment 1 has the most overshoot of a target position when actuating toward a local state of zero. The actuation process of Segment 1’s top piston is underdamped since the weight of a single segment is the only load. The position of Segments 2 and 3 are much more accurate with less overshoot and acceptable steady state error. The rise time appears to be the result of their location in the structure. Both segments 2 and 3 reach the target state with minimal overshoot or steady-state error.

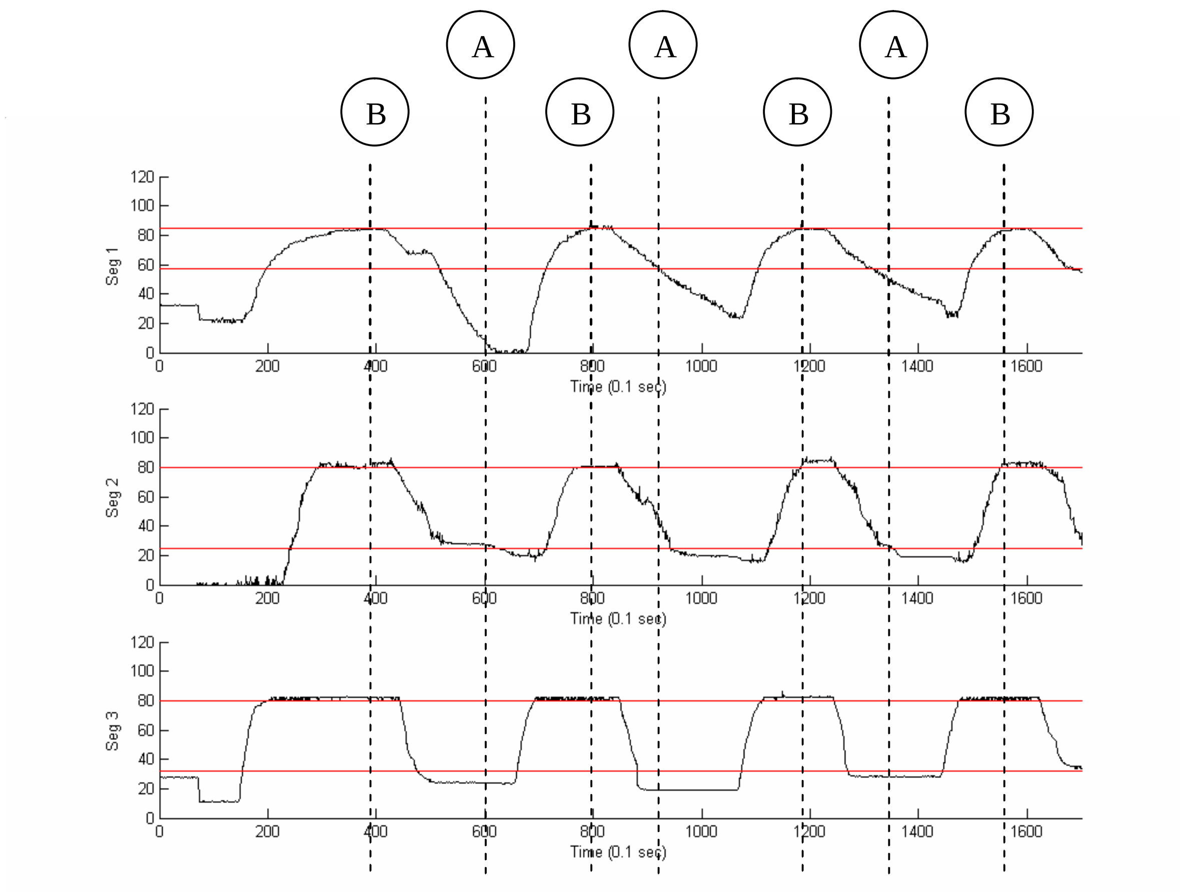


Figure 5-8: Position of Each Segment

Figure 5-8 further shows how Seg 3 changes states in the least amount of time and then waits for the other segments.

To achieve the inching motion in the three-segment test setup the piston is actively controlled since the weight of the structure is a constant disturbance to the position of the plates.

With just a two-position or Bang-Bang controller the position of the piston can oscillate about its target value. Figure 5-9 shows how the weight of the structure is a disturbance pulling against the actuator. The pistons must be re-actuated to maintain a local state; this creates difficulty obtaining a global state especially if several segments oscillate near the target value.

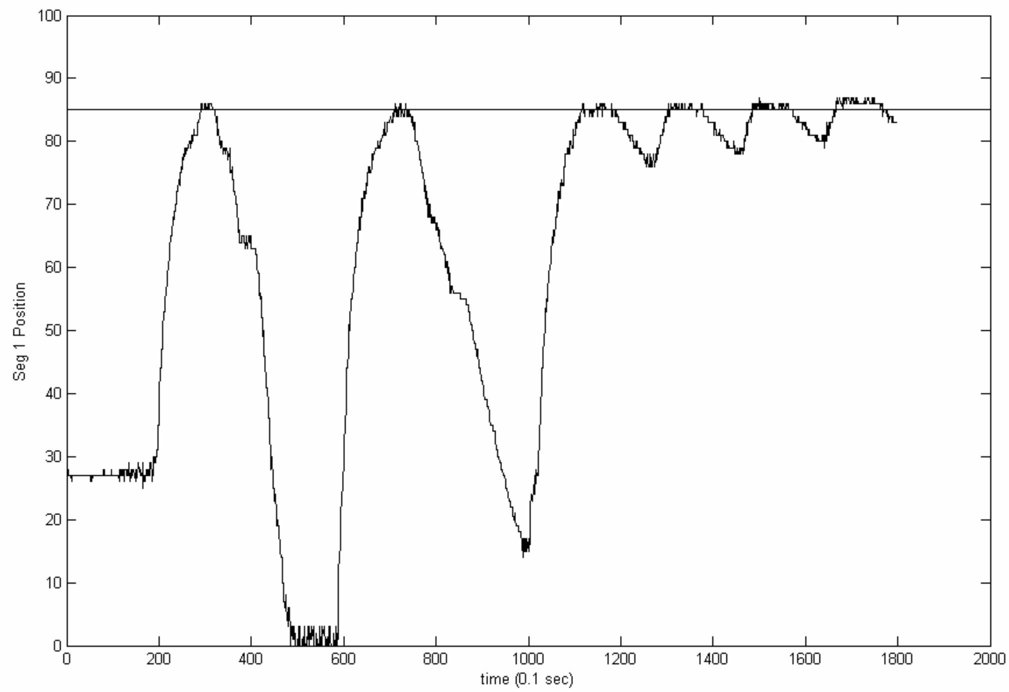


Figure 5-9: Two-position Controller

To avoid this oscillation, current is continually delivered to the SMA, although only enough to maintain the temperature and keep it in an actuated state once a local state is reached. In most three-segment trials no segments oscillated around the target value before a global state was reached. The regular duty cycle of the actuation current is roughly twelve percent and three percent when a state is reached. The two-position controller works in the one and two-segment cases because of the minimal amount of disturbance seen by the plate enabling them to easily hold their positions.

