The development of a carbon-based resistive ink flex sensor for use in an instrumented glove to measure relative finger positions

by

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INTRODUCTION

A large variety of applications exist for the analysis of human movement. Golfers, tennis players, and baseball players have improved their performance and decreased the chance of injury by having their body motions analyzed while performing these activities. Body motion analysis has also been widely used in the last few years to create computer animation.

Although the analysis of whole body movement has many applications, hand motion and the movement of the fingers are of particular interest. Hand tracking devices are used in a diverse array of applications that include virtual reality, interpretation of sign language, rehabilitation, puppetry, music, video games and remote control manipulators.

To date, there are many devices available that track hand movements. However, the vast majority of these systems have drawbacks. The most accurate devices are extremely expensive while other devices are bulky and uncomfortable to wear. An inexpensive glove was developed; however its accuracy and reliability were of some concern, and, in addition, it is no longer commercially available. Therefore, the construction of a device that measures relative finger positions, which is also inexpensive, would be beneficial.

An important aspect of any instrumented glove is the transducers that are used to convert the mechanical motion of the fingers into an electrical signal that can be used to quantify the mechanical motion. Thus, in designing an inexpensive instrumented glove, an inexpensive transducer must first be developed.

This paper presents the development of an inexpensive sensor that could be used in an instrumented glove to measure relative finger positions. It also presents the development of a hardware and software system that was developed to obtain data, in the form of the measured flex angle, for a single sensor. A description of how the system could be expanded to collect data from 16 sensors using the 16 multiplexer channels is also given.

In the first section, a literature review is presented which serves to highlight the advancements made in the field of instrumented gloves and some of the sensors that have been used in them.

Sensor production for the present study will then be discussed. First, materials that were tested and the conclusions from these tests will be shown. Next, the material that was chosen will be discussed, including sensor development and the determination of the optimal sensor production. The hardware and software system that was developed will then be presented.

In the following section, methods for determining the sensor's characteristics, including response time, temperature sensitivity, repeatability, and accuracy will be shown. The results and a discussion of these tests will be given.

The method for obtaining data, in the form of a measured flex angle, using the system will be given and data that was collected using this system will be shown and discussed.

In the future work section of this paper, ideas for incorporating the sensors, hardware and software into a complete glove with up to 16 sensors is presented. In addition possible improvements for each of these components is investigated.

LITERATURE REVIEW

Hand-based computer input is familiar to everyone. Keyboards are the most common interface between a person and a computer, and now a mouse is also a standard feature with any computer system. Unlike keyboards, a mouse uses more natural hand movements and can be used to track the two dimensional position of a hand on a flat surface. Joysticks are also commonly used in video games to translate hand movement. However, none of these intermediary devices take into account actual finger positions or natural hand gestures. For this reason, and because of advancements in computer technology, making real time systems possible, devices that measure actual finger movements are of great interest.

Instrumented Gloves

The development of instrumented gloves is a dynamic field and researchers are continuously testing new techniques. The following discussion serves to highlight some of the advancements made in this field to date.

The first glove, that was described in literature, was developed by Thomas DeFanti and Daniel Sandin at the University of Illinois at Chicago in 1977. They called it the Sayre Glove, and it used flexible tubes with a light source at one end and a photo cell at the other to determine finger bending [15].

Researchers at the MIT Architecture Machine Group and at the MIT Media Lab built the next glove in the early 1980's. They used this glove, the MIT LED, as a motion capture system by focusing a camera on a glove covered with LED's. The images were then analyzed for real-time computer graphics animation. The glove was only used briefly, however, because it was never adequately developed [15].

Gary Grimes of Bell Telephone Laboratories used numerous touch, bend, and inertial sensors sewn into a cloth glove to create the Digital Data Entry Glove in 1983. It was built to recognize the Single Hand Manual for the American Deaf. However, Grimes never put the glove to actual use or commercially developed it [15].

Probably the most well known glove to date is the DataGlove which Thomas Zimmerman and others developed in 1987 [4], [7], [11], [15], [17]. This glove used fiber optics, sewn to the back of a cloth glove, to monitor 10 finger joints within 5 to 10 degrees of accuracy [15]. The data was then sent to a control unit which was updated 60 times per second [11]. Even though this glove was a large improvement over previous gloves, it was still not sufficient for fine manipulations, and the response time was too slow to capture rapid hand movements. In addition, the analog to digital circuitry did not take into account different hand sizes. As a result, the full range of the A/D converters was not utilized which reduced the precision of the glove [4], [15].

The Dexterous HandMaster was developed for the measurement of finer finger manipulation. It was an exoskeleton that used Hall-effect sensors as potentiometers at the joints. Arthur D. Little developed this design to accurately measure the bending of each finger joint as well as the complex motions of the thumb. It can collect data at 200 samples per second to within 1° of accuracy. The Dexterous HandMaster has been marketed and is sold as an instrument for clinical analysis of hand function [15].

The CyberGlove, developed in 1991 as a communication system to translate American Sign Language into spoken English, used 22 sensors. Each sensor was made of a tension strain gage and a compression strain gage. The CyberGlove was a large improvement over the DataGlove as it had a resolution of 0.05 degrees, and data was sent to the controller at a rate of 100 times per second [11]. In addition, the analog to digital offsets were controlled by software that enabled the glove to be calibrated for each user. Therefore, unlike the DataGlove, the CyberGlove unitized the full range of its A/D converters. Although originally intended for the use in a communication system, it is now also used in virtual reality applications [15].

The DataGlove, the Dexterous HandMaster and the CyberGlove are all commercially available. However, the prices of these gloves are between $10,000 and $15,000 each [4].

Mattel toy company, recognizing the potential of such gloves in the entertainment business, started to develop an inexpensive and durable glove for use with their Nintendo home video games [15]. In 1989 they produced the Power Glove which used resistive flex sensors embedded in plastic to measure bending of the fingers and thumb. Mattel made the Power Glove for three years and sold it for about $100. However, Mattel stopped making the glove in late 1991 [5]. Some problems with the Power Glove were accuracy and reliability. The Power Glove only used five sensors: one for the thumb and one for each finger [4]. In addition, the A/D converters used only two bits of precision for each sensor [5]. Other drawbacks of the Power Glove were that it was uncomfortable to wear and that it was designed to only interface with the Nintendo system [15].

In 1993 Richard J. Bozeman, Jr. at the Johnson Space Center also developed an inexpensive instrumented glove to facilitate measuring, translating and recording astronaut analog finger positions. Like the Power Glove, he used only 5 sensors in his glove. But, instead of using resistive flex sensors, flat membrane potentiometers were used to obtain crude measurements of relative positions of fingers [1], [8].

Sensors

All instrumented gloves require a medium to convert the flexing of fingers into an electrical signal that can be processed and analyzed. As can be seen from the previous discussion, transducers that have been used in instrumented gloves are extremely diverse. This section describes in greater detail some of the sensors that have been used in instrumented gloves.

Light Sensors

Both the Sayre Glove and the DataGlove used light sensors as a method to determine relative finger positions. The Sayre glove used flexible tubes with a light source at one end and a photocell at the other. The light that reached the photocell decreased as the finger was flexed. Thus, the voltage from each photocell could be correlated to the corresponding angle [15].

The DataGlove used the same principle but with fiber optics. The fiber optic cables were treated at the joints so that light escaped as the fingers were bent. Phototransistors were used to convert the light into electrical signals which were then digitized and sent to a computer. However, the sensors were non-linear, and so a large amount of signal processing was then required to convert the data into actual joint angles. In addition, the DataGlove sensor readings were dependent on each other. When one of the joint angles changed while the others remained fixed, not only did the corresponding sensor reading change, but in some cases, other readings changed as well. Thus, the signal processing for the DataGlove included a fourteen dimensional function that had been determined experimentally.[7]

Hall Effect Sensors

Hall effect sensors were used in the Dexterous Hand Master to sense relative finger positions [15]. In general, Hall effect devices operate on the principle that when a magnetic field is placed perpendicular to a current-carrying conductor then a transverse electric field is developed which is proportional to the product of the field's magnetic flux density and the current. This voltage, called the Hall voltage, can then be measured [13]. However, information was not available as to which Hall effect devices were used in the Dexterous Hand Master or how they were positioned in the glove to obtain the data.

Flat Membrane Potentiometers

Flat membrane potentiometers consist of a resistive surface with a conductive surface covering, but not touching, it making it a normally open, momentary contact device. They are usually used as touch sensors because the resistance depends on where contact is made [16].

The glove developed by R.J. Bozeman at the Lyndon B. Johnson Space Center had one of these sensors running the length of each finger and the thumb to sense the degree to which each was bent [1]. According to the author, only crude measurements were possible using these sensors [1].

Strain Gages

A strain gage transducer changes resistance when a strain is applied, as the resistance of a conductor is given by:

$$R = \frac{\rho L}{A} \tag{1}$$

where ρ is the specific resistivity of the conductor, L is the length and A is the cross-sectional area [2], [6]. Therefore, the resistance of the conductor will change with the variation of any one of these parameters [2].

Experimental tests have shown that these parameters are usually not independent. As the length of a straight wire increases, the area decreases according to Poisson's effect. This effect is additive in causing the resistance to increase as given by Equation 1 [6].

Experimental tests show that the specific resistivity (ρ) of most alloys is also effected by the applied strain. When a strain is applied, there is an elastic distortion of the internal structure of the material which then influences electron flow through the conductor. The extent to which ρ changes is dependent on the metallic material's composition as well as heat treatments and the degree of cold-working. In fact, the elongation of some alloys actually results in a decrease in resistance [6].

If the elastic range of the conductor is not exceeded, then the resistivity of most metals and alloys will return to their original values when the strain is removed. In order for resistance to change linearly, the change in ρ must be proportional to the internal stress level. Experiments show that this requirement is met by most metals and alloys [6].

Carbon Gages Charles Kearns of Hamilton Standard developed the first resistive strain gage in the early thirties. He took standard, cylindrical, carbon composition resistors and ground them until they were flat. He then bonded them to the surface of propeller blades in order to measure the surface strain applied to the blades while they rotated. Using this method, small changes in applied strain resulted in relatively large changes in resistance. However, resistance stability in regards to time and temperature were poor. Even so, carbon strain gages were then manufactured with painted films of colloidal graphite. However, because of their lack of resistance stability, they could not be used with slowly changing strain levels and, thus, were only used in dynamic strain applications [6].

Bonded Wire Strain Gages Bonded wire strain gages, developed in the late thirties, used small diameter wire made of electrical resistance alloys. With applied strain, the resistance changed in accordance with Equation 1, where A and ρ are functions of L. Although they produced much smaller changes in resistance than carbon gages, they could be used in dynamic as well as static applications [6].

Foil Strain Gages In the CyberGlove, compression and tension strain gages were used to sense finger position [15]. Foil strain gages resulted from the development of printed circuit boards in the 1950's and are based on the same principles as bonded wire strain gages. However, foil strain gages have a significant advantage over bonded wire strain gages as they are manufactured by a photoetching process in which many identical gages of exact size and geometry can be formed. In contrast, wire gages had to be manufactured mostly by hand resulting in reproducibility problems. In addition, the photoetching process could produce strain gages with the optimum geometry. Today, the strain gage that is most commonly used in most applications is the foil strain gage [6].

Semiconductor Strain Gages Semiconductor strain gages are piezoresistive transducers made from a semiconductor which exhibits a change in the resistivity, ρ, when strain is applied. Although strain gages of this type usually have a much higher degree of sensitivity than bonded wire or foil strain gages, they are extremely nonlinear [2].

Other Strain Gages The sensor used in Mattel's Power Glove can be classified as a strain gage. The Power Glove sensors consisted of thin strips of metal coated with an electrically conducive ink encapsulated in a flexible plastic.

Flexing the sensor changed the internal structure of the metal. This produced a change in resistance that could then be measured [5].

Present Study

At this time, only extremely expensive instrumented gloves are commercially available. Although these gloves do work exceptionally well, they are not economically practical for many applications. One example of an application, where an inexpensive instrumented glove would be particularly useful, would be in the rehabilitation of an impaired hand [11], [17].

The development of an automated system for hand therapy could result in more objective, consistent and accurate testing than is now available. Also, the patient's progress in therapy could be more easily monitored and, with faster data analysis, patient examination time would decrease. In addition, the data taken in a particular session could be more easily compared to data taken in other sessions, to determine the progress of the patient and to evaluate the performance of the impaired hand, so that better treatment strategies could be devised.

However, since instrumented gloves are very expensive at this time, it is not economically feasible to readily use the existing technology in a clinical setting. Thus, the development of an inexpensive glove that could be used in hand therapy would be extremely beneficial [11].

The purpose of the present study was to investigate ways of producing an inexpensive sensor for use in such a glove. In this study, it was found that it may be possible to make an inexpensive glove using sensors made from a carbon-based, electrically conductive ink screen printed onto to a polyester plastic. In this paper, the production method of these sensors is first presented. A hardware and software system that was developed to convert the mechanical motion into degrees of bending is given, and a method for implementing these components into a complete glove is then proposed.

SENSOR DESCRIPTION

Overview

The sensors selected for use in this project were produced using a carbon-based electrically conductive ink and thus, can be classified as a type of strain gage. However, unlike the carbon strain gages that Charles Kearns developed in the 1930's or foil strain gages that are now widely used, these sensors are extremely flexible and are able to measure large flex angles.

Tests of Sensor Production Materials

In searching for an inexpensive way to make a transducer to measure bending, the following methods were first attempted.

Conductive Rubber Matting

In this method the resistance change of a strip of thin conductive rubber matting, obtained from McMaster-Carr Supply Company in Chicago, IL, was observed as it was flexed. It was found that the conductive rubber matting did in fact display a small change in resistance as it was flexed. However, it quickly returned to the original resistance value even when it remained in the flexed position.

Thick conductive rubber was then obtained to see if the response could be improved. Even though the response was a little better than that of the thinner material, it was found that it also displayed only a dynamic response when flexed.

Conductive Foam

Copper foil with conductive adhesive backing was attached to either side of a piece of conductive foam. It was then compressed and the response was observed. This transducer also exhibited a change in resistance, but like the conductive rubber matting, it also quickly returned to the original resistance value even when it remained compressed.

Piezoelectric Film

Piezo film sensors were obtained from AMP Incorporated in Valley Forge, PA. The response of these sensors was observed using an oscilloscope. When bent, a large voltage was produced with a high degree of sensitivity. However, this material also produced only a dynamic response as the voltage quickly returned to zero volts even when the film remained in the flexed position.

Flat Membrane Potentiometers

Samples of Softpots were obtained from Spectra Symbol in Salt Lake City, UT. These were the same sensors used in the instrumented glove made by R.J. Bozeman at the Lyndon B. Johnson Space Center. Softpots are usually used as touch sensors, as they consist of two conductive layers and have an infinite resistance until pressure is applied so that the layers make contact. A resistance can then be measured and is dependent on the point at which contact is made [16]. In testing these sensors, it was found that when the sensors were bent, the conductive layers made contact, and a resistance could be measured. This did produce a fairly stable resistance reading. However, there was a low correlation between the resistance and the amount that the sensor was bent.

