A Motorless Artificial Limb and its Control Architecture

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Abstract

In the next generation of robots, there are no motors and construction is from simple everyday materials. One of the stars of this evolution, is a wire which contracts when heated and is known as muscle wire. A simple soda straw provides a strong structure from which segmented limbs can be constructed. A flex sensor is used at the joint to measure the actual bend angle. A microcontroller controls the limb based on input from a higher level controller. This paper covers the construction of a limb, characterizes it and presents some control solutions.

1 Introduction

We started down the path of creating artificial life forms a year ago, after a dream by one of the researchers. In this dream, a limb was constructed from simple materials found in every household. Unlike most dreams, upon awakening, the idea still made sense and a prototype limb was created just like the one in the dream (Fig. 1). This fueled the imagination and laid the basis for a growing area of research (referred to as “Strawbotics”) involving many different engineering disciplines including mechanical, electrical, computer and control with potential forays into fuzzy, neural and evolutionary forms of computing.

Nitinol wires (often referred to as muscle wires or Flexinol) [6] along with flex sensors offer an attractive design alternative to motor-driven artificial limbs [4][5]. In comparison to the latter, this option implies structures that are relatively small, cheap, light, continuous, adaptable, available and easily controlled. The muscle wires act as actuators. The wire itself contracts to a maximum of 8% of its length when warmed with an electrical current signal provided by an external controllable source. The position of a limb is sensed by a flex sensor whose resistance depends on the degree of bending; the more profound the bending, the greater the resistance of the sensor.

The limb can be used as a generic module that, in turn, can be combined with other modules to create larger and more complex architectures [2].

A number of different control architectures were implemented in software on a small microcontroller. These include both open and closed-loop control topologies. It is worth underlining that the system under control exhibits interesting nonlinear dynamics. These aspects make the control problem quite a challenge. In particular, there are a number of factors that cannot be ignored in the design of the controller:

- The actuator can be made to contract much quicker than the rate at which it will expand; a function of environmental heat transfer.
- The actuator has hysteresis in its temperature/length relationship.
- The length and thickness of the wire as well as the temperature rating affect the speed at which the wire contracts and expands.
- The voltage of the battery which provides power for driving the actuator can also vary over time. When the voltage gets low, the reaction of the limb slows down.
- The structure of the straw joint is such that the forces for initiating a bend, maintaining a bend and changing the angle of the bend, can differ by as much as double.

2 Construction

The original limb served as a prototype of the structure for subsequent limbs. Initially, dental floss was used as the actuator and a person served as a feedback sensor and controller. Subsequently, we have employed muscle wire as the actuator, a flex sensor to detect the bending and a microcontroller to be the control system.

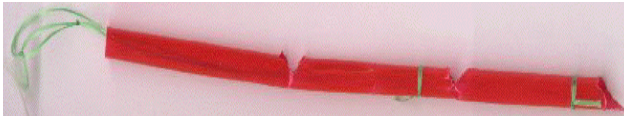

Fig. 1 Original straw limb prototype with dental floss actuators

2.1 Physical Structure

There are three main components to the straw limb assembly:

1. straw

2. muscle wire
3. flex sensor

The generic structure of the limb is built from any size soda straw. A V-notch across the straw which leaves a portion of the straw less than the diameter intact to serve as a hinge, provides structural integrity and restoring force. The relaxed position of the V-notch joint is the normal position of the straw. When the actuator contracts, it pulls the two sides of the joint together. When the actuator is turned off, it expands and allows the two sides of the joint to return to the normal position. The flex sensor is attached outside the straw and it reads the amount of bend in the joint. This is used to feed back actual positional information to the controller, to let it know when the joint has reached the desired position.

2.1.1 Straw

We have experimented with a number of different straws to determine the proper type and characteristics required to successfully construct a limb. The straws we have been using are about 200mm in length and 7mm in diameter.

The straw is required to maintain its columnar shape when subjected to lengthwise compression. When the wire is actuated, it causes a certain amount of compression along the length of the straw. If the straw is not stiff enough, then it can cause the straw to bow. The bowing causes two problems. First, it reduces the amount of actuation available for bending the limb segment at the joint. Second, and more important, it can produce contact between the warmed muscle wire and the side of the straw. This is a serious problem as the wire is warm enough to melt through the side of the straw. Once this happens, structural integrity is further compromised and the wire can become embedded within the side of the straw further reducing the efficiency of the actuator.

The other requirement of the straw is that it be not too stiff. Some straws proved to be too stiff and when they were bent at the joint, the material started to form stress cracks at the joint which subsequently introduced slop into the movement of the limb segments. In a short time these straws became effectively useless.