To avoid overheating a 15 second delay is added in every cycle. The pistons appear to hold their target position while not overheating the SMA wire to the point where the opposing force cannot overcome it. This allows the just-actuated pistons time to cool. Then when the opposing piston actuate they will not oppose the force of those pistons.

Four-Segment

The same distributed control scheme is used to control a four-segment SEW structure. However, this attempt was unsuccessful due to insufficient force provided by the SMA pistons. During actuation of the bottom pistons all force was absorbed by the overextension of the springs causing no displacement in the end plates. Thus the SEW structure did not exhibit any curvature nor forward motion.

Summary of Results

As mentioned earlier the snake structure obtains constant forward motion in an inchworm-like fashion. The combined effect of the pistons further increases the locomotion capabilities as seen in Figure 5-10.

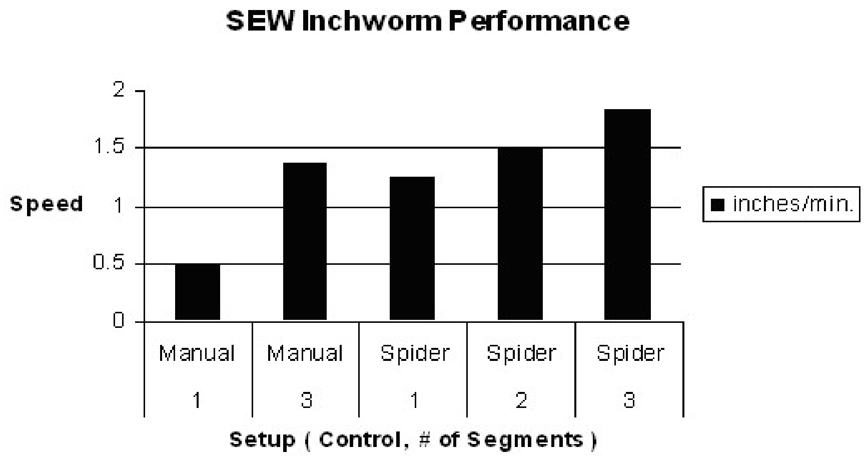


Figure 5-10: Inchworm Result

The single-segment was slower because of the full actuation of the pistons requiring them to reach a higher temperature and take longer to cool, decreasing the frequency of cycles. With the multi-segment setup the pistons are required to actuate less while yielding the same locomotion. And this in turn increased the maximum cycle time. The cycle time of SMA improves as the strain is relatively small compared to the overall length.

CHAPTER 6

CONCLUSION AND SUGGESTIONS

This thesis work accomplished the objective of inchworm motion with a segmented, SMA-actuated SEW structure under distributed control. The resulting platform further supports the ideas and goals of the VIPER project. The segmented structure enables the platform to be modular. Future segments will be added or removed to customize a SEW device for specific applications. The SMA actuation is scalable, furthering SEW technologies to many applications. Although not optimal for this SEW structure the SMA piston proves a segmented structure can move under its own self-contained power. The three-segment structure moves at 1.83 inches per minute compared to the maximum speed of 2.095 inches per minute calculated in Appendix J. The embedded network of Spider computers can be utilized as a cluster to provide processing power, autonomous operations, and difficult tasks, such as image recognition and path planning. The distributed control method further allows the systems to maintain the segmented structure and enable modular capabilities. This protocol permits the segments to collaborate and synchronize their movements into inchworm locomotion. Segments do not receive commands instead they base their actions on environmental information received from neighboring segments. Specifically the goals reached are as follows: 1) A flexible, lightweight, mechanical SEW structure was built 2) Shape memory alloy piston, are effectively incorporated as the actuation method, and 3) A distributed control system was constructed to control and coordinate segment actuation.

The goal of SEW locomotion was accomplished in a three-segment structure but not a four segment structure due to an ineffective actuation force. Had the pistons been optimal for the weight of a four-segment structure it is probable the distributed control system would have resulted in forward locomotion.

This mechanical assemble and future prototypes will help increase the capability of mobile robots to navigate unstructured terrain. The SEW structure of this thesis work is a precursor to a device capable of adapting to any land or sea environment.

Suggestions for Future Work

The next step of the VIPER project is to complete a dynamics study to design an optimal SEW structure. Although this platform is capable of inchworm locomotion with SMA pistons, the size and placement of each is not optimal. This is evident in the structure's speed and cycle time. Shape memory alloys and other smart material have been proven to exhibit an actuation frequency of 1-2 Hz. An actuation frequency in the 1 Hz range would be a significant step forward in achieving SEW locomotion comparable to that of real SEW organisms. This would create a structure optimized with the right SMA wire size as well as piston placement and configuration. The proper actuation force would dictate the proper piston configuration (i.e., straight wire, spring, bundled actuator, etc) and placement.

Several improvements are also needed in the embedded systems. The current control protocol uses a high-level form of message passing which creates extra communication overhead. Rather than transmitting text documents, socket programming could allow communication directly between the C-programs eliminating the need for Linux shell utility commands. Along these lines a more efficient network is possible; instead of communication among only direct neighbors, the segments could send and receive information from all other segments. The optimal approach is to include routing and bridge capabilities with each SBC allowing each segment to send IP packets to all segments when new information becomes available. Information could be routed to segments until it reaches the proper destination. Additionally, with segments functioning as bridges and routers the network has the capability of automatically recognizing its composition (i.e. number of segments and location of each segment). For instance a network could involve segments which connect to the preceding segment on the first Ethernet port and the following segment on the second. This could allow the segment without a connection on the first Ethernet port to begin a message passing scheme to determine the topology. For instance, it could recognize it is the first segment and transmit a message to the second segment with a command to identify itself as the second segment. This could continue down the length of the network structure with the last segment identifying itself by no connection on its second Ethernet port.

Future objectives for the VIPER project include untethered operation as well as locomotion of additional SEW gaits such as lateral undulation. Both possible with optimal actuators and piston configuration.

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APPENDICES

APPENDIX A

SPIDER TOOLCHAIN BUILD

This appendix describes the process of building the toolchain which will create the necessary applications for the Spider SBC. This procedure closely follows the online instructions found at on the Denx website [DENX]. These are the specific steps to create the toolchain for the Spider module using a i686 host development platform.