Carbon-based Electrically Conductive Ink

Carbon-based electrically conductive ink was obtained from Creative Materials in Tyngsboro, MA. In the first tests, the ink was spread with a small spatula onto a sheet of plastic. It was found that this material did indeed change resistance as it was bent to various angles, and that the resistance didn't return to the original value when the material remained in the flexed position. However, some drift was observed and, in addition, when the sensor was bent to a specific angle over several trials, different reading were obtained each time. Despite this, a general trend was apparent.

Sputter Coating Gold

A sputtering system (HUMMER VI) was used to sputter coat gold onto a strip of polyester plastic. When gold is sputter coated, small clusters of gold are formed. It was theorized that if a layer of gold was formed to the point where the gold clusters just touched then, when the plastic was bent to various angles, there would be less contact between the gold clusters and the resistance would increase. Several different variations of pressure, current, temperature and time were attempted as shown in Table 1.

Table 1. Gold sputter coating results

Sample	Pressure mTorr	Current (mA)	Time (min)	Resistance
1	200	25	10	60 Ω
2	200	25	5	>30 MΩ
3	200	25	6	2 MΩ
4	100	25	6	6 Ω
5	100	10	1	>30 MΩ
6	100	25	1	60 Ω
7	100	15	1	1 kΩ
8	100	15	0.75	>30 MΩ
9	200	25	6	3 kΩ

From the results shown in Table 1, it can be seen that it was difficult to obtain predictable results as the resistance of the film as a function of deposition time changed rapidly from a high resistance (> 30 MΩ) to a low resistance (< 1 kΩ). It was therefore difficult to obtain reproducible results. In addition, it was found that, for the films that were less then 30 MΩ, there was not a noticeable change in resistance when they were flexed.

Method Used

It was decided to use the carbon-based electrically conductive ink since the preliminary tests with it produced the best results of the methods that were tried. It was also believed that, if the sensor production method were improved, then better results could be obtained. In addition, these sensors are extremely inexpensive to produce. Flex sensors made in this fashion are not commercially available.

Sensor Development

The list of materials used in the sensor development is given in Table 2. The basic procedure for producing the sensors was as follows: First, the carbon-based conductive ink was combined with thinner. The mixture was then screen printed onto a 22 cm by 6 cm piece of the polyester plastic. After a 24 hour drying time, it was cured at 100 °C for 10 minutes and then cut into twenty, 1 cm by 5 cm, strips. Wires were attached to each strip, and cured again at 100 °C for 10 minutes. The entire sensor was coated with a flexible silicone rubber adhesive and allowed to dry at room temperature for 24 hours.

Determination of Optimal Sensor Production

Since the sensor resistance range is dependent on many variables including the thickness of the ink, the thickness of the plastic and the way in which the wires are attached, the optimal procedure for making the sensors had

Table 2. Materials used in sensor development

Material	Description	Supplier	Curing Temperature
Polyester plastic (#8567K2)	• 0.002" thick • Clear polyester	McMaster-Carr Supply Company Chicago, IL	Up to 130°C
Polyester plastic (#8567K4)	• 0.005" thick • Clear polyester	McMaster-Carr Supply Company Chicago, IL	Up to 130°C
Various other plastics			
Conductive Ink (CM #101-80)	• Carbon-based • Electrically conductive • Very resistant to flexing and creasing.	Creative Materials Tyngsboro, MA	50°C to 150°C for 10 Minutes
Thinner (CM #113-12)	• 2-butoxyethyl acetate	Creative Materials Tyngsboro, MA	
Adhesive (CM #102-32)	• Silver filled silicone in toluene • Electrically conductive (.0001 ohm - cm) • Excellent crease resistance • Consistency - smooth paste	Creative Materials Tyngsboro, MA	50°C to 180°C for 10 Minutes
Adhesive (CM #107-02)	• Silver filled polymer • Electrically conductive (.001 ohm - cm) • Excellent crease resistance • Consistency - liquid	Creative Materials Tyngsboro, MA	55°C to 120°C for 10 Minutes
Cooper foil tape (#76555A642)	• 0.5 " wide by 0.00275 " thick • Conductive adhesive backing	McMaster-Carr Supply Company Chicago, IL	
Sealant (#00Z021)	• GC Electronics silicone rubber adhesive sealant • Waterproof • Stays flexible	Newark Electronics Chicago, IL	

to be experimentally determined. As discussed previously, the resistance of the sensors is based on the specific resistivity, the length, and the area of the ink applied. Ideally, the sensor should have a large change in resistance as it is flexed. In addition, reproducibility in a given sample is an important consideration, as it would be beneficial for all of the sensors in the glove to have the same parameters.

Plastics Tested

Several plastics were tested and varying results were obtained. Most of the samples were of unknown chemical composition. However three samples of known compositions were tested. These were kynar, polypropylene and polyester. Varying results were obtained from the sensors made with the different plastics. For the polypropylene sample, the layer of resistive ink separated from the plastic sheet after flexing. During curing, the kynar sample curled and could not be flattened again. Many of the other samples that were tested melted when cured at 100 °C while others exhibited extremely slow response times as the plastic was not flexible enough to return to its original shape immediately after flexing. Fortunately, of all the plastics tested, the one that worked the best also had a known composition of polyester. More polyester sheeting with known thickness' and temperature ranges were then ordered from McMaster-Carr Supply Company in Chicago, IL.

Wire Attachment Tests

In attaching the wire leads to the conductive ink, two different methods were tested. In the first method, copper foil with a conductive adhesive backing was attached to either end of the sensor. Wires were then soldered to the foil.

In the second method, two different conductive adhesives were tested. The first was a silver filled polymer (Creative Material, CM #107-02). This adhesive had a low volume resistance of 0.001 ohm-cm and was also resistant to flexing and creasing. Since the adhesive had a liquid consistency, the wires were attached to either end of the sensor by first taping the very end of the wire to the sensor to hold it in place and then covering the rest of the wire with the conductive adhesive as shown in Figure 1. The conductive adhesive was allowed to dry at room temperature for 24 hours. The sensors were then cured for 10 minutes at 100 °C.

The other conductive adhesive that was tested consisted of silver filled silicone in toluene (CM #102-32). This adhesive had the consistency of a smooth paste and was also very resistant to flexing and creasing. In addition, it had a lower volume resistance of 0.0001 ohm-cm. Since CM #102-32 was a smooth paste, it could easily be molded around the wire. The wires with the adhesive on them were then pressed onto either end of the sensor. This was followed by a curing time of 10 minutes at 100 °C.

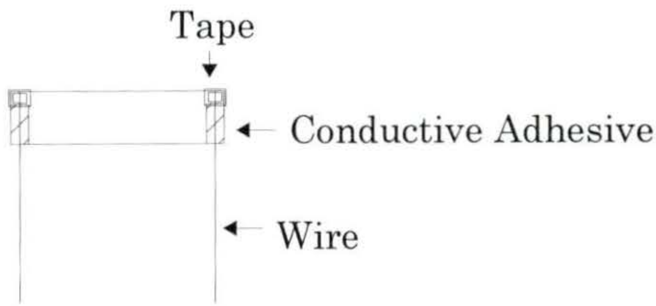

Figure 1. Wire attachment scheme

Of the three materials that were used for attaching wires to the sensors, it was determined that the CM #102-32 conductive adhesive produced the best results. It was found that the copper foil with the conductive adhesive backing was extremely pressure sensitive and in some cases produced an open circuit unless pressure was applied. Thus, useful measurements could not be obtained with this method.

The CM #107-02 conductive adhesive worked better, but consistent measurements were also difficult to obtain since the resistance continually changed dramatically when left in a static position. It was therefore determined that this method of attaching the wires was also not very useful.

Using the CM #102-32 conductive adhesive to attach the wires was the final method that was tested. It was found that using this material produced results that exhibited a similar, but even more stable response, to those obtained by just holding the multimeter leads on either end of the sensor as it was flexed. Thus, it was determined that using CM #102-32 would be an adequate method for attaching the wires to the sensors.

In addition, different gage wires were tested using the CM #102-32 adhesive. It was found that larger gage (smaller diameter) wires produced more stable results. However, if the wire gage was much larger than thirty, then the contact was not as good and the wire was more easily detached from the sensor when stressed. Thirty gage wire was therefore used to produce the sensors.

Ink Application Tests

The first method that was tested, in applying the ink, was to simply spread the ink with a small spatula onto the plastic. While this produced promising results, it was impossible to make two sensors with resistance ranges that were matched.

The next method was to mask the sensor area with tape and then spread the ink with a straight edge onto the exposed plastic. Tape with different thickness' were tried in an attempt to find an optimal resistive ink thickness. It was found however, that this method did not work much better than the first as a smooth ink layer was still difficult to obtain.

In order to produce a more smooth and evenly distributed film of resistive ink, a screen printer was used. In this method, the ink was screen printed onto plastic sheets which were then cut into strips to make the individual sensors. Although this method worked much better than the first two methods, it was still impossible to produce two sensors with exactly the same resistance. However, while no two sensors exhibited the same resistance, or change in resistance, it was found that there was a considerably smaller deviation between the sensors of a given sample produced this way compared to any of the previous methods. Since no other inexpensive methods were available to apply the ink to the plastic, this was the method that was chosen.

Variation of Ink Thickness

Since the resistance of a conductor is dependent, in part, on its area, the effect of varying the thickness of the conductive ink layer was studied. This was done by varying the number of coats that were screen printed onto 22 cm by 6 cm sheets of plastic and by using different ink-to-thinner ratios as shown in Table 3.

Table 3. Coats and ink-to-thinner ratios tested

Sample #	1st Coat	2nd Coat	3rd Coat
3	10:4		
6	10:4	10:4	
7	10:2	10:2	10:2
8	10:3	10:3	10:3
9	10:4	10:4	10:4

Twenty, 1 cm by 5 cm, strips were cut from the samples. Due to a limited amount of conductive adhesive, wires were not permanently attached to these sensors. The resistance range of each strip was then determined by holding the leads of a multimeter on either end of the strip and recording the resistance when it was straight (0°) and then again when it was bent to 180°. The maximum and minimum values for each sensor from sample 9 are shown in Figure 2.

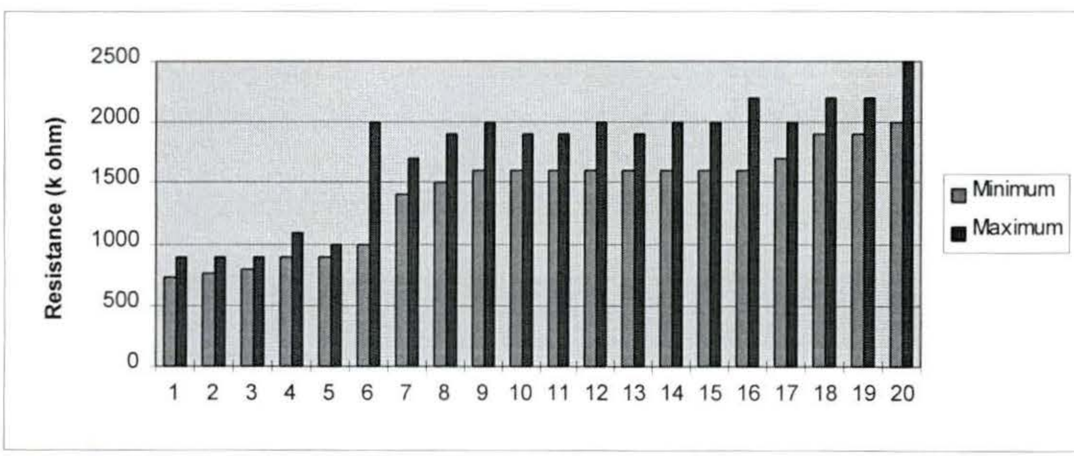

Figure 2. Minimum and maximum resistance of 20 sensors from sample #9

This data shows a distribution that was typical for all of the samples that were measured. It can be seen that, even though the sensors are from the same sample, there is a wide distribution of the minimum resistance and the maximum resistance for each sensor within a given sample. While some error was introduced in the measurement process by simply holding the multimeter leads on the sensor, the wide distribution of values is probably the result of not being able to produce a perfectly smooth coating with the screen printer that was used. However, it can also be seen that there were some sensors in the sample that did have similar resistance characteristics.

A summary of the results that were obtained from each sample is shown in Table 4.

Table 4. Summary of the 20 sensors measured from each sample

Sample #	Coats of Ink	Ink to Thinner Ratios	Range of Min Values (kΩ)	Ave. Min Value (kΩ)	Range of Max Values (kΩ)	Ave. Max Value (kΩ)	Range of Change in Resistance (kΩ)	Ave. Change in Resistance (kΩ)	% Change
3	1	10:4	x	x	x	x			
6	2	10:4	830 - 3200	1922	1100 - 3900	2405	200 - 900	484	25%
9	3	10:4	730 - 2000	1415	900 - 2500	1760	100 - 1000	346	24%
8	3	10:3	450 - 3200	1653	530 - 3700	1951	80 - 700	298	18%
7	3	10:2	540- 2400	1237	680 - 2800	1511	100 - 800	275	22%

,x: Resistance was greater than 30 MΩ

The change in resistance of each sensor was calculated by subtracting the minimum resistance from the maximum resistance, and it is thus an indicator of how sensitive the sensor is to flexing. The average percent change in resistance from the unflexed position to the flexed position was then calculated.

These results showed that increasing the number of applied coats noticeably decreased the resistance of the sensor as would be expected. However, the percentage change in resistance for each sensor was not significantly affected.

The effect of changing the ink-to-thinner ratio is shown in Figure 3.

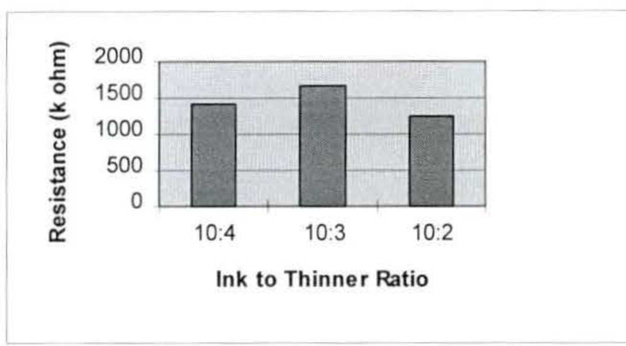

Figure 3. Effect of varying the ink-to-thinner ratio

It was expected that ink with a thicker consistency would produce sensors with lower resistance. However, the sensors from the sample with the 10:3 ink-to-thinner ratio produced sensors that were larger in resistance than the sensors from the other two samples. One possible explanation for this could be that it was difficult to screen print the samples with the larger ink-to-thinner ratios. It was noted during the screen printing process that the layers were not smooth for samples with ink-to-thinner ratios of 10:3 and 10:2, and because of this, these results probably don't show the actual effect of changing the ink-to-thinner ratios.

To obtain resistance values in a usable range, the sensors were made with three coats of ink with ink-to-thinner ratios of 2:1. This produced an ink layer approximately 0.002" thick.

Application of a Grid Pattern

A grid pattern, similar to the kind used in wire strain gages, was etched into the sensor with a sharp knife. The grid pattern that was used is shown in Figure 4. The principle behind this method was to increase the effective length of the sensor without changing its actual dimensions. Thus, the grid is the electrical equivalent of several straight sensors connected in series [6].

It was found that adding the grid pattern greatly increased the resistance of the sensor as would be expected. However, it did not noticeably increase the percent change in resistance that was measured from the unflexed to a flexed position. In addition, adding the grid pattern introduced additional reproducibility problems.