The best straws are from StarBuck's coffee house. They are quite stiff, maintaining good structure when actuated and they do not exhibit cracking around the joint. Macdonald's straws are slightly less stiff but they work quite well too. Wendy's straws are a slightly smaller diameter than the flex sensors and are not stiff enough, so they tend to bow.

2.1.2 Muscle Wire

Muscle wire is part of a class of metal alloys known as shape memory alloys (SMA). It has a short history [6] dating back to 1932 when the first SMA, gold-cadmium, was discovered. The nickel-titanium alloy currently used, was first alloyed in 1963 and it has found various uses over the years in research laboratories with some commercial products such as cryofit couplings for hydraulic lines in airplanes. Production and quality have improved to the point that it is a readily available, high quality product for a low cost.

The wire form comes in different thicknesses and strengths. We have tried four different thicknesses of wire. The thinner wire has less contractual strength but responds faster and consumes less power. The wire best matched to the straw joint is .003 of an inch thick and can pull up to .8 newtons. It takes about .4 to .5 newtons of linear force to bend the joint.

The reason the wire can contract and expand is due to the two phases of its crystalline structure. These two phases of its crystalline structure are obtained through heating and cooling. In the martensite phase, or the cooled state, it is somewhat elastic and can be stretched from its contracted length by up to 8%. But 5% is the recommended value for the longest life. When it is heated past its transition temperature (90^{o}C), it enters the austenite state where it contracts.

The simplest way to heat the wire is to pass an electric current through the wire. The resistance of the wire is about 5 ohms/inch. To expand the wire, the current is stopped and the wire cools through convection. By carefully controlling the current through the wire (indirectly, the temperature), it can be made to partially contract. This achieves a continuous range of motion.

On earlier prototypes of a limb, the wire was on the outside of the straw. This made it quite susceptible to breezes and thereby, temperature fluctuations which caused positional variations. With the current design of the wire on the inside of the straw, there seems to be little temperature fluctuation and control is much firmer.

2.1.3 Flex Sensor

The flex sensor is a long thin strip of plastic (0.3mm x 6mm x 112mm) which has a flexible deposit of carbon on one side. When the carbon side is on the outside of a bend in the plastic, its resistance increases. The initial resistance is about 10K ohms and it increases up to about 45K ohms. By putting this sensor outside the straw, at the joint, it can be used to measure the bend angle. It also provides some of the restoring force for straightening the limb.

These sensors are used in PC data gloves and they are fairly cheap. They may also be cut into narrower strips to fit inside of smaller diameter straws or to reduce the amount of restoring force. Along the carbon film are a series of square pads which can be bonded to with a flexible bonding agent allowing it to be tapped so that one sensor can be used to sense two joints which are close together.

2.1.4 Assembly

The actual construction of the limb requires a bit of care and skill, although a refinement of techniques through trial, error and insight, has improved this process.

The cut for the joint is quite important to the operation of the limb. The cut should be two thirds of the way through the straw so that the hinge part that remains is less than the diameter of the straw. If too much of the straw remains, then it will crumple and compromise the operation of the joint. If too little remains, then the limb will be flimsy and exhibit lateral tendencies.

Initially V-notches were carved using a very sharp, small, utility knife. This proved to be a laborious procedure; prone to asymmetrical cuts; demanded artistic talent; consumed a lot of time and was subject to many failures. One of the authors came up with a very simple technique for cutting the straw by holding it down with a thumb and fore finger straddling either side of the joint maintaining enough pressure to partially collapse the straw while the other hand uses the utility knife to cut a V directly on the straw going through both sides (upper and lower) at once. This technique produces reliable and accurate joints quickly. We call this the Rae cut. There have been other refinements of construction techniques which improved the overall quality of the final product and we expect to make further improvements.

At the joint, the end of the muscle wire is attached using a simple knot around a perpendicular steel wire which penetrates the sides of the straw. The coating on the end of the muscle wire is removed with sandpaper. The contact resistance of the wire is low enough that it does not affect performance (on the contrary, it makes it easy to service a limb should the wire need to be changed). The other end of the muscle wire is attached to the notch of an M-shaped steel wire inserted in the end of the straw. Wires for the electrical connections are attached to the two steel wires with a small copper crimp (Fig. 2).

The flex sensor is either inserted into the straw so that it straddles the joint or it can be attached to the back of the straw on both sides of the joint with plastic tape to allow a greater degree of bend. On the outside, the sensor is secured at one end while the other end feeds through a sleeve so that it can slip and not bind the joint upon contraction. In either case, as the joint bends more, the sensor impedes its progress. Without a sensor it is quite easy to obtain greater than 90 degrees of bend. With the sensor inside the straw the maximum bend angle is about 45 degrees. With the sensor on the back of the straw, the bend angle can reach 60 degrees. Greater bend angles might be achieved by using the next stronger wire or doubling the current wire.