1. Download the Embedded Linux Development Kit (ELDK)

Use the ncftp server to connect to one of the places which has the ELDK. If the ncftp client is not available on your current Linux distribution you can download it from http://www.ncftp.com/download/

Connect to one of the servers listed in [denx].

```
ncftp ftp.sunet.se
```

Change to the directory with the desired distribution and download. For this example the current directory is

```
ncftp / > cd /pub/Linux/distributions/eldk/3.1.1
ncftp /pub/Linux/distributions/eldk/3.1.1 > bin
ncftp /pub/Linux/distributions/eldk/3.1.1 > get -R \
ppc-linux-x86/distribution

ncftp /pub/Linux/distributions/eldk/3.1.1 > bye
```

2. Initial Instillation

The initial installation is performed using the `install` utility located in the root of the ELDK directory tree. The `install` utility has the following syntax:

```
./install [-d <dir>] [<cpu_family1>] [<cpu_family2>] ...
```

`-d <dir>`	Specifies the root directory of the ELDK being installed. If omitted, the ELDK goes into the current directory.
`<cpu_family>`	Specifies the target CPU family the user desires to install. If one or more <cpu_family> parameters are specified, only the target components specific to the respective CPU families are installed onto the host. If omitted, the target components for all supported target architecture CPU families are installed.

You can install the ELDK to any empty directory you wish, the only requirement being that you have write and execute permissions on the directory. The installation process does not require superuser privileges.

```
./install –d /home/oj/ ppc_4xx-
```

3. Working With ELDK

After the installation utility completes, export the `CROSS_COMPILE` variable:

```
export CROSS_COMPILE=ppc_4xx-
```

Add the directories */opt/eldk/usr/bin* and */opt/eldk/bin* to `PATH`:

```
PATH=$PATH:/home/oj/eldk/usr/bin:/home/oj/eldk/bin
```

Compile a file:

```
ppc-linux-gcc -o hello_world hello_world.c
```

See Appendix B for a more specific program compiling

APPENDIX B

USING THE TOOLCHAIN

We can now used to tool chain to create the applications for the Spider module. First we will compilethe main c-program which will run on the Spider.

Change to the directory on the host workstation which contains the c-program:

To statically compile the program use the `–static` option. In the following command the program snake_motion_seg1.c is compiled with the toolchain. The executable is placed in the /tftpboot directory.

```
ppc-linux-gcc -static -w -o /tftpboot/snake_motion_seg1 \
snake_motion_seg1.c
```

In the early stages of development it is often not necessary to create a new RAM disk Image. Instead it is often easier to modify an existing one. This procedure follows the instruction found at [x]. These are the specific steps to modify the RAM disk Image for the Spider computer.

1. Obtain the RAM disk image. General Micro Systems provide and initial image in their Board Support Package (BSP). Extract the compressed RAM disk image.

   ```
   cd /home/oj/eldk/ppc_4xx/images
   dd if=p501Ramdisk_8_seg1 bs=64 skip=1 of=ramdisk.gz
   ```

2. Uncompress the RAM disk image.

   ```
   gunzip -f ramdisk.gz
   ```

3. Mount the RAM disk image.

   ```
   mount -o loop ramdisk /mnt/tmp
   ```

4. Modify RAM disk.
   This particular command copies a program to the Spider’s /util directory in the root filesystem.

   ```
   cp -f /tftpboot/snake_motion_seg1 /mnt/tmp/util/snake_motion_seg1
   ```

5. Unmount the RAM disk

   ```
   umount /mnt/tmp
   ```

6. Compress the RAM disk

   ```
   gzip -v9 ramdisk
   ```

7. Create a U-boot image.
   In this case the gzip image is made into the RAM disk image for the U-boot.

```
mkimage -T ramdisk -C gzip -n 'Ramdisk Image #8 seg1' \
-d ramdisk.gz p501Ramdisk_8_seg1
```

APPENDIX C

P501 SPIDER DEVELOPMENT ENVIRONMENT SETUP

This appendix describes the Hardware Set-up for the Spider Development Environment.

The Spider development environment is the same as pictured in Figure A-1 with the exception that the development environment workstation also functions as the Console workstation connected to the Spider through the COMM port with an RS-232 interface. The Spider is also connected to the development environment workstation through the Ethernet network.

Cabling:
The Ethernet connections use a standard CAT 5 cable. The serial cable is specially made to connect the Spider's RJ-45 connector to the development workstation's DB-9 connector. Reference [12] describes how to make this cable.

Start Mincom on the Development workstation by typing "`minicom`" at the Linux command prompt.

Press ctrl-A and then z to bring up the minicom menu. Configure the "comm" parameters:

```
Speed: 9600
Parity: None
```

Connect the serial cable and power to the Spider. The power supply is specified in the Spider User's Manual [12].

The U-boot bootloader prompt should appear. From this prompt we can configure the IP address among other environment settings.

Ethernet Address
The Spider and development workstation must be on the same local network. In this development the Spider IP address is 153.90.197.251 and the workstation IP is 153.90.197.188. The Spider's IP address is set from the U-boot prompt. When the prompt comes up type the following commands

```
setenv ipaddr 153.90.197.251
setenv serverip 153.90.197.188
```

You may also need to specify the IP address of the router

```
setenv gatewayip 153.90.94.254
```

After you do this, save the environment variables:

```
saveenv
```

It is often necessary to disable both the IP tables and firewalls. Both may prevent any tftp transmission.