Protective Coating Tests

A protective coating was necessary to decrease the motion of the wire at the point where it was attached to the sensor and to protect the resistive ink

Figure 4. Grid pattern that was used

coating from moisture and other contaminants. A flexible silicone rubber adhesive sealant made by GC Electronics was chosen as it provided adequate protection while remaining flexible. The effect of the silicone rubber on the sensor was determined by measuring the response of the sensor before it was coated with the silicone rubber and then again 48 hours later. No significant change was found in the response of the sensor indicating that silicone rubber could be used.

Variation of Plastic Thickness

Sensors were made from both 0.002" thick polyester and from 0.005" thick polyester sheets. In theory, increasing the plastic thickness should produce a larger change in the length of the ink coating as the sensor is bent. If the layer of resistive ink were to be coated on Thickness 1, rather than on Thickness 2 in

Figure 5, then the circumference would be less and, in effect, the change in length from the unflexed to the flexed position would be less. Thus, applying the resistive ink coating to a thicker plastic should produce a larger change in resistance when flexed.

To produce the sensors for this test, a 0.002" sample of polyester and a 0.005" sample of polyester were placed under the screen printer and a layer of conductive ink was applied to both of the samples at the same time. This was followed by a 24 hour drying time. Two more coats were then applied to the samples following the same procedure.

Ten 1 cm by 5 cm sensors were then made from each sample. The samples were made using CM #102-32 conductive adhesive and 30 gage wire as described previously. The sensors were then coated with the flexible silicone adhesive. The minimum resistance was measured when the sensor was in the unflexed position, and the maximum resistance was measured when the sensor was flexed to 180°. The change in resistance and the percent change were then calculated. These results are shown in Tables 5 and 6.

From these results it can be seen that the sensors made from the 0.005" plastic produced a much higher percent change in resistance then the sensors made from the 0.002" plastic as was expected.

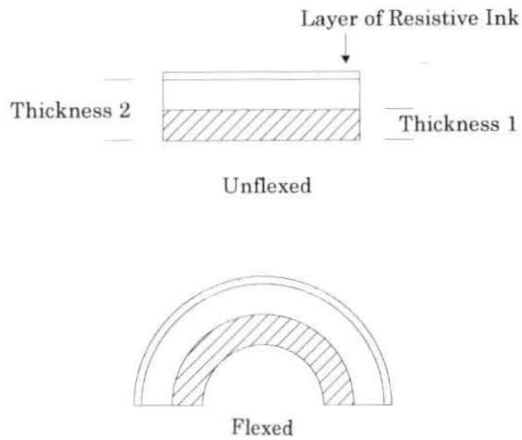

Figure 5. Change in surface length with change in plastic thickness

Table 5. Resistance range for sensors made with 0.002" plastic

Sensor #	Minimum Resistance (Ω)	Maximum Resistance (Ω)	Resistance Change (Ω)	% Change
16.1	360k	460k	100k	28%
16.2	410k	500k	90k	22%
16.3	380k	470k	90k	24%
16.4	355k	430k	75k	21%
16.5	420k	540k	120k	28%
16.6	330k	380k	50k	15%

Table 6. Resistance range for sensors made with 0.005" plastic

Sensor #	Minimum Resistance (Ω)	Maximum Resistance (Ω)	Resistance Change (Ω)	% Change
15.1	820k	1170k	350k	43%
15.2	600k	900k	300k	50%
15.3	720k	960k	240k	33%
15.4	600k	800k	200k	33%
15.5	570k	700k	130k	23%
15.6	920k	1300k	380k	41%

Final Sensor Production Method

The following outlines how the sensors were made in accordance with the optimal method of sensor production that was determined by the tests previously described.

1. Polyester plastic (#8567K2 and #8567K4) from McMaster-Carr Supply Company were cut into 22 cm by 6 cm sheets.
2. The carbon-based electrically conductive ink (Creative Material, CM #101 - 80) was mixed with thinner (2 - butoxyethyl acetate, CM #113-12) in an ink-to-thinner ratio of 2:1.
3. Three layers of the conductive ink/thinner mixture were screen printed onto the polyester plastic. Each application was followed by a 24 hour drying time.
4. The sheets were cured at 100 °C for 10 minutes.
5. The sheets were cut into twenty, 1 cm by 5 cm, strips.
6. Wires were attached to each strip using a conductive adhesive made of silver-filled silicone in toluene (Creative Material #102-32).
7. The sensors were cured at 100 °C for 10 minutes.
8. The entire sensor was coated with a flexible silicone adhesive (Newark Electronics #00Z021) and allowed to dry at room temperature for 24 hours.

HARDWARE

A hardware and software system was developed to show one possible way to incorporate the sensors into a complete device that displays and stores the data from the sensors. In the hardware design presented here, only one sensor was used to illustrate this concept. However, the design can easily be expanded to collect data from 16 sensors. This is described in detail in the future work section of this paper.

The hardware system consists of six main parts: the sensor, the calibration circuitry, the multiplexer, the A/D converter, the microcontroller and a computer. In general, the purpose of the hardware is to obtain a voltage that corresponds to the resistance of the sensor, convert it from an analog signal into a digital one and then send this result to a computer. The block diagram for the hardware is shown in Figure 6 and a detailed circuit diagram is shown in Figure 7.

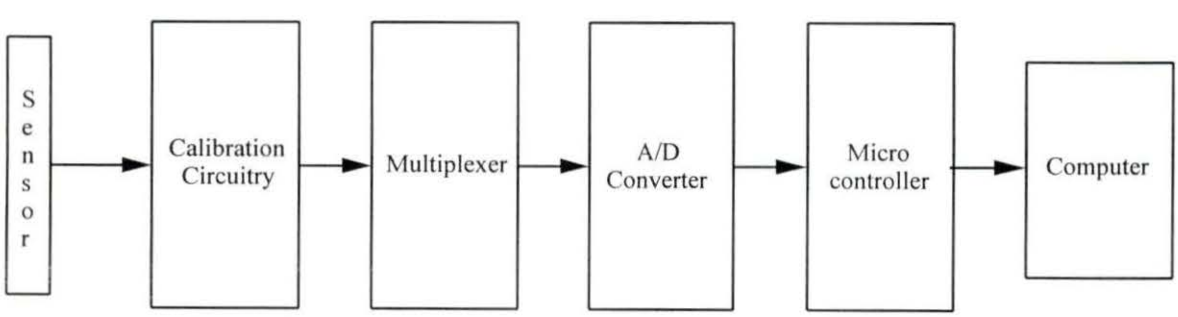

Figure 6. Block circuit diagram

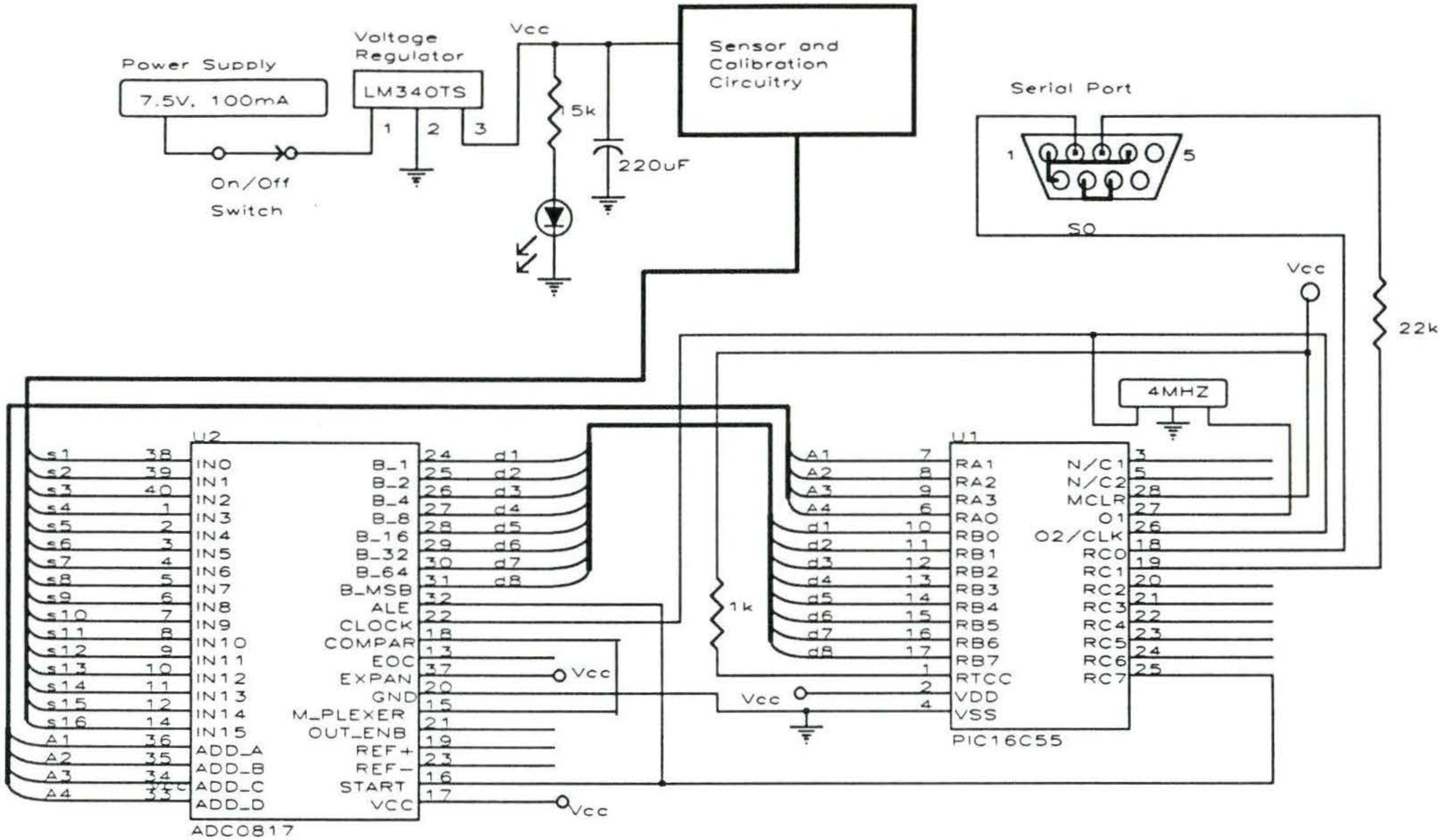

Figure 7: Circuit Diagram

Sensor and Calibration Circuitry

Since the sensors are resistive, they are passive elements, and either a regulated voltage across the gage, or a regulated current through the gage, is necessary so that an observable output can be obtained [6]. In this design, a regulated voltage supply was used. The sensor and calibration circuitry that was used is from Wobschall (1987) and is shown in Figure 8. The parts list for this circuit is given in Table 7.

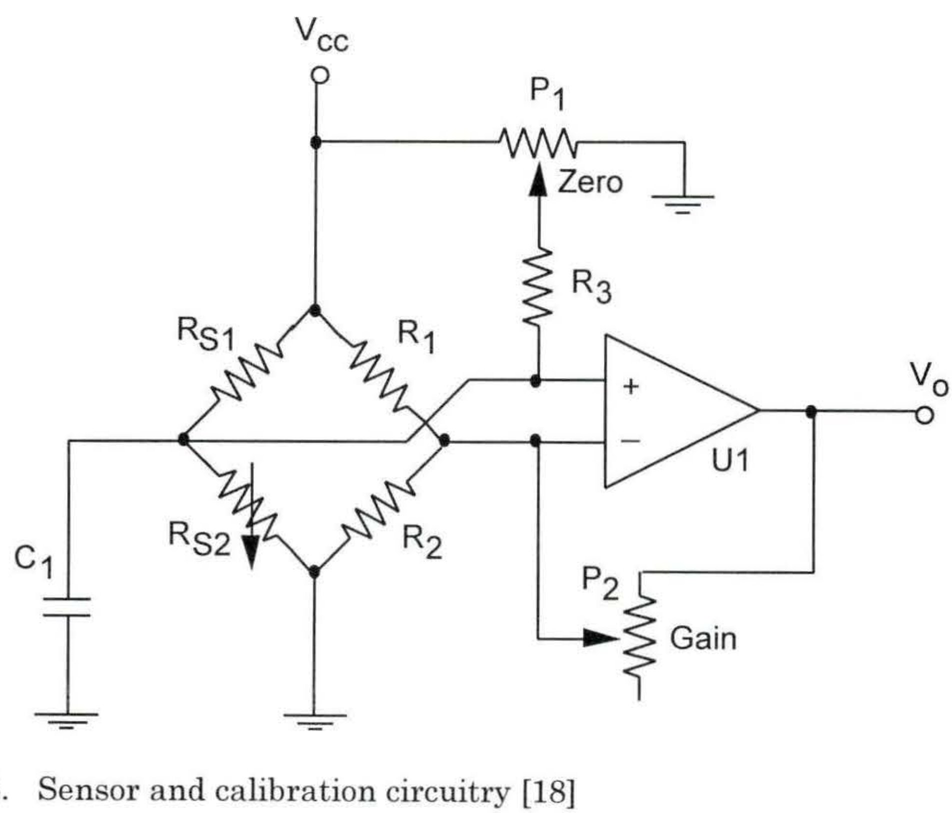

Figure 8. Sensor and calibration circuitry [18]

Table 7. Parts list for calibration circuitry

Reference	Part	Description
R_{S1}	Sensor	Stationary sensor
R_{S2}	Sensor	Flex sensor
R_1	100 kΩ Resistor	Bridge resistor
R_2	100 kΩ Resistor	Bridge resistor
R_3	1 MΩ Resistor	
P_1	1 MΩ Potentiometer	Zero setting potentiometer
P_2	1 MΩ Potentiometer	Gain setting potentiometer
C_1	10μF Capacitor	
U_1	LM741 Op-Amp	

As given by [18], if $R_{S2} = R_x + \Delta R$ and R_g is the feedback resistance set by P_2, then, for small changes in resistance, the output voltage for this circuit can be written as:

$$V_o \approx \frac{AVcc\Delta R}{4R_x} \qquad [2]$$

where $A = \frac{R_1 + 2R_g}{R_1}$.

Since this circuit uses two sensors in a bridge configuration, it compensates for sensor temperature sensitivity. R_{s1} should be stationary and mounted in a position where it is at the same temperature as R_{s2}, the sensor being measured. The resistance change in both of the arms due to thermal output will be the same and will cancel in the bridge circuit. However, the output voltage of this circuit is non-linear for large changes in resistance [18].

As given by Wobschall, the circuit is calibrated by first adjusting P_1 so that the output is zero volts at the minimum sensor resistance. The gain setting potentiometer, P_2, can be adjusted so that the maximum voltage is obtained when the sensor is flexed and the resistance is at a maximum [18]. By calibrating the sensor in this manner, the maximum voltage range is available for the A/D conversion.

The capacitor, C_1, shown in Figure 8, was added to the circuit to reduce the large amount of noise that was present.