A limb can be constructed from the basic materials in about twenty minutes.

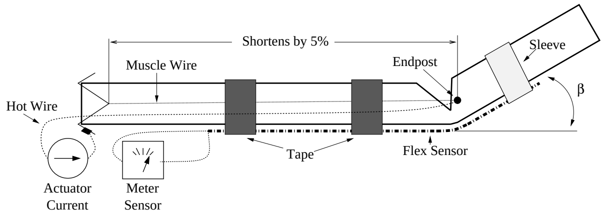

Fig. 2 Schematic of a straw limb showing the bend angle beta.

2.2 Electrical Structure

The interface from the microcontroller to the muscle wire and sensor requires very few parts. A MOSFET is employed as a switch to drive the current required by the actuator and to make use of a separate voltage source (Fig. 3). The gate is grounded with a resistor to prevent the actuator from being actuated when not attached to the microcontroller.

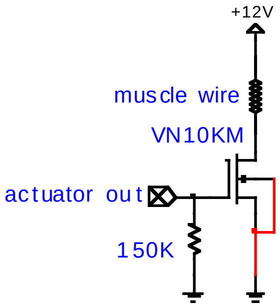

Fig. 3 Muscle wire interface to microcontroller.

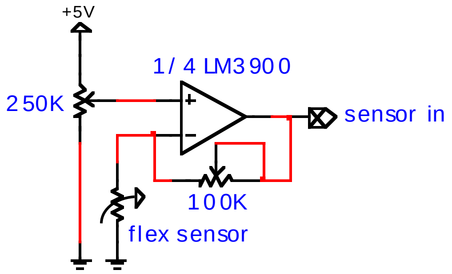

Fig. 4 Sensor interface to microcontroller. The potentiometers were used to find optimum values.

To read the sensor, its variable resistance (Fig. 5) is converted to a variable voltage and amplified with an op-amp (Fig. 4). This is then read by the microcontroller through its A/D input.

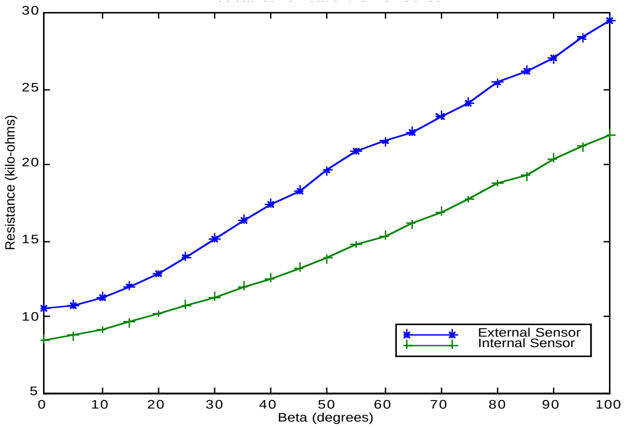

Fig. 5 Resistance of the flex sensor for different bend angles positioned on the inside or outside positions on the straw.

2.3 Control Structure

The control structure is quite simple as dictated by the sensor and actuator components. For our experiments, we used a 68HC11 micro-controller board from New Micros. It provides ample computing power as well as an interactive interface which makes prototyping rapid. One output pin is connected to the gate of the MOSFET and one input pin to the A/D converter is connected to the output of the op-amp. By controlling the amount of time that the output pin is high, the actuator can be controlled. The sensor can be read at any time to determine the bend angle of the straw limb.

3 Measurements

It is important to understand the characteristics of the system before going on to implement a controller. There are three main components of the system which needed to be measured, these include the muscle wire, the sensor, and the complete system.

3.1 Wire

The muscle wire project book [Gilbertson] discusses the hysteresis properties of the wire. In order to investigate how hysteresis was going to affect the system, measurements were taken of the relationship between the voltage across the wire, actuator voltage, and the degree of bend, beta. It quickly became clear that the relationship between the actuator voltage and beta was non-linear and also that the voltage required to attain a certain degree of bend was different depending on whether beta was increasing or decreasing (Fig. 6).