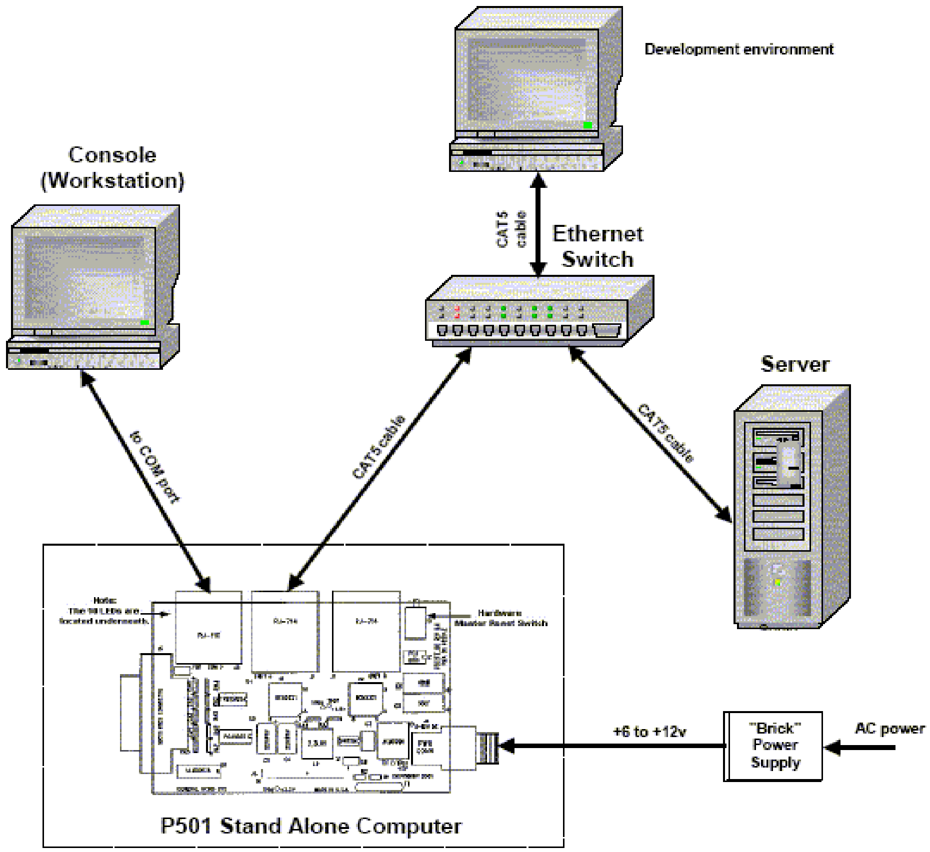
Development environment
Console
(Workstation)
CAT5
cable
Ethernet
Switch
Server
to COM port
CAT5 cable
CAT5 cable
Hardware
Master Reset Switch
+6 to +12v
"Brick"
Power
Supply
AC power
P501 Stand Alone Computer

Figure A-1:

APPENDIX D

LOADING SPIDER IMAGES

Updating the U-boot

For the “flash” command to work as specified in the P501 Uboot User’s Guide [3], the Uboot image must be updated. This is for updating the Uboot firmware from Release 1.0 to 1.1. The Uboot image file, p501Uboot.bin is included in the BSP and must be placed in the /tftpboot directory on the development workstation.

Once the Spider is powered type the following at the Uboot prompt:

```
flash “/tftpboot/p501uboot.bin”
```

Type a “y” to continue loading the image.

Loading a RAM disk image

For this example the RAM disk image is located in the /tftpboot directory on the development workstation. The IP addresses are the same as Appendix.

Fom the U-boot you have to type this:

```
flash u 0xc00000 “/p501Ramdisk”
```

Type a “y” to continue loading the image.

Loading a Kernel Image

Similar to loading a RAM disk image but with a different address. The kernel image, p501_kernel, is in the /tftpboot directory on the Development workstation.

```
flash u 0xe00000 “/p501_kernel”
```

Again you will need to type a “y” to continue.

APPENDIX E

BUSYBOX CONFIGURATION

For this project we had to configure Busybox to include several Linux commands, such as nc and gawk, into the binary executable. Below is a description of how to configure Busybox for other applications.

1. Download the Busybox source code from http://busybox.net/downloads/

2. Select functionality with the menu configuration. Be sure to select the cross-compiler option and also its path in the “Build Options”

```
make menuconfig
make dep
make
```

3. Install

```
make install
```

Then Busybox executable should now be in the current directory which can be loaded into /bin directory in the RAM disk image.