Multiplexer and A/D Converter

A National Semiconductor ADC0817 was used to select the input channel and perform the A/D conversion. The ADC0817 is a monolithic CMOS device that has a built-in 16-channel multiplexer with an 8-bit analog-to-digital converter and is microcontroller compatible. The 16-channel single-ended multiplexer can directly access any one of 16 analog signals and provides the logic for additional channel expansion. A particular input channel is selected by using the address lines, ADD_A, ADD_B, ADD_C and ADD_D as shown in Figure 7. The 8-bit A/D converter uses successive approximation as its conversion technique which features a high impedance chopper stabilized comparator. The ADC0817 is a complete data acquisition system for ratiometric conversions [10]. Thus, the physical variable being measured is expressed as a percentage of the full-scale which is from Ref(-) to Ref(+). Since the calibration circuitry provides voltages levels from zero volts to Vcc, Ref(-) was tied to ground and Ref(+) was tied to Vcc as shown in Figure 7.

Microcontroller

A Microchip PIC16C55 microcontroller was used in this design. The PIC16C55 is an 8-bit, fully static CMOS microcontroller that employs a RISC-like architecture. It has 12-bit wide instructions and an 8-bit wide data path, with an onboard ROM size of 512 by 12 and a 32 by 8 RAM with seven special function hardware registers.

Serial Port

The RS-232 serial port of the computer was used to both send and receive information asynchronously to and from the microcontroller. The circuit was connected to the computer through a modular cable. A DB9 to RJ11 jack was plugged into the serial port of the computer. The modular cable was then used between the RJ11 jack and a modular jack on the circuit board.

The QuickBASIC program and the microcontroller program were written to use a baud rate of 4800. Asynchronous serial data is commonly sent as a string of 10 bits consisting of a start bit, eight data bits and a stop bit. The start and stop bits help the receiver to synchronize the incoming data bits. Since the transmission is 10 bits long, the actual number of bytes per second is one-tenth the baud rate, or 480 bytes per second for a baud rate of 4800.

None of the RS 232 handshaking lines were used. Thus, it was necessary to loop them back as shown in Figure 7. In this way, when the computer asks for permission to send, for example, the signal appears at its own clear-to-send pin [3].

Assembly Language Program

The assembly language program was written in the Parallax Version of the PIC instruction set, and the PIC assembler was used to convert the assembly language source code into object code that could then be used by the PIC Programmer and PIC Downloader. The PIC Downloader was used in the assembly code development. When plugged into the target system, the PIC Downloader reads assembled code and executes it, acting like an actual PIC programmed with code. Once the code was in its final version, a one-time-programmable PIC16C55 was programmed using the PIC Programmer. The program used a total of 91 instructions out of the 512 available. The general flow chart for the code is shown in Figure 9. The code for the PIC and the computer were written so that when the computer is ready to receive a byte of data, it sends "r" (72 Hex) to the microcontroller. The microcontroller then sends

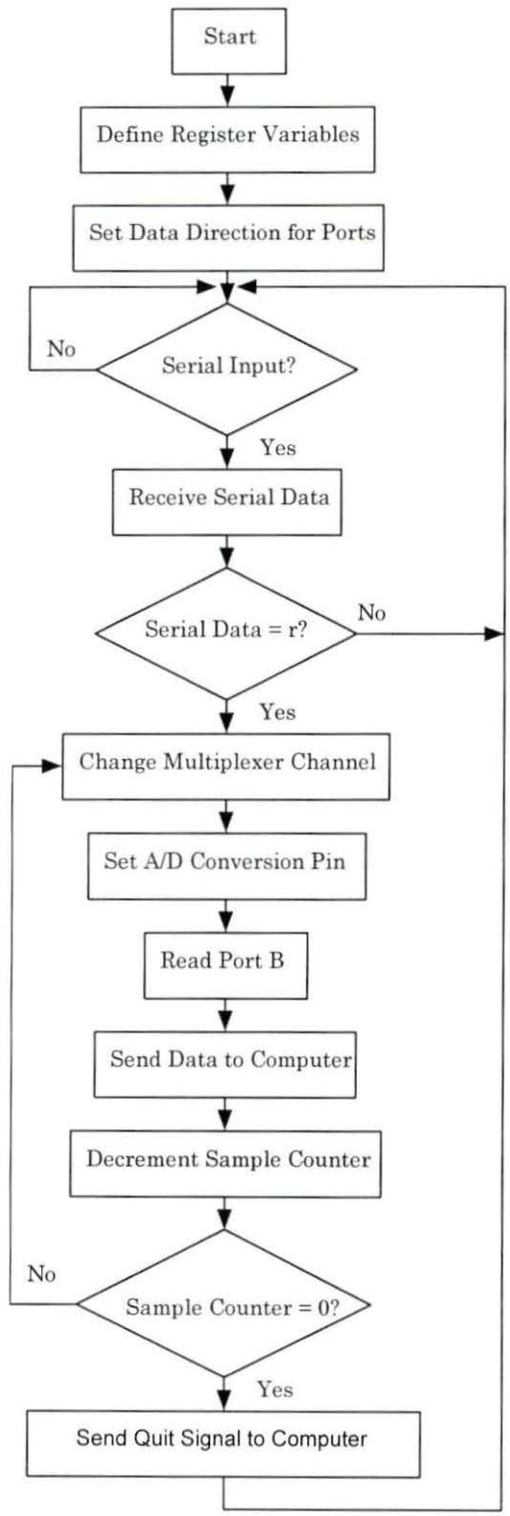

Figure 9. Basic flow chart for the assembly language code

the data to the computer followed by a quit signal. Since the PIC microcontroller does not have a receive function or onboard serial communication hardware (both of which are available with more expensive controllers) it had to be programmed to add these capabilities [12].

When receiving the data from the computer, the microcontroller receives a single bit at a time. First, the microcontroller waits for an input signal on pin rc.1. When an input is detected, the microcontroller determines if it is a start bit or a false signal. This is accomplished by pausing for a length of time slightly shorter than the start bit before reading the pin again. If it is not set, then it goes back and waits for another input signal. If it is still set, then the microcontroller goes to the receive data subroutine. In this subroutine, the input pin is read, and the data bit is put into the carry which is then rotated into the receive byte. After waiting one bit time, this is repeated until all eight bits have been received. [12]

A similar procedure is used to send data to the computer. In this case the start bit is sent to the computer through rc.0, followed by each bit of the data, until all eight bits have been sent. This is followed by the stop bit. After each bit, there is a one-bit delay time until the next bit is sent. Opposite to the receive procedure, the data in the microcontroller register is rotated into the carry, which is then put at the output pin (rc.0) to be read by the computer. [12]

Power Supply

An AC adapter with an input of 120 VAC, 60 Hz and an output of 7.5 VDC, 100mA was used to power the circuit. A subminiature PC mount phone jack was used connect the adapter to the circuit. The voltage from this power supply was regulated by a 5V, 1A voltage regulator. However, because of the calibration circuitry that was used, a negative voltage was also required to power the op-amps. Thus, a 9V battery was added to supply the negative voltage to the op-amps.

A DPDT slide switch turns the unit 'on' and 'off', and a green LED indicates when there is power to the circuit.

Two capacitors filter noise. A 220 μF capacitor was placed between the positive supply and ground, and a 10 μF capacitor was placed across the sensor.

Various sensors can easily be tested with this circuit, as there are three wires extending from the circuit. The two sensors in the bridge configuration of the calibration circuitry can then be attached to these wires.

Production of the Printed Circuit Board

The artwork for the printed circuit board was produced using the computer program SuperPCB by Mental Automation, Inc.. A single layer board was designed, and all of the routing and component placements were done manually. The connectors for the power, serial communication, and sensors were all placed at the outside of the board so that they could be easily accessed. The materials used to produce the printed circuit board were obtained from Circuit Specialists in Scottsdale, AZ.

To produce the PCB, the artwork was printed with a laser printer onto a transparency. The transparency was then taped to a presensitized positive acting PCB and placed under a fluorescent lamp for 11 minutes. A developer was used to remove the photoresist that had been exposed to the light. The circuit board was then placed in an etching tank that contained anhydrous ferric chloride until all of the exposed copper had been removed (about 8 minutes). The photoresist was removed from the traces on the board by exposing the board to fluorescent light and then using the developer to remove the remaining photoresist. Holes were drilled for the components which were then inserted and soldered. The final circuit board is shown in Figure 10. The actual dimensions are 6.9 cm by 9.8 cm. The price list for the hardware is given in Table 8. All of the parts shown in Table 8 were obtained from Digi-Key in Thief River Falls, MN

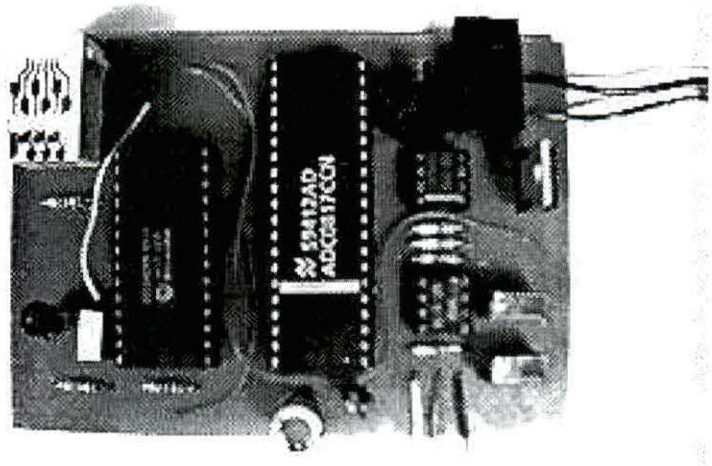

Figure 10. Final circuit board

Table 8. Hardware price list

Description	Quantity	Unit Price
PIC16C55 - One Time Programmable Microcontroller	1	6.88
ADC0817CCN - A/D Converter with 16 Channel Multiplexer	1	18.90
741 - Op Amp	2	0.98
DB9S to RJ11 Jack	1	4.95
Modular Jack	1	3.06
Modular Cable	1	2.91
1 MΩ, Ceramic, 25 Turn Potentiometer	2	0.79
DPDT Slide Switch	1	1.69
Sub miniature PC Mount Phone Jack	1	2.00
4 MHz Ceramic Resonator with Built in Capacitors	1	0.86
Power Supply	1	5.40
LM34OT - Voltage Regulator, +5 VDC, 1 Amp	1	1.51
Green LED	1	0.27
10 μF Capacitor	1	0.12
220 μF Capacitor	1	0.25
9 Volt Alkaline Battery	1	2.88
9 Volt Battery Clip	1	0.30
Total		$53.75

SOFTWARE

The computer software was written in Microsoft QuickBASIC version 4.5 and was converted to an executable file so that it could run independently of the QuickBASIC shell. It was designed for use in the MS DOS environment of an IBM, or an IBM compatible, personal computer.

The purpose of the software is to collect data from the microcontroller, processes it, display it in real time and write it to a file for further analysis. The program receives the data by sending the microcontroller a byte that signals the microcontroller that the computer is ready to receive the data. It then waits for the microcontroller to send the data. After the microcontroller has sent the data, it sends a byte that signals the computer that all of the data has been sent. The data is then processed, displayed and stored before the next data sample is received.

Anytime during the execution of the program, the user can exit the program by typing 'q'. If q is typed at any time before the data collection has begun, the user is asked whether the computer should exit the program, restart the program, or continue. If data collection has begun, the program simply terminates when 'q' is typed.

When the user starts the program by typing 'sensor', a prompt to choose between four modes is given. They are:

1. Unprocessed data in numerical form
2. Unprocessed data in graphical form
3. Units in numerical form
4. Units in graphical form

For all of the modes, the user is also prompted to enter a file name for the data from that run.

In the unprocessed data modes, the data from the microcontroller is displayed on the screen without going through any preliminary signal processing. Thus, the values that are displayed on the screen (either numerically or graphically) are from 0 to 255 (00 hex to FF hex). The zero control potentiometer can then be adjusted in the unflexed position to obtain a 0 reading, followed by the adjustment of the gain setting potentiometer to reach a reading of 255 for the maximum flexed position. In this way, the maximum voltage range for the sensor can be obtained.

After calibrating the sensor, the user can restart the program and collect flex angle data with modes 3 or 4. In these modes, the data is processed before it is displayed. An adjusted data value is first calculated using the following instruction from Short, 1981:

$$dat(x,y) = \frac{dat(x,y) - dat(S,y)}{dat(F,y) - dat(S,y)} * 255 \qquad \text{Instruction 1}$$

Where dat(x,y) is the data received from the microcontroller, dat(S,y) is the minimum value of the sensor and dat(F,y) is the maximum value. If the sensor is exactly calibrated then dat(S,y) = 0 and dat(F,y) = 255, and thus, dat(x,y) is unchanged. However, if the sensor is not exactly calibrated, then this instruction ensures that the data for each run will still be from 0 to 255. This will also compensate for variations in temperature between runs, zero drift and, once the sensors are incorporated into a glove, it will also compensate somewhat for different hand sizes

There are two ways to obtain the minimum and maximum values for this equation. The user can choose to find the actual range or choose to type in minimum and maximum values. In the first method, the user is prompted to straighten the sensor and type 's'. Then the user is then prompted to flex the sensor and type 'f '. In the second method, the user is prompted to simply type in the maximum and minimum values for the sensor. All of the data received from the microcontroller are then adjusted using these values.

The data is further processed by taking a 10-point moving average. This is done by summing the sample with the nine previous samples and dividing by 10.

The data is then scaled so that when graphed, the entire screen is utilized. Thus, the data, that is collected in modes 3 and 4, is in the form of "Units", of unknown quantity, as a function of time.

For all of the modes, the time in seconds, calculated from the time that data collection began, is written to the file name that was selected. Also, for all of the modes, the unprocessed data is written to this file, and for modes 3 and 4, the processed data for each step is also sent to the file. The file can then be opened in a spreadsheet program at a later time for further analysis.

For all of the modes, the data is displayed either graphically or numerically in real time on the computer screen. The graphical display uses 640 x 350 graphics resolution. Thus, 640 samples per screen are graphed from left to right. When the right edge of the screen is reached, the screen is cleared, and the graphical display continues on the left side of the screen.

The sampling rate is 15.8 samples/sec for the graphical modes and 1.29 samples per second for the numerical modes. The sampling rate for the numerical modes was decreased to give the user enough time to see the data before it scrolls off of the screen.

SENSOR CHARACTERISTICS

Tests were performed to determine sensor characteristics, including time response, temperature response, flex response and repeatability, and the repeatability of the dynamic response. The sensors used in these tests were complete sensors produced using the optimal production procedure that had been experimentally determined. In this section, the tests that were performed are explained and the results from each test are given. A discussion of each test is also presented.

General Method used for Testing

With the exception of the temperature sensitivity test, the following procedure was used to test the sensor characteristics.