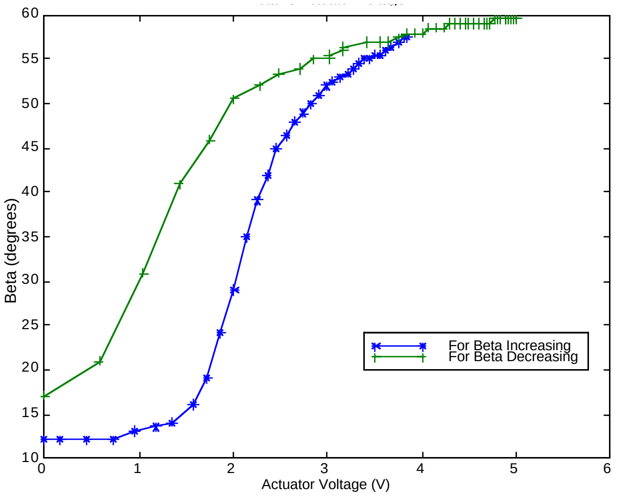

Fig. 6 As the voltage across the wire is increased or decreased, the angle of bend increases or decreases.

3.2 Sensor

As with the muscle wire, non-linearities were expected in the flex-sensor. A clearer understanding of its properties required measuring the voltage across the sensor for varying degrees of beta (Fig. 7). It is apparent that there is little change in the relationship between beta and the sensor voltage when beta is increasing or decreasing. Slight non-linearities are however present when the sensor is more acutely bent.

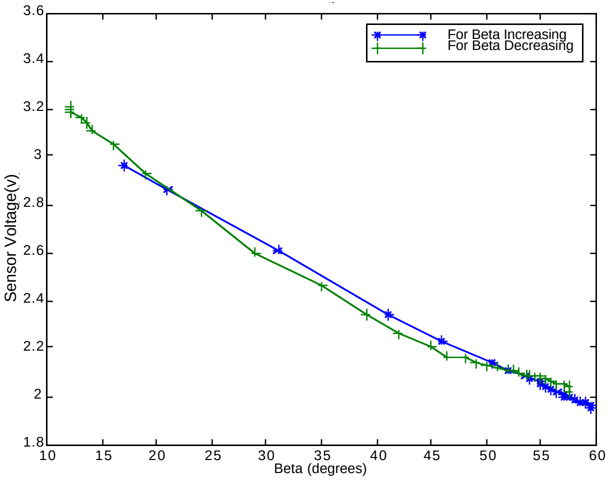

Fig. 7 The output of the sensor is fairly linear with the bend angle for both increasing and decreasing the angle.

3.3 Limb (system)

After gaining an understanding of the properties of the muscle wire and the sensor, it was useful to capture a picture of the combined system. This was achieved by plotting the sensor voltage versus the actuator voltage. It clearly shows the hysteresis of the system and the non-linearities that exist between the input and the output of the controller (Fig. 8).

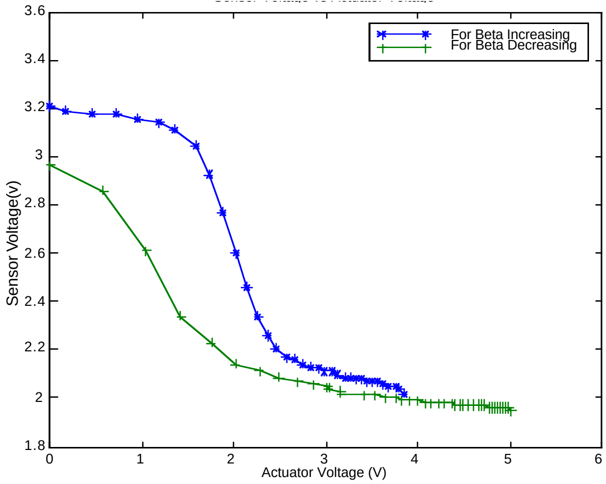

Fig. 8 The nonlinear relationship between the actuator and sensor as well as the hysteresis are shown clearly here.

4 Control

With a limb constructed and characterized, it is time to add a controller. The objective of the controller, or the interface to the next higher level entity (in this case it is just an interactive connection to the host computer) is to move the limb to a desired set point and return the result of the attempted action (Fig. 9). To this end, we first constructed an open loop controller which would apply a certain voltage to the actuator. Then we closed the loop and tried a simple proportional controller. This was further refined with a proportional-derivative controller.

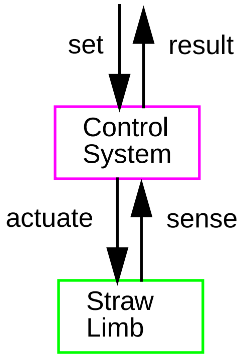

Fig. 9 Control architecture for straw limb.