APPENDIX F

MAIN C-PROGRAM FLOWCHART

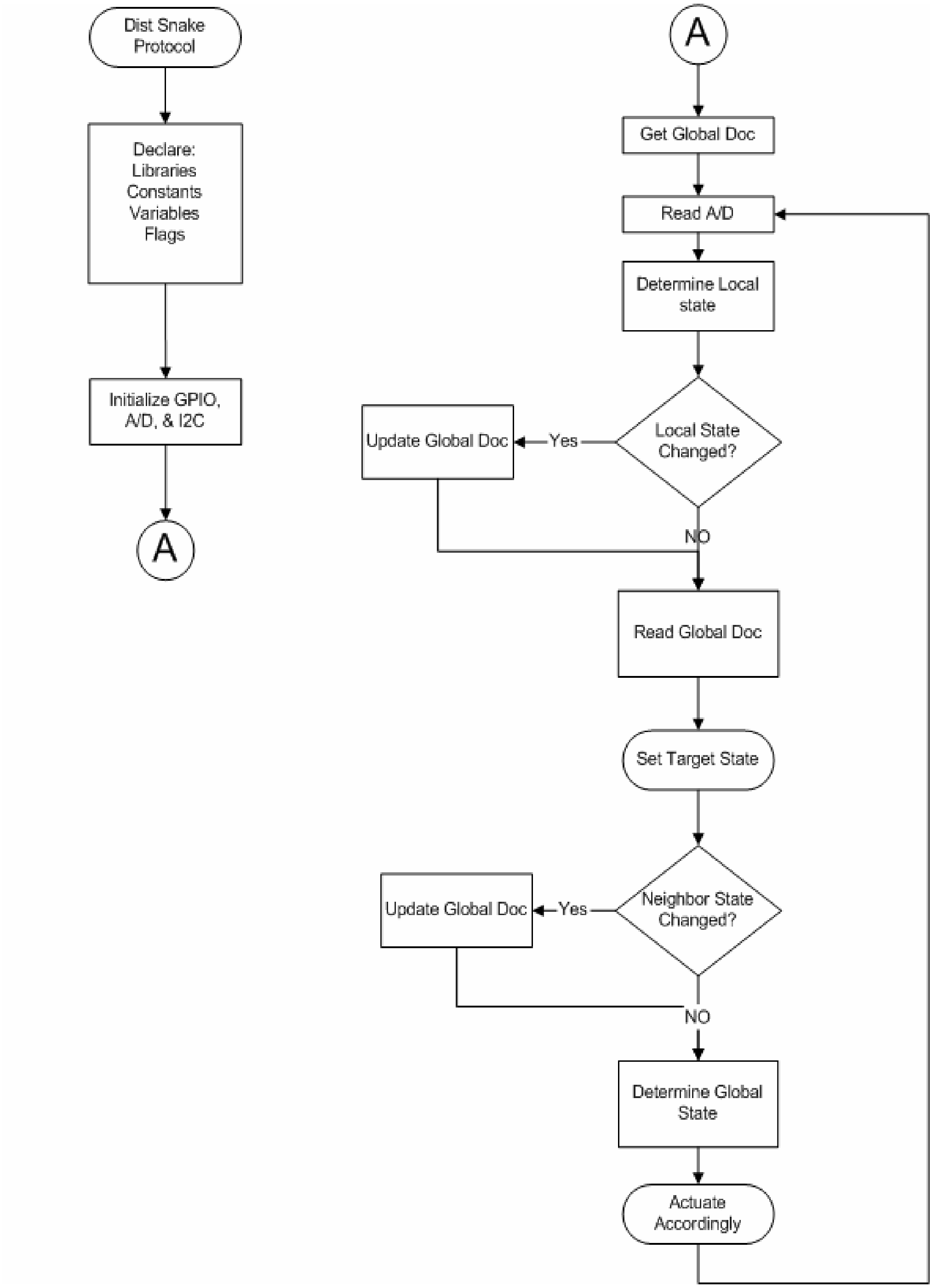

Figure A-2: Main C-Program Flowchart

APPENDIX G

MAIN C-PROGRAM

```
/* rect_motion_seg3.c
************************************************************************
Author:             Oliver Schubert
                    Idaho National Labs, Montana State University,
                    Department of Electrical and Computer Engineering

Date:               April 12, 2005
Description:        This program coordinates one segment with several
others
                    into an inchworm motion. By communicating over the
                    Ethernet links this segment actuates between two
                    positions.
************************************************************************
*/

// Included Libraries
#include <stdio.h>
#include <stdlib.h>
#include <linux/i2c-dev.h>
#include <errno.h>
#include <string.h>
#include <fcntl.h>

// Define Constants
#define ARRAY_SIZE 500
#define pwm1_address 0x28
#define pwm2_address 0x29
#define pwm3_address 0x2a
#define pwm4_address 0x2b
#define ad1_address 0x48
#define gpio_address 0x20
#define BUFSIZ 1000

#define state_1_threashold 0x75
#define state_0_threashold 0x27

// Define Variables
int   file;
int   i;
int   adapter_nr = 1;
int   local_state;
int   previous_local_state;
int   pseudo_local_state,global_state;
int   cooling_cntr = 100;
int   cool_delay = 60;

char  i2c_output[10];
char  filename[20];
char  buff1[10],buff2[10],buff3[10],buff4[10];
char  buff[10];
char  buff_state[1];
int   buff_val;
char  ad_output[10];
char  pwm_data[10];
char  current_on = 0x03;
char  current_off = 0x00;
```

```
char  current_hold = 0x01;
char  error;

char  bottom_on_flag = 0;
char  bottom_holding_flag=0;
char  top_on_flag = 0;
char  cooled_off_flag = 1;
char  state_set_to_zero = 0;
char  state_set_to_one = 0;

char  local_state_change;
int   seg1_state_set,seg2_state_set,seg3_state_set,seg4_state_set;
char  target_state = 1;

char  seg1_state;
char  seg2_state;
char  seg3_state;
char  seg4_state;

time_t      cool_start;
int         cool_time;

int main(){

// Initialize I2C on GPIO
      printf("Configuring GPIO\n");
      gpio_init();

// Initialize all the PWM duty cycles to 0% so that no current flow to
the SMAs
      pwm_init();

// Initialize A/D
      ad_init(ad1_address);
      i=0;

// Start Data Logging program in background
      system("./util/AD_data_log &");

// Begin Main Loop
      while(1){
      i++;

// Get Global Document
      if(i==3){
      printf("\nGetting Global Document from Seg #2\n");
      system("nc 153.90.197.252 3000 > /util/from_lower.txt");

      printf("\nGetting Global Document from Seg #4\n");
      system("nc 153.90.197.254 3000 > /util/from_upper.txt");
      i=0;
      }

// Read the A/D Sensor
      printf("\f");
      read_ad(ad1_address);
```

```
// Save previous Local state
      previous_local_state = local_state;
      printf("DEBUG: previous local state = %d\n",
previous_local_state);

// Deterimine Local state
      if(ad_output[0] >= state_1_threashold){
      local_state = 1;
      pseudo_local_state=1;
      }

      if(ad_output[0] <= state_0_threashold || ad_output[0]
<=state_1_threashold){
      pseudo_local_state = 0;
      }

      if(ad_output[0] <= state_0_threashold){
      local_state = 0;
      pseudo_local_state = 0;
      }

      printf("DEBUG: local_state = %d\n",local_state);
      printf("DEBUG: pseudo_local_state = %d\n",pseudo_local_state);

// Update Global doc w/ local_state if changed
      if(local_state==1 && state_set_to_one==0){
            printf("Writing a 1 to Seg3\n");
            // Call a shell script which writes a "1"
            FILE *fp = popen( ". /util/write_one_to_seg3", "w" );
            pclose( fp );
            state_set_to_one=1;
            state_set_to_zero=0;
            local_state_change=1;
            }

      if(local_state==0 && state_set_to_zero==0){
            printf("Writing a 0 to Seg3\n");
            // Call a shell script which writes a "0"
            FILE *fp = popen( ". /util/write_zero_to_seg3", "w" );
            pclose( fp );
            state_set_to_zero=1;
            state_set_to_one=0;
            local_state_change=1;
            }

      else{
      local_state_change=0;
      }

// Read Global document
      get_states();

// Set Global State
      if(local_state==1 && seg1_state==1 && seg2_state==1 &&
seg4_state==1){
```

```
      global_state=1;
      }

      if (local_state==0 || seg1_state==0 || seg2_state==0 ||
seg4_state==0){
      global_state=0;
      }

// Set Target State
      if (local_state==0 && seg1_state==0 && seg2_state==0 &&
seg4_state==0){
      target_state=1;
      }

      if ( local_state==1 && seg1_state==1 && seg2_state==1 &&
seg4_state==1){
      target_state=0;
      }

      printf("Global State: %d\n", global_state);
      printf("Target State: %d\n", target_state);

// Put states out to LEDs
      if(global_state==1){
            put_leds(0x06,0x00);
            }
      else if (global_state==0){
            put_leds(0x06,0x55);
            }

      if(local_state==1){
            put_leds(0x05,0x00);
            }
      else{
            put_leds(0x05,0x55);
            }

// Update Global doc if any neighbor states have changed
      update_global_doc();

// Actuate Accordingly

// Cooling period of 15 seconds every time Local state transitions 1->0
      if(local_state == 0){
            if(previous_local_state == 1){
            pwm_init();
            cool_start = time(NULL);
                  }
            }

      cool_time = difftime(time(NULL),cool_start);
      printf("Elapsed Cooling Time: %d\n", cool_time);

// Test to see if still cooling
      if(cool_time >= 15){
```

```
// Actuate Bottom Pistons if Local State is "0" and Target State is "1"
      if(pseudo_local_state == 0 && target_state==1 &&
bottom_on_flag==0){
            // Bottom pistons ON
            write_pwm(pwm1_address, current_on);
            write_pwm(pwm2_address, current_on);
            bottom_on_flag=1;
            printf("Bottom Piston:  ON \n");
            //Top pistons OFF
            write_pwm(pwm3_address, current_off);
            write_pwm(pwm4_address, current_off);
            top_on_flag=0;
            }

      // If State reached turn bottom pistons OFF and wait
      else if(pseudo_local_state==1 && target_state==1 &&
bottom_holding_flag==0){
            write_pwm(pwm1_address, current_hold);
            write_pwm(pwm2_address, current_hold);
            bottom_holding_flag=1;
            printf("1 state reached. Bottom pistons OFF\n");
            }

// Actuate Top Pistons if Local State is 1 and Target State is 0
      if(local_state!=0 && target_state==0 && top_on_flag==0){
            // Bottom pistons OFF
            write_pwm(pwm1_address, current_off);
            write_pwm(pwm2_address, current_off);
            // Top pistons ON
            write_pwm(pwm3_address, current_on);
            write_pwm(pwm4_address, current_on);
            printf("Top Pistons:  ON \n");
            top_on_flag=1;
            bottom_on_flag=0;
            bottom_holding_flag=0;
            printf("actuating top pistons\n");
            }

      // If State reached turn Top pistons OFF
      else if(local_state==0 & top_on_flag==1){
            write_pwm(pwm3_address, current_off);
            write_pwm(pwm4_address, current_off);
            top_on_flag=0;
            bottom_on_flag=0;
            bottom_holding_flag=0;
            printf("0 state reached.  Top pistons OFF\n");
            }

      printf("\nTop Actuators: %d\n", top_on_flag);
      printf("Bot Actuators: %d\n", bottom_on_flag);

      } // End 'delay' IF

      else {
      printf("Cooling:  No Actutors ON\n");
      }
```

```
	usleep(100000);

	}	// End For loop
	return(0);
}		// End main()

/**********************************************************************/
/* Subroutines                                                        */
/**********************************************************************/

/**********************************************************************/
/* pwm_init                                                     */
/* inputs: NONE                                                       */
/* outputs: NONE                                                */
/* description:   Set all duty cycles to 0 %
	*/
/**********************************************************************/
void pwm_init(){
	write_pwm(pwm1_address, current_off);
	write_pwm(pwm2_address, current_off);
	write_pwm(pwm3_address, current_off);
	write_pwm(pwm4_address, current_off);
	}

/**********************************************************************/
/* write_pwm                                                          */
/* inputs: I2C address to write to (addr), Value to write (duty)
	*/
/* outputs: NONE                                                */
/* description: Sets the duty cycle of the PWM chip
	*/