First, the sensor was mounted to a hinge, used to represent a finger joint, as shown in Figure 11. The hinge, with the sensor attached to it, was then placed on a protractor and bent to different angles as shown in Figure 12. The hinge had a radius of curvature of 1/8", and the sensor was mounted so that the entire plastic side of the sensor was in contact with the hinge at all times. The right side of the sensor was attached to the right side of the hinge with tape. Since the sensor was not elastic, the other side of the sensor could not be firmly attached to the other side of the hinge. Instead, it was held in place by taping a piece of paper to the hinge, over the sensor. This held the sensor in place

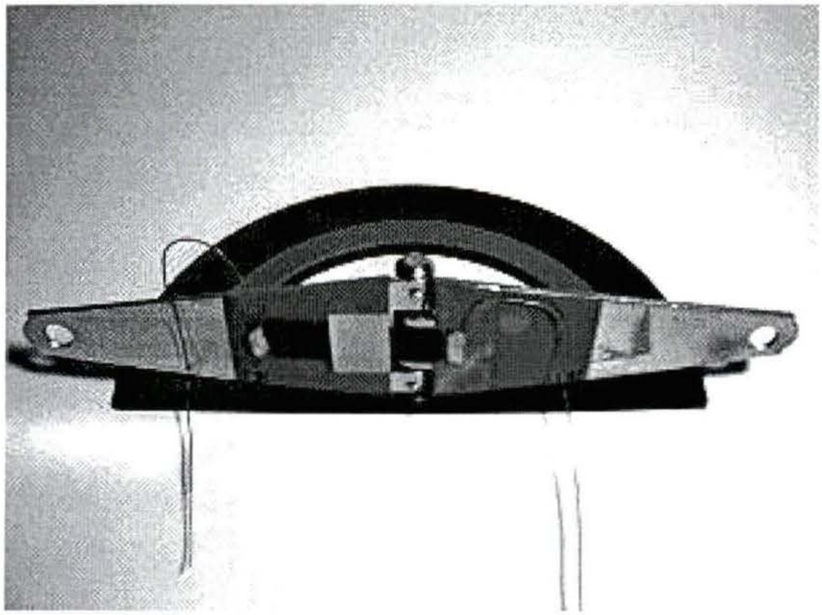

Figure 11. Sensor mounted to a hinge

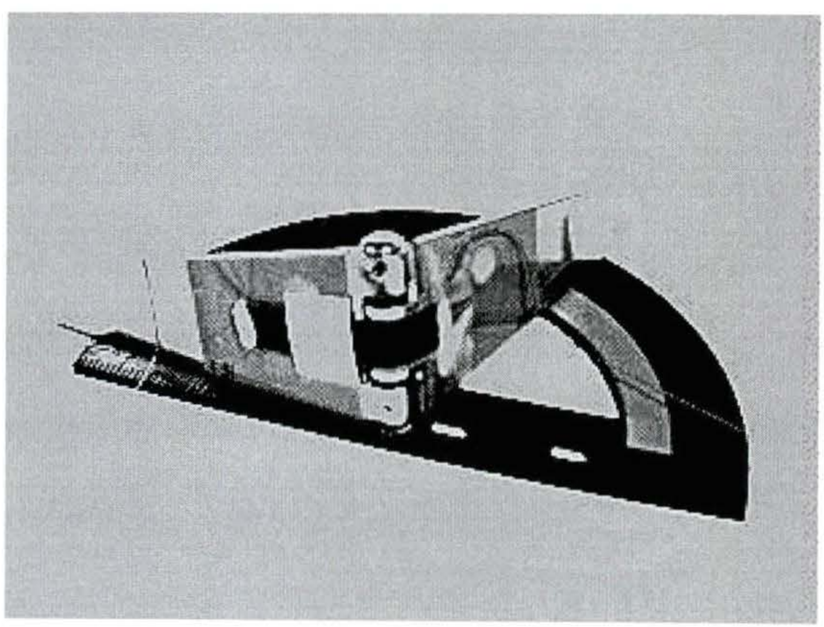

Figure 12. Determining the flex angle

against the hinge while still allowing the sensor to slide as the hinge was flexed and unflexed.

To test the sensor response, the hinge was bent to known angles and the resistance of the sensor was measured using a Radio Shack RS22-168 Manual/Auto Dual-Display Digital Multimeter with a PC interface.

Time Response

The time response of the sensors was measured by using the multimeter's PC interface to record the resistance at one sample per second as the sensor was flexed and then unflexed.

Testing and Results

Before the measurement began, the sensor was allowed to "settle" in the nonflexed position (0°). It was then bent to 90 °, held there, and again unflexed as shown in Figure 13.

The time response was determined by first drawing a line tangent to the curve as illustrated in Figure 13. The time response was then calculated as the difference between the time at which the tangent line crossed the time-axis and the time at which the sensor had been straightened. The time response of four sensors is tabulated in Table 9.

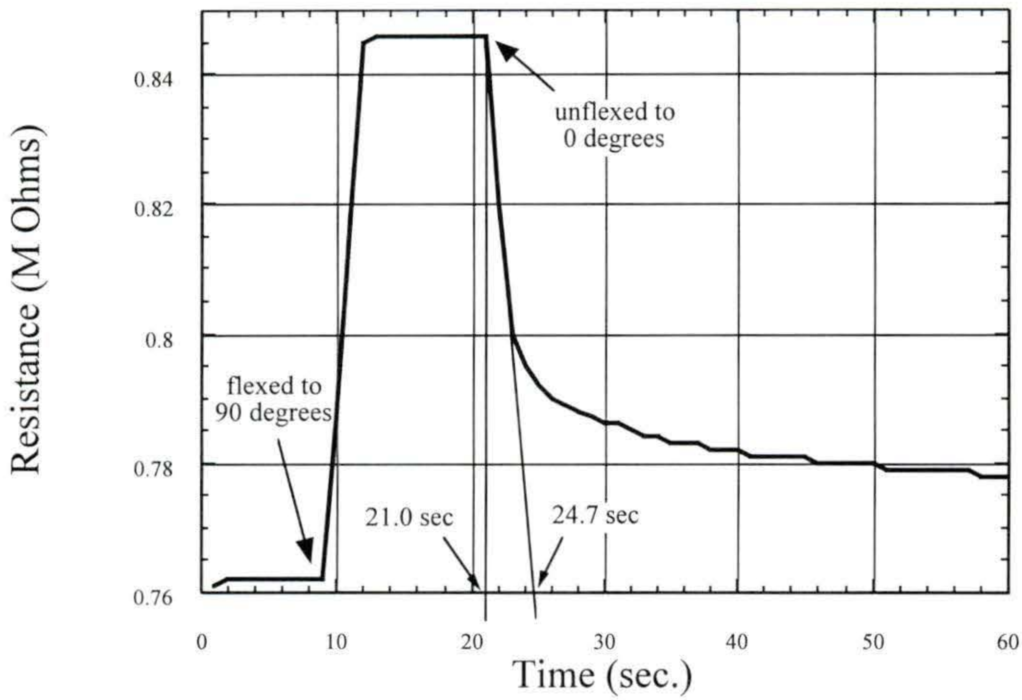

Figure 13. Time response for sensor 15-1 bent to 90° and then straightened

Table 9. Time response of four sensors

Sensor	Time (sec)
15-1	3.25
15-2	5.25
16-1	4.50
16-5	4.75

Discussion of Results

In this test, the time response of the sensor was measured by flexing the sensor, unflexing it, and allowing it to settle again. It was found that the response of the sensor when flexed was very good. The amount of time that it took going from the minimum value to the maximum value can be attributed mostly to the time it took to physically bend the sensor from 0 to 90°.

When unflexed, however, the response was not as good. At first, the resistance decreased relatively fast as can be seen from the values in Table 9. However, the time it took for the sensors to decrease to their original value was several minutes. This response was typical for all of the sensors tested without a noticeable difference between the sensors made from the 0.002" plastic and 0.005" plastic.

Temperature Sensitivity

The temperature response of the sensors was tested by first increasing the temperature from 40° F to 120° F and then decreasing it again to 80° F. Measurements were taken in increments of 5 °F. The temperature response of two sensors was measured. One was from the 0.002" thick plastic and the other was from the 0.005" thick plastic.

Testing and Results

To control the temperature of the sensors, they were measured while submersed in water, as the water temperature could easily be changed and measured. To do this, the sensors were taped to a cards so they could not be flexed. They were then placed in water-proof bags. The bags were left open at the top so that multimeters could be attached to the sensor leads. They were then placed in a tank so that the sensors were well below the water line. A heater, a digital thermometer and a bubbler were also present in the tank. The heater was used to increase the temperature while the bubbler was used to ensure a uniform temperature.

The water in the tank was first cooled by adding ice cubes to the water. The temperature was then increased and resistance measurements were taken every 5 °F until 120 °F was reached. The tank was then cooled again by turning off the heater and adding ice cubes. The resistance of the sensors were then recorded every 5 °F until the temperature had decreased to 80 °F. The results of this test is shown in Figure 14.

Discussion of Results

These results show that the sensors are extremely sensitive to even small changes in temperature. For example, in going from 70° F to 90° F, the resistance for sensor 16-6 changed 7.5%. In addition, an apparent zero shift was

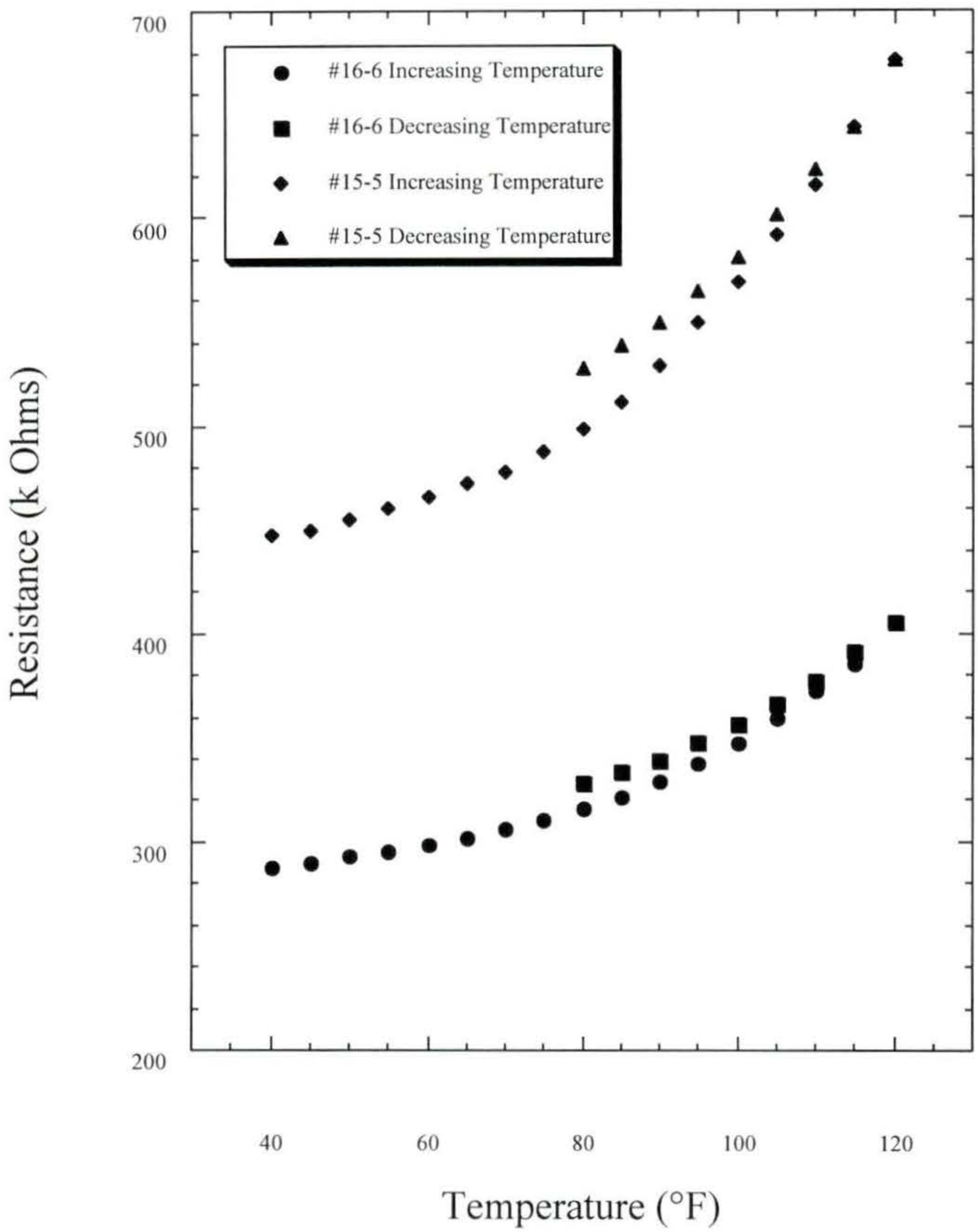

Figure 14. Temperature response of two sensors

observed following the heating cycle as seen in Figure 14. Since the minimum curing temperature for the conductive ink and the adhesive is 50° C (122° F), it is possible the internal structure of the sensor was changed when the sensor was heated to 120° F causing the zero shift.

From these results it is clear that it is necessary to design the hardware or software, for use with these sensors, to compensate for temperature effects.

Flex Response and Repeatability

To test how the resistance of the sensors varied as a function of flex, the following test was performed and repeated for four different sensors. Two of the sensors tested were made from the 0.002" plastic (sample 16) and two were made from the 0.005" plastic (sample 15).

Testing and Results

The resistance of the sensors was first measured as a function of the flex angle. This was done by measuring the resistance of the sensor as it was flexed in steps of 10° from 0° to 100°.

The measurements were then repeated 2-3 times for each sensor. The average of each point was then taken, and the resultant data for each sensor was fit to a second-order polynomial using the graphics program, KaleidaGraph from Abelbeck Software. The results from the four sensors are shown in Figures 15, 16, 17 and 18. The error bars in these graphs indicate that the hinge could be bent to within 1° of the desired angle.

The correlation coefficient and the polynomial for each sensor are shown in Table 10. The percent change in the average resistance from a minimum at 0° to a maximum at 100° was also determined from the graphs and is shown in Table 11.

Discussion of Results

In this test, four different sensors were bent to known flex angles, and the resistances were recorded. It was found that a second-order polynomial ($r=0.999$) could be fit to all of the sensors measured in this way which demonstrates that the resistance of the sensors changed in a predictable manner when the sensor was bent.

Despite this, these figures also show that it was often difficult to determine the flex angle to within 10 degrees of accuracy for low flex angles. However, in general, as the flex angle increased, so did the accuracy. Thus, the larger flex angles could be measured with a greater degree of accuracy.

It is apparent that, even though the % change in the resistance for the sensors made with the thicker plastic is greater, they are not as accurate as the sensors made with the thinner plastic. This can be seen by the wider distribution of the resistance measured for a given angle for the thicker plastic.