4.1 Open Loop

In the open loop controller we used a simple keyboard interface to adjust the parameters and view some of the control parameters. To control the voltage across the muscle wire, the voltage was applied as a periodic signal and the duty cycle was varied. This mode was useful for testing different straws and wires and for making measurements. With this controller the limb could be bent to any angle and adjusted in small steps. The limb was quite stable at any angle.

4.2 Closed Loop

The first type of closed loop control is the simplest: measure the difference between the desired position and the actual position and drive the actuator with a signal proportional to this. The parameters in this type of controller were varied but the limb exhibited a tendency to jitter. With different parameters, the response time, and speed of the jitter could be varied, but smooth rigid control was not possible.

4.3 PD Controller

Next a proportional-derivative (PD) controller was built. The derivative was taken as two discrete points divided by the time interval and added to the output of the proportional controller. The following equation was implemented:

$$A(t) = A(t-1) + K_1 P + K_2(S(t-1) - S(t)) \qquad (1)$$

Where:

$A(t)$ is the current actuator voltage
$A(t-1)$ is the last actuator voltage
$S(t)$ is the current sensor voltage
$S(t-1)$ is the last sensor voltage
P is the square of the error with its sign
K_1, K_2 are scaling variables

It was found that the derivative control did not appreciably change the performance of the controller. In general, the controller worked well with low values of the parameters (Fig. 10).

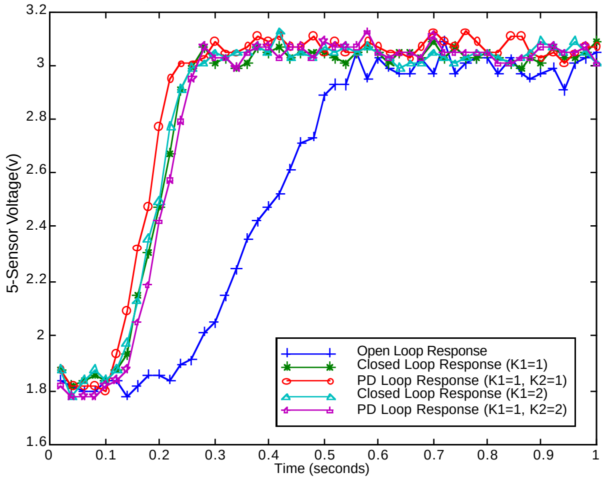

Fig. 10 Comparison of the step response of the open loop against the PD controller with a few different values for K_1 and K_2.

5 Discussion

5.1 Nonlinearities

The nonlinearities in the system manifested themselves in the actuator control. When the controller is adjusting the position of the limb, it varies the voltage across it. To change direction of the position adjustment, the actuator voltage must be changed by up to 1 volt (Fig. 6). This voltage value was not consistent over the bend angle and it gave rise to jitter at certain angles. Different values of K_1 worked better for different angles. A more robust controller would be sensitive to the bend angle and could adjust K_1 accordingly.

5.2 Results

With a simple closed loop control architecture, we were able to improve response time of the limb to go to a particular setting from rest, by at least a factor of three (Fig. 10). The simple nature of the system makes for a simple controller. Our results show what a controller would be like but at the same time indicate that a small microcontroller is quite adequate for controlling a limb. The additional property of the closed loop controller which was not measured, is the ability to adapt to a variety of system parameters and changing environmental conditions.

5.3 Alternate Components

The simple structure of the straw limb is not unlike an exo-skeleton limb of an insect. Using different sized straws and different strengths of muscle wires, the limb could be scaled up or down in size.

For small implementations there exists another material which could be exploited as an actuator and a sensor. A relatively new technology, the electroactive polymer [3], does not provide the strength of the muscle wire but it consumes much less power and in an autonomous system this is a big concern. The polymer will curl when a differential voltage is placed across it. When bent, it will produce a voltage proportional to the degree of bend.

6 Future

As our species is breaching our planetary boundary and reaching for space, robots will play a bigger role in our missions. The new space station will make an ideal environment for testing robots that can navigate in 3-D space or crawl and climb over varying surfaces either for inspections or repairs. “Faster, better, cheaper” is the theme behind current NASA spacecraft development and this is the same theme which will permeate the robotic research conducted here.

As more graduate students work in this area and time allows, various related research topics can include:

- simple limb and controller as a pluggable module
- optimal limb construction
- remote operation of limbs from a hand
- insect-like multi-limbed robots
- optimal adaptive mobility behaviours
- autonomous reactive behaviours [1]
- navigation in zero-gravity environments

7 Conclusion

The beginnings of the structure and control of a new artificial life-form have been covered here and it will take more innovation and time to realize grander creations. The goal of simple, autonomous, motorless robots lies ahead.

Acknowledgements

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