/**********************************************************************/
int write_pwm(char addr, char duty){

	char tmp[10];
	sprintf(filename, "/dev/i2c-%d", adapter_nr);
	if ((file = open(filename,O_RDWR)) < 0) {
		printf("ERROR openning device file\n",strerror,(errno));
		exit(1);
		}
		else{
			}

	if (ioctl(file,I2C_SLAVE,addr) < 0) {
		printf("ERROR with ioctl function in
write_pwm()\n",strerror,(errno));
		exit(1);
		}
		else{
			}

	tmp[0] = duty;
	if (write(file,tmp,1) != 1) {
		printf("Error writing to file (i.e. pwm
chip)\n",strerror,(errno));
```

```
            }
            else{
            //printf("PWM duty cycle:  %x\n", duty);
            }
      close(file);
      }

/*********************************************************************/
/* read_ad                                                         */
/* inputs: I2C address to write/read to (addr)
      */
/* outputs: Reading from the A/D in hex (ad_output)
      */
/* description: Reads the analog voltage input (00-ff hex)
      */
/*********************************************************************/
int read_ad(char addr){

      sprintf(filename, "/dev/i2c-%d", adapter_nr);
      if ((file = open(filename,O_RDWR)) < 0) {
            printf("Error openning device file in
read_ad()\n",strerror,(errno));
            exit(1);
            }
            else{
            //printf("Device file opened\n");
            }

      if (ioctl(file,I2C_SLAVE,addr) < 0){
            printf("Error with ioctl function in
read()\n",strerror,(errno));
            exit(1);
            }
            else{
            //printf("iotcl stuff cool\n");
            }

      if (read(file,ad_output,2) != 2){
            printf("Error reading A/D chip\n",strerror,(errno));
            }
            else{
            printf("Device file (A/D chip) reads %x\n", ad_output[0]);
            }
      close(file);
}

/*********************************************************************/
/* ad_init                                                         */
/* inputs: I2C address to write to (address)                       */
/* outputs: NONE                                                   */
/* description:   Initialize the A/D to read Channel 1             */
/*          Auto increment flag set to 0 (successive reading of Channel
1) */
/*          Also sets the output to 0xff which is 5 volts just    */
/*          as a test                                             */
/*********************************************************************/
```

```
void ad_init(char address){

      sprintf(filename, "/dev/i2c-%d", adapter_nr);
      if ((file = open(filename,O_RDWR)) < 0)   {
            printf("Error openning device file i
ad_init()\n",strerror,(errno));
            exit(1);
            }
            else{
            //printf("Device file opened\n");
            }

      if (ioctl(file,I2C_SLAVE,address) < 0){
            printf("Error with A/D ioctl function\n",strerror,(errno));
            exit(1);
            }
            else{
            //printf("iotcl stuff cool\n");
            }

      buff[0]=0x40;
      buff[1]=0xff;
      if (write(file,buff,2) != 2){
      printf("\nError writing to file (voltage not
set)\n",strerror,(errno));
            }
            else{
            printf("\nAnalog voltage set to %x\n", buff[1]);
            }
      close(file);
}

/********************************************************************/
/* get_states                                                     */
/* inputs: NONE                                                   */
/* outputs: seg1_state, seg3_state, etc                           */
/* description: Gets the local states of neighboring segments     */
/********************************************************************/
void get_states(){
// Get state of neighborring segments

      FILE *fp1 = popen( ". /util/getseg1", "r" );
      fgets ( buff1,  BUFSIZ, fp1 ) ;
      pclose( fp1 );
      buff_val = atoi(buff1);
      seg1_state=buff_val;
      printf("Segment #1 state is %d\n",seg1_state);

      FILE *fp2 = popen( ". /util/getseg2", "r" );
      fgets ( buff2,  BUFSIZ, fp2 ) ;
      pclose( fp2 );
      buff_val = atoi(buff2);
      seg2_state=buff_val;
      printf("Segment #2 state is %d\n",seg2_state);

      FILE *fp4 = popen( ". /util/getseg4", "r" );
```

```
      fgets ( buff4,  BUFSIZ, fp4 ) ;
      pclose( fp4 );
      buff_val = atoi(buff4);
      seg4_state=buff_val;
      printf("Segment #4 state is %d\n",seg4_state);
}

/*********************************************************************/
/* gpio_init                                                        */
/* inputs: NONE                                                     */
/* outputs: NONE                                              */
/* description:   Configures GPIO pins on the Micro DB-25 to allow 
access to*/
/*                I2C signal                                        */
/*********************************************************************/
void gpio_init(){

      sprintf(filename, "/dev/i2c-%d", adapter_nr);
      if ((file = open(filename,O_RDWR)) < 0)   {
            printf("Error openning device file 
gpio_init()\n",strerror,(errno));
            exit(1);
            }
            else{
            //printf("GPIO Device file opened\n");
            }

      if (ioctl(file,I2C_SLAVE,gpio_address) < 0){
            printf("Error with GPIO ioctl 
function\n",strerror,(errno));
            exit(1);
            }
            else{
            //printf("GPIO iotcl stuff cool\n");
            }

      buff[0]=0x07;
      buff[1]=0x0f;
      if (write(file,buff,2) != 2){
      printf("Error writing to file ( Analog voltage not set)\n");
      }
            else{
            printf("GPIO Configured\n");
            }
      close(file);
}

/*********************************************************************/
/* put_leds                                                   */
/* inputs:                                                    */
/* outputs: NONE                                              */
/* description: Puts info on LEDs                             */
/*********************************************************************/
void put_leds(char led_sel, char data){
      char led_address = 0x60;
      sprintf(filename, "/dev/i2c-%d", adapter_nr);
```

```
	if ((file = open(filename,O_RDWR)) < 0) {
		printf("ERROR openning device file in put_led
\n",strerror,(errno));
		exit(1);
		}

	if (ioctl(file,I2C_SLAVE,led_address) < 0) {
		printf("ERROR with ioctl function in
put_led\n",strerror,(errno));
		exit(1);
		}
	buff[0] = led_sel;
	buff[1] = data;
	if (write(file,buff,2) != 2) {
	printf("Error writing to control
register(i.e.put_led\n",strerror,(errno));
		}
		else{
		}
	close(file);
}

/********************************************************************/
/* update_global_doc                                              */
/* inputs: seg1_state, seg3_state, etc
	*/
/* outputs: NONE                                            */
/* description: Since this is a middle segment it must update the
output */
/*		document to pass segment state information to other
segments*/
/********************************************************************/
void update_global_doc(){
	if(seg1_state==1 && seg1_state_set==0){
	// Call Scipts to update Global doc with neighbor state info
	// Call a shell script which writes a "1"
	FILE *fp = popen( ". /util/write_one_to_seg1", "w" );
	fgets ( buff,  BUFSIZ,  fp ) ;
	pclose( fp );
	seg1_state_set=1;
	}
		else if(seg1_state==0 && seg1_state_set!=0){
		// Call a shell script which writes a "0"
		FILE *fp = popen( ". /util/write_zero_to_seg1", "w" );
		fgets ( buff,  BUFSIZ,  fp ) ;
		pclose( fp );
		seg1_state_set=0;
		}

	if(seg2_state==1 && seg2_state_set==0){
	// Call Scipts to update Global doc with neighbor state info
	// Call a shell script which writes a "1"
	FILE *fp = popen( ". /util/write_one_to_seg2", "w" );
	fgets ( buff,  BUFSIZ,  fp ) ;
	pclose( fp );
	seg2_state_set=1;
```

```
        }
              else if(seg2_state==0 && seg2_state_set!=0){
              // Call a shell script which writes a "0"
              FILE *fp = popen( ". /util/write_zero_to_seg2", "w" );
              fgets ( buff,  BUFSIZ,  fp ) ;
              pclose( fp );
              seg2_state_set=0;
              }

        if(seg4_state==1 && seg4_state_set==0){
        // Call Scipts to update Global doc with neighbor state info
        // Call a shell script which writes a "1"
        FILE *fp = popen( ". /util/write_one_to_seg4", "w" );
        fgets ( buff,  BUFSIZ,  fp ) ;
        pclose( fp );
        seg4_state_set=1;
        }

              else if(seg4_state==0 && seg4_state_set!=0){
              // Call a shell script which writes a "0"
              FILE *fp = popen( ". /util/write_zero_to_seg4", "w" );
              fgets ( buff,  BUFSIZ,  fp ) ;
              pclose( fp );
              seg4_state_set=0;
              }
}
```