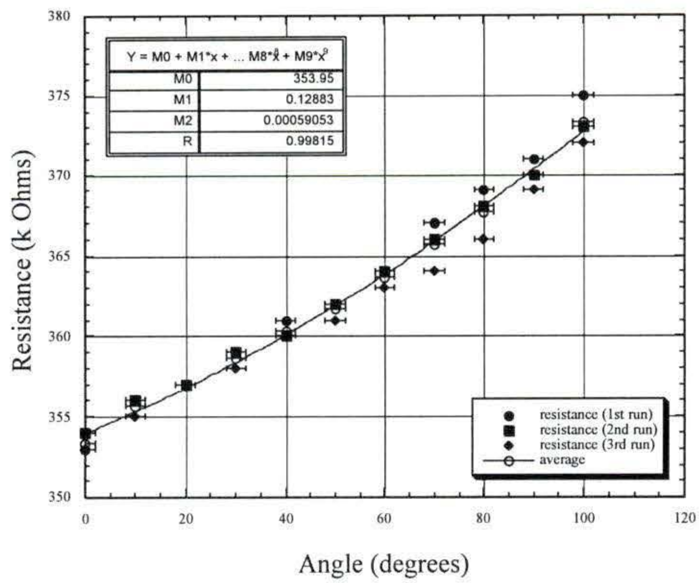

Figure 15. Resistance for different flex angles (sensor 16-1;0.002")

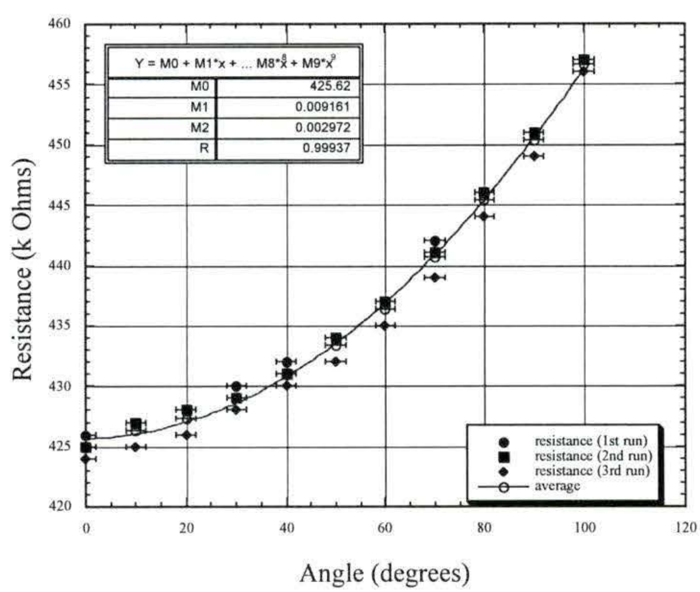

Figure 16. Resistance for different flex angles (sensor 16-5;0.002")

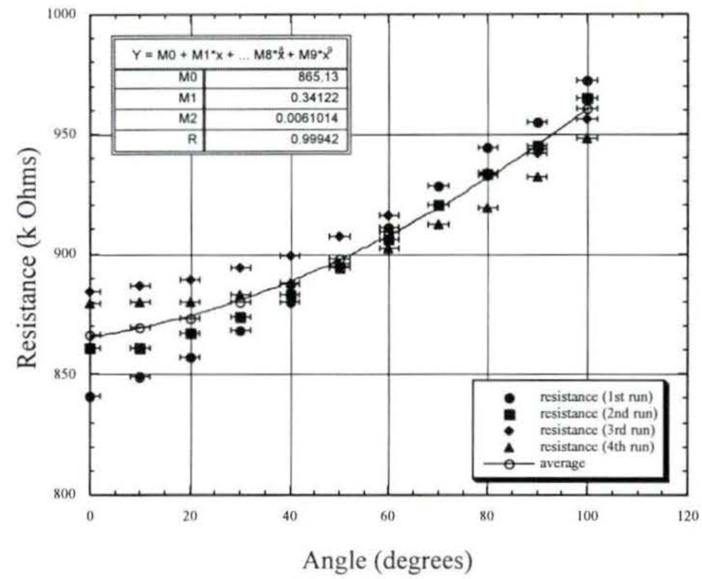

Figure 17. Resistance for different flex angles (sensor 15-1; 0.005")

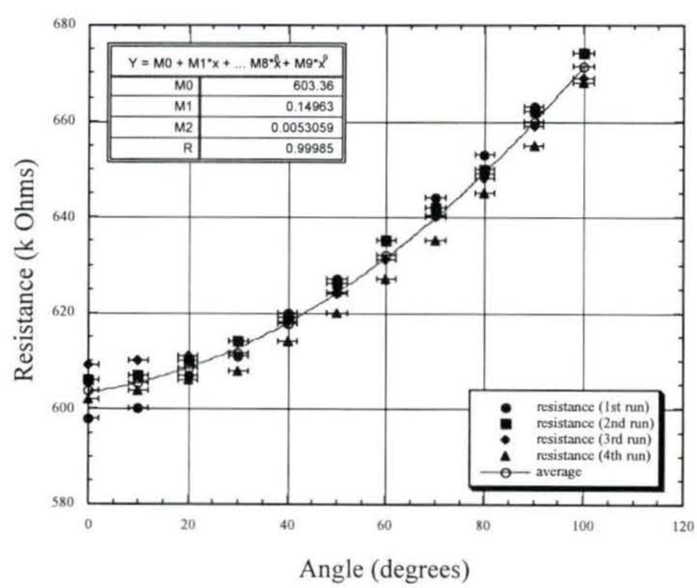

Figure 18. Resistance for different flex angles (sensor 15-2; 0.005")

Table 10. Second order polynomials calculated for four sensors

Sensor #	2nd Order Equation	Correlation Coefficient
16.1	Y = 354 + .129 * x + .000590 * x ^ 2	.99815
16.5	Y = 426 + .00916 * x + .00297 * x^ 2	.99937
15.1	Y = 865 + .341 * x + .00610 x ^ 2	.99942
15.2	Y = 603 + .150 * x + .00531 x ^ 2	.99985

Table 11. Percent change in resistance from 0° flex to 100° flex

Sensor #	Average Resistance at 0°	Average Resistance at 90°	% Change
16-1; 0.002" plastic	353	373	5.7%
16-5; 0.002" plastic	426	457	7.3%
15-1; 0.005" plastic	865	960	11.0%
15-2; 0.005" plastic	605	670	10.7%

One possible explanation for this could be that the internal structure of the conductive ink is under too much strain in the sensors made from the thicker plastic. Resistivity changes occur when a conductor is strained because of an elastic distortion of the lattice structure. The distortion of the internal structure then influences electron flow through the conductor. It is possible that the internal structure of the sensors made from the thicker plastic is changing too much when flexed and perhaps they are approaching their elastic limit. This seems to particularly be the case with sensor 15-1, shown in Figure 17, where the unflexed resistance of the first run is lower than that of the second run which is also much less than that of the third run. It appears that when the sensors are unflexed, they may not be returning to their original resistance.

Another possibility could be that it may take the sensors, made from the thicker plastic, a longer time to completely "settle" than the sensors made from the thinner plastic. The time response of the sensors (Table 9), that were calculated by using the tangent line to the curve, displayed no noticeable difference for different plastic thickness'. However, the time that it took for the resistance of the sensors to decrease back to the original values was not measured. It is therefore possible that the response time of the sensor is causing these results.

In comparing the % change in resistance shown in Table 11 to the % change in resistance that was shown in Tables 5 and 6, there appears to be a discrepancy, as the values reported in Tables 5 and 6 show a % change of about 23% for the 0.002" plastic and 37% for the 0.005" plastic. This discrepancy is the result of the sensors being bent to 180° for the values reported in Tables 5 and 6, whereas the sensors were bent to 100° for the results shown in Table 11. This shows that only a fraction of the sensor range is being utilized in the tests where the sensor is only being bent to 100°. However, this is more realistic when considering the intended application for these sensors in an instrumented glove.

Repeatability of the Dynamic Response to 90°

To test the repeatability of the dynamic response of the sensor to a given angle, the sensor was bent repeatedly between 0° and 90°.

Testing and Results

The same method was used in this measurement as in the time response measurements with the exception that the sensor was continuously bent between 0 and 90 degrees and was never allowed to settle between trials. The graph obtained from sensor 15-1 is shown in Figure 19.

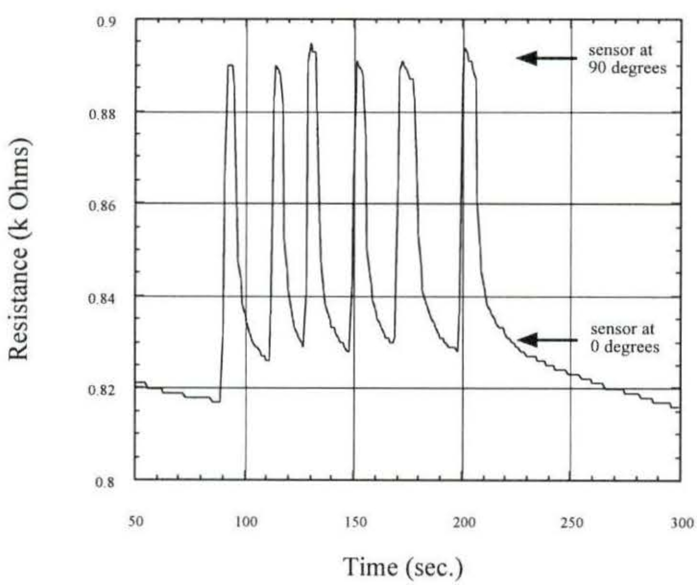

Figure 19. Sensor 15-1 flexed and unflexed repeatedly between 0° and 90°

The peak values (corresponding to 90°) from these graphs were then tabulated and the average, difference, standard deviation, and percent error were calculated using the graphics program KaleidaGraph. The results are shown in Table 12.

Table 12. Response of sensors when flexed continuously to a 90° angle

	Sensor 15-1 resistance (kΩ)	Sensor 15-2 resistance (kΩ)	Sensor 16-1 resistance (kΩ)	Sensor 16-5 resistance (kΩ)
1 (90°)	890	620	365	442
2 (90°)	890	621	364	440
3 (90°)	895	624	364	442
4 (90°)	891	623	364	444
5 (90°)	891	624	364	442
6 (90°)	893	626	365	441
7 (90°)		626	363	442
8 (90°)		627		440
9 (90°)		624		
10 (90°)		626		
11 (90°)		625		
12 (0°)	821	564	345	415
average	891.6	624.2	364.1	441.6
difference	70.6	60.2	19.1	26.6
standard deviation	1.79	2.08	0.64	1.22
% error from average	2.5%	3.4%	3.3%	4.6%

Discussion of Results

From these results it can be seen that the percent error in bending the sensor repeatedly to 90° is less than 5%. However, since the accuracy is better for larger flex angles, this percent error would probably increase for smaller flex angles. Despite this, it is clear that the response is reproducible in a dynamic setting, and for large flex angles, the percent error is small.

SYSTEM CALIBRATING AND TESTING

Sensor 16-1 was used to calibrate and test the hardware and software system that had been developed. In this section, the response time of the system is first shown and discussed. The method that was used to determine the flex angle from the data collected by the system is then given, and the results showing the correlation between the measured angle and the actual angle are shown. Discussions of the determination of the flex angle using this system are then given.

Response Time of System

The response time of the entire system including the response time of the sensor, the hardware, and the 10 point moving average used in the QuickBASIC program was measured.

Testing and Results

To test the time response of the system, sensor 16-1, which was mounted to a hinge, was used as R_{s2} (see Figure 8) and sensor 16-6, which was taped to a card so that it could not be moved, was used as R_{s1}. Mode 1 (unprocessed data in numerical form) of the QuickBASIC program was used to obtain a reasonable output range as the sensor was bent between the 0° and 90°. Mode 4 (processed data in graphical form) was then used to obtain the time response of the system. The actual range was found and recorded by the QuickBASIC program by straightening the sensor, typing 's', and then flexing the sensor and typing 'f '. These values were 45 and 160, respectively. The sensor was then allowed to settle for two minutes before starting the data collection. The sensor was then flexed to 90°, held there, and then unflexed back to 0°. The response, graphed in the form of "Units" as a function of time, is shown in Figure 20.

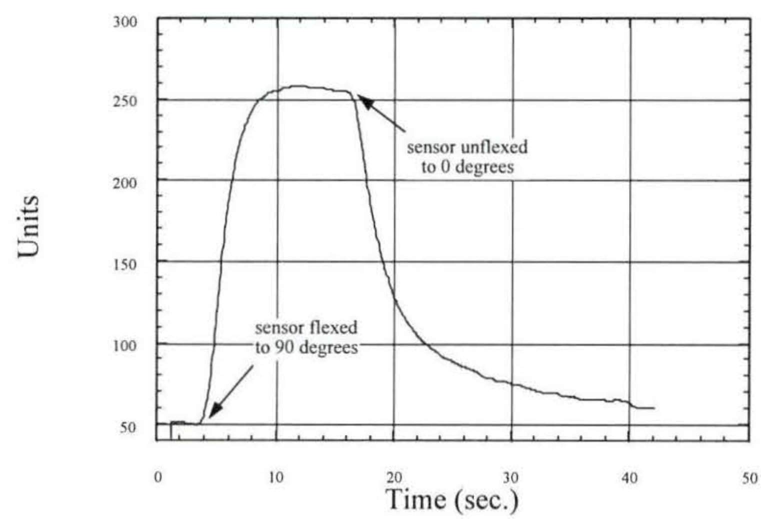

Figure 20. System response time

Discussion of Results

In comparing the time response of the entire system with the time response of just the sensor (Figure 13), it is apparent that the rise time (from 0°

to 90°) of the system is somewhat slower than that of the sensor. This slower rise time is mainly the result of the 10μF capacitor that was placed across the sensor to eliminate noise. The response time (from 90° to 0°) is also somewhat slower because of this capacitor.

Before the capacitor was added, the time response of the system was much better. However, there was so much noise present, that accurate measurements could not be obtained. This noise was probably the result of using long leads to connect the sensors to the printed circuit board and in mounting the sensors to a metal hinge. Before adding the capacitor across the sensor, several other methods were tried in an attempt to eliminate the noise. First a capacitor was placed from the input of the multiplexer to ground. While this reduced the noise significantly, it did not completely eliminate it. Next, the hinge was connected to circuit ground. This also decreased the noise significantly and showed that, even though the conductive part of the sensor was not in direct contact with the metal hinge, the metal hinge was introducing noise into the system. Even though these two methods reduced the noise, there was still a significant amount of noise present. A capacitor was then placed across the sensor. Once this was done, the other capacitor and the connection from the hinge to ground, were no longer necessary.

Determining the Flex Angle

In general, calibrating and testing the measured flex angle consisted of collecting data in the form of Units using the hardware and software that had been developed. This data was collected and averaged, and a polynomial that expressed angle = f(Units) was found. This equation was added to the basic program. The sensor was again tested, and the angles that were generated by the computer were compared to the actual flex angles.

Obtaining an Equation for the Flex Angle

The following procedure was used to the collect data with the hardware and software system that had been developed. First, the sensor was allowed to completely "settle" in the non-flexed position (0°) for several minutes. Mode 4 of the program was used, and the minimum and maximum values from the non-flexed to the flexed position were obtained and recorded. The sensor was then allowed to settle back to the original value. Data was then collected as the sensor was bent in steps of 10° from 0° to 100°. A sample of this data is shown in Figure 21. Four of these runs were obtained using the same sensor values of 37 Units for the minimum and 168 Units for the maximum. The data files were incorporated into the graphics program, KaleidaGraph, and the Units were then read from the graph for each step which correspond to changes of 10°. This data was tabulated and then graphed as shown in Figure 22.