APPENDIX H

SPIDER SCRIPTS

Initialization program that runs every time Linux is booted on the Spider.

```
#!/bin/sh
# rcS
# Authors:  OJ Schubert, Idaho National Labs, Montana State Univ., ECE
Dept.
#           Todd Trotter, Montana State University, Computer Science
Dept.
# init startup file

# mount the proc pseudo filesystem
/bin/mount /proc

# start the viper programs and scripts
/bin/server.sh &

# Configure Ethernet ports
ifconfig eth0 ipaddr 153.90.197.253 netmask 255.255.255.0 \
broadcast 153.90.197.255

ifconfig eth1 ipaddr 153.90.197.253 netmask 255.255.255.0 \
broadcast 153.90.197.255

# Add neighbor segments to route table
route add -host 153.90.197.252 dev eth0
route add -host 153.90.197.254 dev eth1

# Main Program, w/ path, here
./util/rect_motion_seg1
```

```
#!/bin/bash
# server.sh
# Authors:  OJ Schubert, Idaho National Labs, Montana State Univ., ECE
Dept.
#           Todd Trotter, Montana State University, Computer Science
Dept.
# This script sets up a netcat server.
# The document output.txt is served to anyone that requests it.
# After a document is served that the netcat server closes the process
# Therefore we put it in a continuous to state after each execution.

while true
do
      nc -l -p 3000 < /util/output.txt
done
```

```
#!/bin/bash
# getseg2
# Author:   OJ Schubert, Idaho National Labs, Montana State Univ., ECE
Dept.
# This script gets the local state from a neighboring segment

grep seg2: /util/from_lower.txt | awk '{print$2}'
```

```
#!/bin/bash
# write_zero_to_seg2
# Author:   OJ Schubert, Idaho National Labs, Montana State Univ., ECE
Dept.
# This script writes a zero to segment 2 in the output document

awk '$1=="seg2:"{$2="0"}{print}' /util/output.txt \
> /util/tempfile
cp -f /util/tempfile /util/output.txt
```

```
#!/bin/bash
# write_one_to_seg2
# Author:   OJ Schubert, Idaho National Labs, Montana State Univ., ECE
Dept.
# This script writes a one to segment 2 in the output document

awk '$1=="seg2:"{$2="1"}{print}' /util/output.txt \
> /util/tempfile
cp -f /util/tempfile /util/output.txt
```