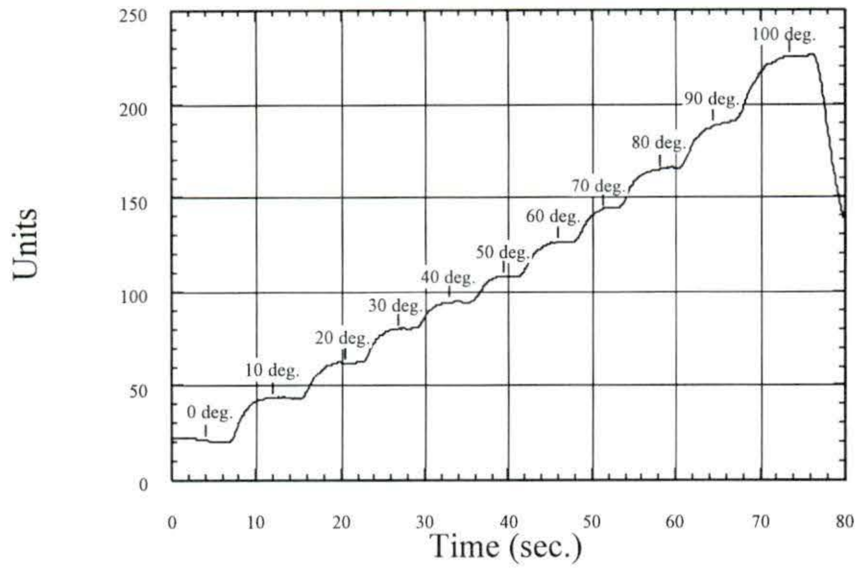

Figure 21. Sensor flexing in steps of 10° to obtain units

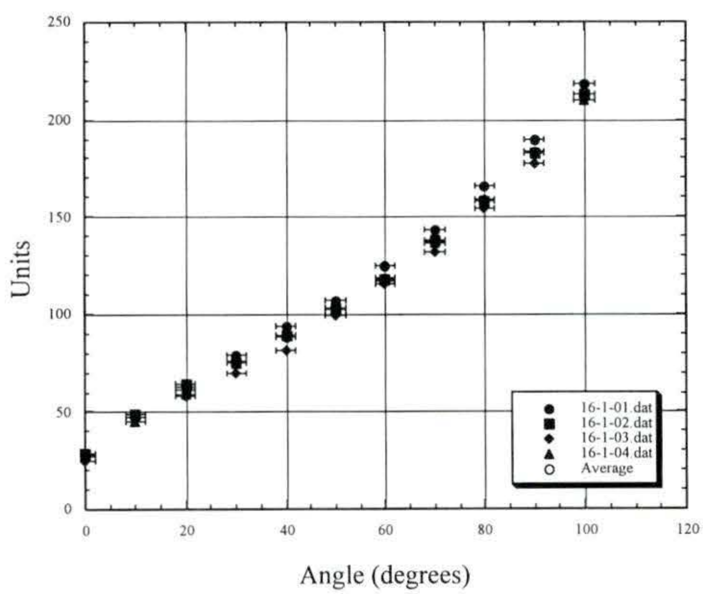

Figure 22. Units as a function of angle

An equation, that could be added to the basic program which expressed the angle as a function of Units, was needed to convert Units, an unknown quantity, into measured flex angles. It was found however, that a third-order polynomial was needed, instead of a second-order polynomial, to adequately represent the data. Thus, it was necessary to obtain the equation, Angle = f(Units) from a third order polynomial expressed as Units = f(Angle). Since obtaining a simple equation from this would be difficult, the axes of the graph were switched so that the angle was graphed as a function of units. This curve could also be fit to a third order polynomial as shown in Figure 23.

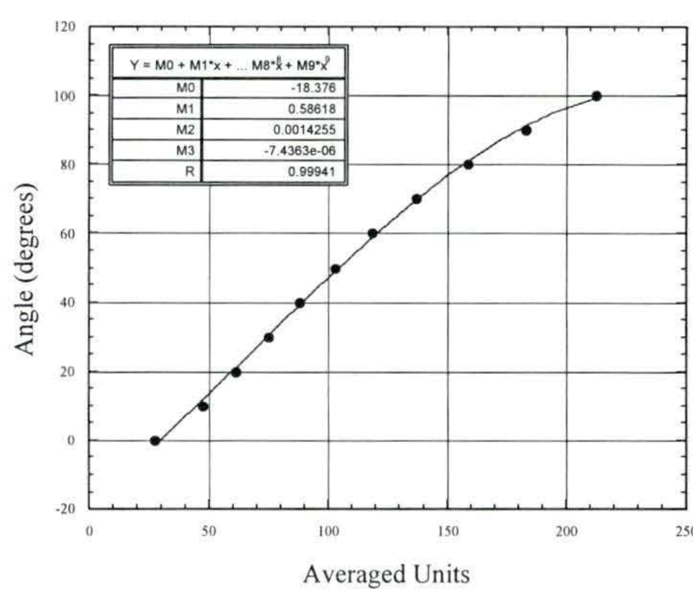

Figure 23. Angle as a function of the averaged units

The following third-order polynomial was added to the QuickBASIC program so that the actual flex angle could be calculated.

Angle = - 18.38 + 0.59 * Units + 0.0014 * Units^2 - 0.00000744 * Units^3

Data was then obtained in the form of the measured angle as a function of time using the same technique as shown in Figure 21.

The angle that corresponded to each step was read from the graph using KaleidaGraph. This procedure was then repeated to test the repeatability and accuracy of the measurements. In doing these measurements, the sensor calibration was varied by adjusting the calibration potentiometers. It was found, however, that the measured flex angle was significantly different from the actual flex angle in these cases. Thus, the potentiometers were again adjusted so that the maximum and minimum values were the same as those used in calculating the polynomial. Five more runs were then made and the results of these runs are shown in Figure 24.

Discussion of Results

The straight line in Figure 24 shows how the data points would have fallen in an ideal system. The error that is seen can attributed to the accuracy of determining the actual flex angle from the protractor, the accuracy of the sensors, and the accuracy of the polynomial that was used to calculate the

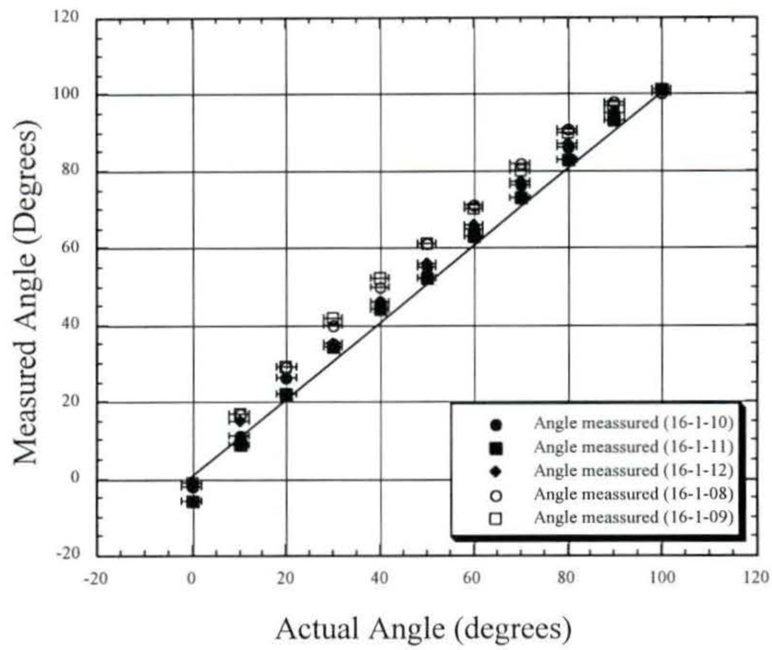

Figure 24. Measured angle as a function of actual angle

measured flex angles. Since the polynomial was determined experimentally, some error was introduced in this step. However, a more significant source of error comes from the fact that the third order polynomial was determined from a system in which two non-linear parameters are operating independently.

First of all, the sensor resistance as a function of the flex angle is non-linear. Also, the calibration circuitry that was used is non-linear for large changes in resistance. Since the resistance, as a function of the flex angle, could be fitted to a second-order polynomial, whereas the response of the whole system required a third-order polynomial, it can be concluded that the calibration system is indeed non-linear.

Thus, changing the calibration of the sensors also changes the coefficients of the polynomial that is needed to represent the data. This effect was seen when the potentiometers were adjusted after the polynomial was found. The angles that were calculated, in this case, were extremely far from the actual flex angle. However, it was found, that the potentiometers could again be adjusted to obtain the same range used when calculating the polynomial, and that in doing this, better results could then be obtained.

From these results it can be seen that it is possible to experimentally determine a polynomial from which the measured flex angle can be calculated. It is also clear from these results that the system does work, to some extent, as a general tendency corresponding to the actual flex angle can be observed.

FUTURE WORK

Sensor Improvements

In the hardware design used in this paper, the flex angle of only one sensor can be measured at a time. The expansion of a system to incorporate more sensors would be greatly simplified if all of the sensors had the same resistance and resistance range from the unflexed to the flexed position.

The sensors made for this work were made by screen printing the resistive ink onto the plastic. While this was an extremely inexpensive way to produce the sensors, it was impossible to produce sensors that had the same range and magnitude in any given sample. It is possible that the screen printing procedure could be improved by further decreasing the ink-to-thinner ratios used while increasing the number of coats applied. Better result might also be obtained by using a larger mesh silk screen.

Although it would be possible to expand the system using different sensor values, the design would be greatly simplified if all of the sensors were the same. Thus, if it is found that the silk screening method could not be improved, it might be economically beneficial to find a better method for applying the ink.

Since the overall accuracy of the system cannot be better than the accuracy of the sensors, it is important to make the sensors as accurate as possible. One way that the accuracy of the sensor could be improved would be to improve the connection between the wire and the conductive ink.

While the conductive adhesive used in the production of the sensors did produce a fairly good connection, it was noted that there was some change in the measured resistance when the wires were moved and the sensor remained stationary. This in turn, decreased the accuracy of the sensors. To improve accuracy, an improved method for connecting the wires to the conductive ink should be investigated.

It also may be possible to produce more accurate sensors by changing the thickness of the plastic. In this paper, 0.002" plastic and 0.005" plastic were tested. It was found that while the 0.005" plastic produced a much greater percent change in resistance when flexed, the repeatability to a given flex angle was better for the sensors made from the 0.002" plastic. It is therefore possible that there is an optimal plastic thickness between 0.002" and 0.005".

In addition, further testing should be done to find a plastic and a protective coating that exhibit the minimum amount of creep. In particular μ-Coat A from Measurements Group should be tried as a protective coating as it was made for use with strain gages.

Further Testing of the Sensors

To fully understand the behavior of the sensors, further tests should be performed so that better hardware and software can be developed to compensate for variations in sensor response. In particular, the response of the sensors when going from a flexed position to an unflexed position should be further investigated. In this paper, the flex response of the sensors was investigated as the sensors were bent from a 0° to a 100° angle. It would also be beneficial to measure the flex response of the sensors when bent in a more random fashion.

The dynamic response of the sensors was tested by flexing the sensor repeatedly to 90° without allowing it to settle. While this produced errors that were less than 5%, the same test should be performed for different angles. It would also be beneficial to repeat this test for random angles.

The response time of the sensors should also be further investigated. In this paper the response time was measured by drawing a line tangent to the curve and defining the x axis crossing minus the time at which it was unflexed as the response time. However, it took several minutes for the sensor to return its original value. This response time should be measured and the zero drift should also be investigated.

Hardware Improvements

The most notable improvement, that could be made to the hardware, would be to improve the calibration circuitry so that it is linear. A circuit that would be an improvement over the one that was actually used is shown in Figure 25.

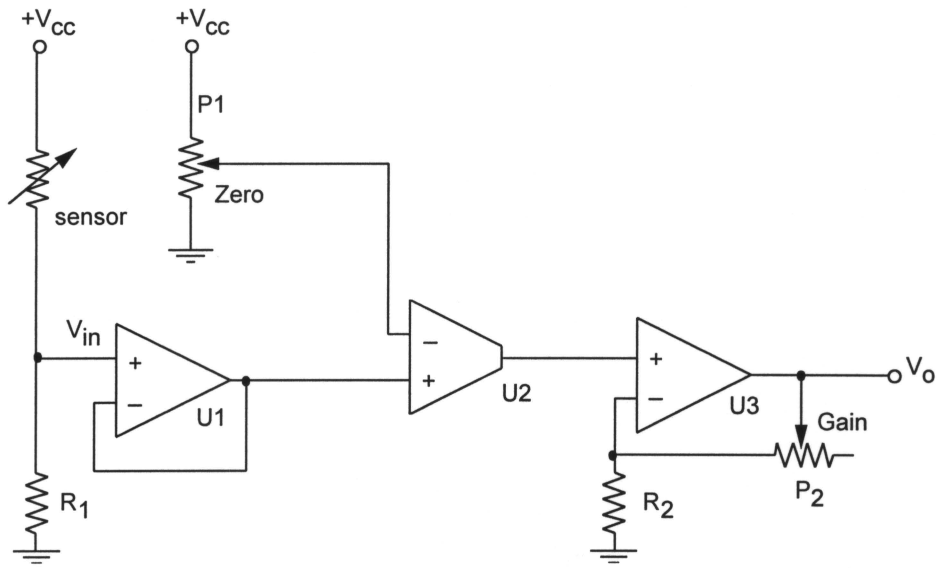

Figure 25. Alternative calibration circuitry

In this circuit, the potentiometer, P_1 can be adjusted to obtain a zero reading when the sensor is flexed, and P_2 can be adjusted to obtain a maximum reading when the sensor is unflexed. Thus, like the calibration circuitry shown in Figure 8, this circuit could also be adjusted so that a range of 0 to 5 volts is obtained for Vo.

The main disadvantage of this circuit is that it does not compensate for temperature. However, Instruction 1 in the QuickBASIC program compensates somewhat for temperature fluctuations between runs by calibrating the data from the minimum and maximum values of the sensor at that time. Additional circuitry could be added to further compensate for temperature fluctuations.

Although this circuit does not compensate for temperature, it has several advantages over the calibration circuit that was used. First of all, this circuit is linear. In the calibration circuitry that was used, not only was the sensor non-linear, but the circuitry itself was non-linear. Because of this, there were two non-linear systems operating independently of one anther. When the zero and gain potentiometers were adjusted, the coefficients of the third-order polynomial that had been experimentally determined were affected. If the circuit were linear, than the error in calculating the measured angle from an experimentally determined polynomial would be reduced.

Furthermore, it would be easier to expand the system using this calibration circuitry. The ADC0817 multiplexer and A/D converter allow for direct access to the "multiplexer out" and "comparator in" pins for signal conditioning. If all of the sensors could be made with the same magnitude and range, then only one calibration circuit would be necessary as it could, in effect, be placed between the multiplexer and the A/D converter.

Another improvement that should be made to the hardware would be to design it so that only one power supply would be necessary instead of two.

Software Improvements

There are numerous ways in which the software could be improved. The first modification of the software should be the addition of a mode that shows a graphical display of the data in the form of the measured angle.

Other modifications could be done to increase the amount of signal processing that is done to compensate for variations in the parameters of the sensors.

Expanding the System

The hardware and software can easily be expanded to work with 16 sensors. To do this the PIC controller simply needs to be programmed so that the number of samples is equal to 16 instead of 1. When the PIC receives the signal from the computer to send data, it sends the data from channel 1. It then decrements the sample counter, selects the next channel and sends that data. It repeats this loop until the sample counter is zero. At this time it then sends a quit signal to the computer.