APPENDIX I

CURRENT CONTROLLER CIRCUIT SCHEMATIC

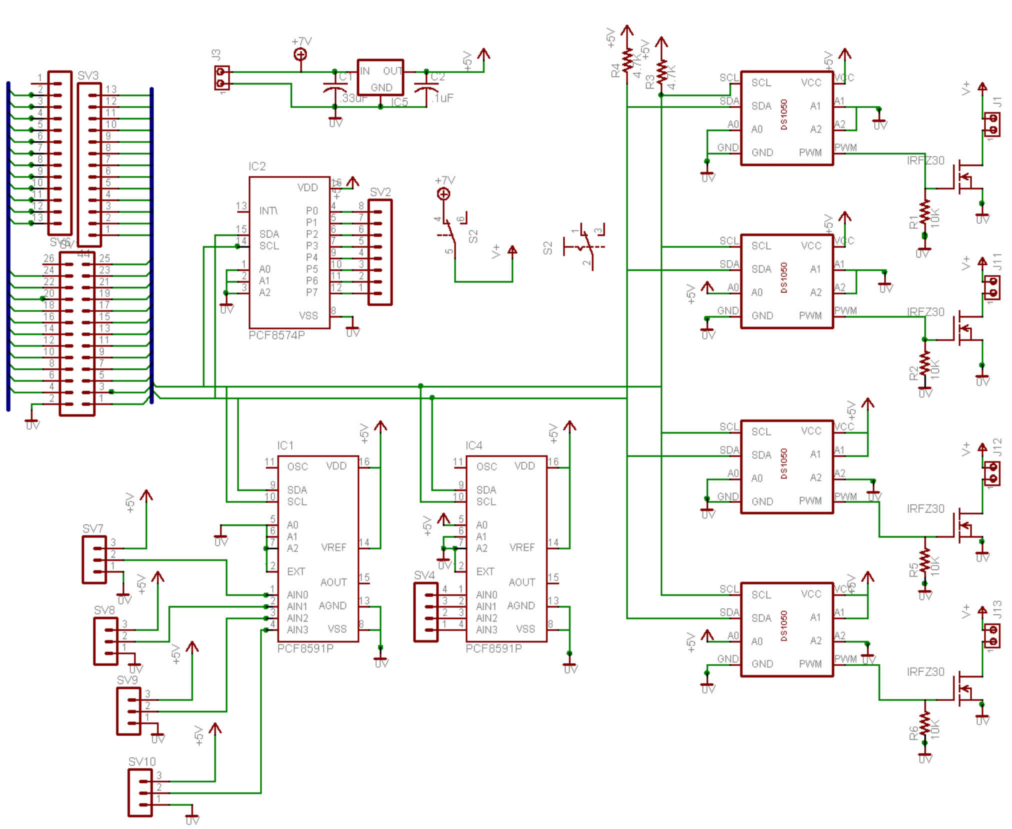

Figure A-3: Circuit Schematic for the Current Controller

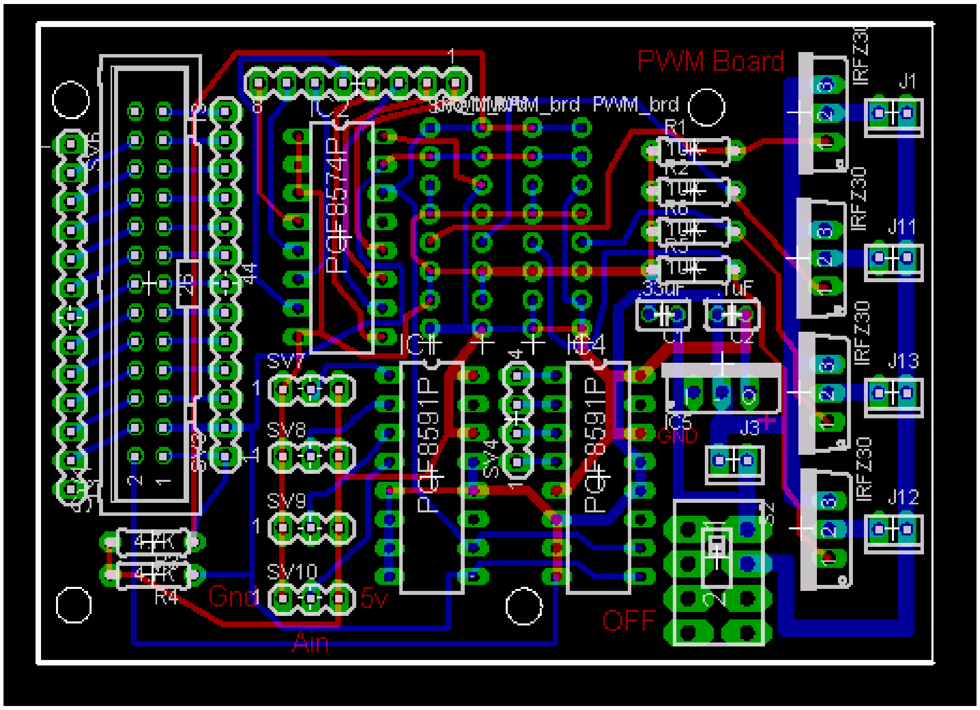

Figure A-4: Current Controller PCB Layout

APPENDIX J

INCHWORM VELOCITY CALCULATION

The maximum speed of an inching segment is easily calculated. The distance the snake is able to move foreword in one actuation cycle is directly related to its geometry.

Therefore the velocity of the snake is the actuation frequency, f, multiplied by the actuation distance of the entire snake, d.

$$v = fd$$

The distance of actuation is the length of the structure, L, minus the resulting chord length, C.

$$d = L - C$$

The length is simply the length of a single segment, l, multiplied by the number of segments, n.

$$L = nl$$

Using the following equation we can calculate the length of the chord where r is the radius of the curvature and θ , is the angle of the arc of the inchworm structure.

$$C = 2r\sin(\theta / 2)$$

The radius r, is calculated by the number of segments needed to form a complete circle. Because each segment produces a deflection of roughly 20 degrees, 18 segments can make a circle. The radius of this circle is determined by the following equation:

$$r = \frac{9l}{\pi}$$

The angle θ depends of the number of segments in the structure.

$$\theta = 20$$

The amount of position displacement for a segment is then:

$$d = nl - 2r\sin(n\theta / 2)$$

Therefore the velocity of theoretical velocity of this structure is

$$v = f(nl - 2r\sin(n\theta / 2))$$

For a three-segment structure with an actuation frequency of 1/35 Hz. The velocity is 2.095 inches per minute.