Each piece of data from the PIC controller is stored in a two dimensional array by the QuickBASIC program as dat(x,y). When the computer sends the ready to receive signal to the PIC, "x" is at a fixed value. "y" is incremented each time a sample is received. When the computer receives the quit signal from the microcontroller, "x" is incremented and "y" is set back to 0. Thus, the only change that needs to be made to the QuickBASIC program is to increase the number of samples in the "y" direction.

Other modifications could also include graphing the response of more than one sensor at a time or changing the graphical display so that it scrolls across the screen rather than clearing the screen and starting over from the left.

Another important step would be to incorporate the sensors into an actual glove. There are many things that need to be considered in doing this including placement of the sensors, method of attachment, connection between the sensors and the circuit board and compensation for different hand sizes.

Since the hardware is easily expanded to 16 sensors, three sensors could be used for each finger and perhaps four sensors could be used to monitor the more complex movement of the thumb. The sensors could also be placed so that they overlap. If the accuracy of the sensors were improved it would be feasible that software could be written to correlate all of the data from each finger, to more accurately represent the actual bending of the fingers.

Also, producing double sided sensors might also be useful. When flexing these sensors, one side would be in compression while the other would be in tension. This data could then be appropriately correlated to determine the flex angle of the sensor.

It would be necessary to mount the sensors on the outside of the glove to reduce the effect of changes in temperature. In addition it is only possible to attach one side of the sensor to the glove. This is because the sensors are not elastic and will not stretch, as the glove will, when the fingers are bent.

If the connection between the sensors and the circuit was made so that it was not permanent, then it would be possible to use one hardware unit for many different gloves. This would be beneficial in a clinical setting as gloves for different hand sizes and patients could all be used with a single hardware unit.

CONCLUSIONS

It was found that an inexpensive sensor can be made, using a carbon-based electrically conductive ink, which produces significant changes in resistance when flexed. In testing the sensors, it was found that the response time, in going from a flex angle of 0° to 90°, was extremely good. However, when unflexed, it was several minutes before the original resistance was again obtained even though the initial response was acceptable. It was also found that the sensors are extremely temperature sensitive.

The sensors exhibited a good dynamic response with an error of less than 5% when flexed repeatedly to an angle of 90°. In addition, a second-order polynomial could be found to express the resistance as a function of angle with a correlation coefficient of 0.999 for all of the sensors tested. Despite this, it was found that it was often difficult to determine the flex angle to within 10 degrees of accuracy especially for low flex angles.

Although the precision of these sensors isn't as good as more expensive sensors that are available, it is estimated that, with the present production method, the cost of the sensors is less then $0.50 apiece. In addition, there are many ways that the sensor production method might be improved to produce more accurate sensors using the carbon-based electrically conductive ink.

In connecting the sensors to the hardware system that was developed, a correlation of the actual flex angle to the measured flex angle was produced. This was done by experimentally determining a third-order polynomial that represented the sensor and hardware system. This polynomial was added to the QuickBASIC program to calculate the measured flex angle. While this produced promising results, it would be beneficial to change the calibration circuitry so that it is linear. The polynomial would then be unaffected when the calibration potentiometers were adjusted which would reduce the error.

While additional work is still necessary, it is believed that the system presented in this paper could be incorporated into a complete device to monitor the rehabilitation of an impaired hand. Unlike other systems that are presently commercially available, this system would be extremely inexpensive and therefore, could be readily used in a clinical setting.

REFERENCES

[1] Bozeman R.J. Jr., "Instrumented Glove Measures Positions of Fingers," *NASA Tech Briefs*, Vol. 17, No. 9, Sept. 1993, p. 52.

[2] Brindley, K., Sensors and Transducers, Heinemann Professional Publishing, London, England, 1988.

[3] Edwards, S., "The Picture Stick," *Electronics Now*, Oct. 1994, pp. 35-41.

[4] Eglowstein, H., "Reach Out and Touch Your Data," *Byte*, July 1990, pp. 283-290.

[5] Gradecki, J., The Virtual Reality Construction Kit, John Wiley & Sons, Inc., New York, NY, 1994.

[6] Hannah, R.L. and Reed, S.E., Strain Gage Users' Handbook, Elsevier Science Publishers Ltd., New York, NY, 1992.

[7] Hong, J. and Tan, X., "Calibrating a VPL DataGlove for Teleoperating the Utah/MIT Hand," *Proceedings (IEEE International Conference on Robotics and Automation)*, Vol., 3, 1989, pp. 1752-1757.

[8] Lyndon B. Johnson Space Center, "Instrumented Glove Measures Position of Fingers", Technical Support Package, Houston, TX, 1993.

[9] Microchip, Microchip Databook, Microchip Technology Inc., Chandler, AZ, 1994

[10] National Semiconductor, Data Acquisition Databook, National Semiconductor Corporation, Santa Clara, CA, 1992.

[11] Ojha, A., "Application of Virtual Reality in Rehabilitation," *Conference Proceedings - IEEE Southeastcon 1994*, 1994, pp. 4-6.

[12] Parallax Inc, "Pic Application Notes", Parrallax Inc., Rocklin, CA, 1994.

[13] Popovic, R.S., Hall Effect Devices: Magnetic Sensors and Characterization of Semiconductors, A. Hilger, Philadelphia, PA, 1991.

[14] Short, K. L., Microprocessors and Programmed Logic, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1981.

[15] Sturman, D. and Zeltzer, D., "A Survey of Glove-based Input," *IEEE Computer Graphics & Applications*, Jan., 1994, pp. 30-39.

[16] Spectra Symbol, Product Literature on SoftPot (Membrane Potentiometers), Spectra Symbol, Inc, 3101 W. 2100 S., Salt Lake City, Utah 84119, 1994.

[17] Wise, S. et al, "Evaluation of a fiber optic glove for semi-automated goniometric measurements," *Journal of Rehabilitation Research and Development*, Vol. 27, 1990, pp. 411-424.

[18] Wobschall, D., Circuit Design for Electronic Instrumentation, McGraw-Hill, Inc., New York, NY, 1987.

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Finally, I would like to thank my fiancé, André Flöter, for all of his help, support and encouragement during this past year.

APPENDIX A: ASSEMBLY CODE

```
bit_k           =       50                      ;4800 for 4M, 9600 for 8M
half_bit        =       bit_k/2
s_in            =       rc.1
s_out           =       rc.0
n_dat           =       rc.7
data_in         =       rb
ch_select       =       ra
samples         =       3

                org     8
delay_cntr      ds      1
bit_cntr        ds      1
msg_cntr        ds      1
rcv_byte        ds      1
xmt_byte        ds      1
temp            ds      1
count1          ds      1
count2          ds      1

                org     0

                device  pic16c55,xt_osc,wdt_off,protect_off
                reset   begin

begin           mov     !ra,#00000000b          ;ra.2 is s_in, ra.1 is s_out
                mov     !rb,#11111111b          ;port b is data in
                mov     !rc,#00000010b

:start          call    start_bit
                call    receive
                cjne    rcv_byte,#72h,:start    ;send data if "r"
:again          call    new_input
                mov     xmt_byte,data_in        ;get contents of port b
                call    send
                cjbe    msg_cntr,#samples,:again
                call    long_pause
                mov     xmt_byte,249#           ;send quit signal
                call    send
                goto    begin:start             ;wait to send next data


start_bit       mov     msg_cntr,#0
                sb      s_in                    ;wait for serial input
                jmp     start_bit
                call    start_delay
                jnb     s_in,start_bit          ;jump back if bit not good
                ret
```

```
receive         mov         bit_cntr,#8              ;8 data bits to be recieved
                clr         rcv_byte                 ;get ready for new data
:receive call   bit_delay                            ;wait one bit time
                movb        c,/s_in                  ;put data into carry
                rr          rcv_byte                 ;put bit into rcv_byte
                djnz        bit_cntr,:receive        ;dec count, get next bit
                call        bit_delay
                ret

new_input       mov         temp,msg_cntr
                and         temp,#3
                mov         ch_select,temp
                call        bit_delay
                setb        n_dat
                call        bit_delay
                clrb        n_dat
                call        bit_delay
                ret

send            mov         bit_cntr,#8              ;8 data bits to be sent
                setb        s_out    ;start bit
                call        bit_delay
:xmit           rr          xmt_byte                 ;move bit into carry
                movb        s_out,/c                 ;send carry to computer
                call        bit_delay
                djnz        bit_cntr,:xmit           ;dec and transmit next bit
                clrb        s_out    ;stop bit
                call        bit_delay
                inc         msg_cntr
                ret


bit_delay       mov         delay_cntr,#bit_k
:loop           nop
                djnz        delay_cntr,:loop
                ret

start_delay     mov         delay_cntr,#half_bit
:loop           nop
                djnz        delay_cntr,:loop
                ret

long_pause      mov         delay_cntr,#250
:loop           nop
                djnz        delay_cntr,:loop
                ret
```

APPENDIX B: QUICKBASIC PROGRAM

```
DECLARE SUB keybrd (inky AS STRING, q)
DECLARE SUB serial (quit, x, dat())
DECLARE SUB pause (graph)
DECLARE SUB time (graph, startTime)
DECLARE SUB prntdat (graph, x, dat())
DECLARE SUB nwscrn (x, y, dat())
DECLARE SUB calc (x, dat(), datP, angle, baddat)
DECLARE SUB intro (q)
DECLARE SUB scrn ()

DIM times(1000)
DIM dat(700, 16) AS SINGLE
COMMON fs1$, fs2$
LET fs1$ = "########"
LET fs2$ = "###.###"

CLS
q = 0
graph = 0


OPEN "com2:4800,n,8,1,bin,cd0,cs0,ds0,op0" FOR RANDOM AS #1

'**************************************************
7    x = 0
     CALL intro(q)
     IF q = 1 THEN GOTO 70
9    PRINT "please select a number or press q to quit:  ";
     CALL keybrd(inky$, q)
     IF q = 2 THEN GOTO 7
     IF q = 3 THEN GOTO 9
     PRINT inky$
     mode$ = inky$
     IF (mode$ = "2" OR mode$ = "4") THEN
          graph = 1
     END IF

     PRINT
     INPUT "Please enter a data file name:  ", datfile$
     OPEN "o", #2, datfile$
     PRINT #2, "  time     "; "sample   "; "data     "; "calib    "; "aver"


     IF (mode$ = "1" OR mode$ = "2") THEN GOTO 40
'***********************************************
10   PRINT "do you want to calibrate(c) or enter max and min values (m)?"
     CALL keybrd(inky$, q)
     IF q = 2 THEN GOTO 7
```

```
    IF inky$ = "m" THEN
        INPUT "minimum value"; dat(1, 3)
        INPUT "maximum value"; dat(2, 3)
        GOTO 30
    END IF
    IF inky$ <> "c" THEN GOTO 10

11  PRINT "straighten sensor and press s"
    CALL keybrd(inky$, q)
    IF q = 2 THEN GOTO 7
    IF inky$ <> "s" THEN GOTO 11     'something other than s was typed

    x = 1
    CALL serial(quit, x, dat())
    PRINT USING fs1$; dat(x, 3)


20  PRINT
    PRINT "flex sensor and press f"
    CALL keybrd(inky$, q)
    IF q = 2 THEN GOTO 7
    IF inky$ <> "f" THEN GOTO 20     'something other than f was typed


    x = 2
    CALL serial(quit, x, dat())
    PRINT USING fs1$; dat(x, 3)


30  PRINT
    PRINT "continue (c) or recalibrate (r)?"
    CALL keybrd(inky$, q)
    IF q = 2 THEN GOTO 7
    IF inky$ = "r" THEN GOTO 10
    IF inky$ <> "c" THEN GOTO 30

35   PRINT "type d when you are ready to collect data"
    CALL keybrd(inky$, q)


    IF inky$ <> "d" THEN GOTO 35     'something other than d was typed
    PRINT #2,
'****************************************************

40  x = 2
    IF graph = 1 THEN CALL scrn

    startTime = TIMER
50   x = x + 1
```

```
    CALL time(graph, startTime)
    CALL serial(quit, x, dat())

    IF quit = 1 THEN GOTO 70
    PRINT #2, USING fs1$; x; dat(x, 3);

    IF (graph = 0 AND mode$ = "1") THEN PRINT USING fs1$; dat(x, 3);
    IF (graph = 1 AND mode$ = "2") THEN PSET ((x - 25), dat(x, 3)), 14

    IF (mode$ = "3" OR mode$ = "4") THEN
        CALL calc(x, dat(), datP, angle, baddat)
        IF baddat = 1 THEN GOTO 50
        PRINT #2, USING fs1$; dat(x, 3); datP; angle
        IF x < 26 THEN GOTO 60
        IF graph = 0 THEN PRINT USING fs1$; datP;

        IF graph = 1 THEN PSET ((x - 26), datP), 14
    END IF

    IF x = 659 THEN CALL nwscrn(x, y, dat())

60  CALL pause(graph)

    GOTO 50

70  CLOSE #1
    CLOSE #2

    END



SUB calc (x, dat(), datP, angle, baddat)
    baddat = 0
    datP = 0
    y = 3
    den = dat(1, y) - dat(2, y)
    IF den = 0 THEN EXIT SUB

    dat(x, y) = 100 * (dat(x, y) - dat(2, y)) / den

    IF x = 3 THEN EXIT SUB

    IF (dat(x, y) - dat(x - 1, y)) > 50 THEN
        x = x - 1
        baddat = 1
        EXIT SUB
    END IF

    IF x < 26 THEN EXIT SUB
    FOR z = 0 TO 10
```

```
        datP = datP + dat((x - z), y)
    NEXT z
    datP = 250 - 2 * datP / 10

    IF datP < 0 THEN datP = 0
    angle = -18.38 + .59 * datP + .0014 * datP ^ 2 - .00000744# * datP ^ 3



END SUB

SUB intro (q)
    IF q = 2 THEN GOTO 5
    IF q = 3 THEN GOTO 8
    PRINT "This program receives data from the flex sensor."
    PRINT
    PRINT "NOTE:  The unit should be turned 'on' before starting this program.  If"
    PRINT "the unit is 'off', then quit the program, turn the unit 'on' and restart"
    PRINT "the program.  continue?"

4    DO
        inky$ = INKEY$
    LOOP WHILE inky$ = ""
    IF inky$ = "n" THEN
        q = 1
        EXIT SUB
    END IF
    IF (inky$ <> "y") THEN
        PRINT "please answer yes or no."
        GOTO 4
    END IF
5   CLS
    PRINT "There are four ways in which this program can display the data"
    PRINT "from the flex sensor."
    PRINT
    PRINT "In the actual data modes, data directly from the microcontroller is displayed."
    PRINT "In the processed data mode, the data is adjusted using the maximum and minimum "
    PRINT "values."
    PRINT
    PRINT "The four modes are:"
    PRINT "    1.  Actual data in numerical form."
    PRINT "    2.  Actual data in graphical form."
    PRINT "    3.  Processed data in numerical form."
    PRINT "    4.  Processed data in graphical form."
8   PRINT

END SUB

SUB keybrd (inky$, q)
        q = 0
        DO
```

```
            inky$ = INKEY$
        LOOP WHILE inky$ = ""
        IF inky$ = "q" THEN
            INPUT "(1) exit, (2) restart or (3) cancel"; q
        END IF

        IF q = 3 THEN PRINT
        IF q = 2 THEN CLS

        IF q = 1 THEN
            CLOSE #1
            CLOSE #2
            END
        END IF


END SUB



SUB nwscrn (x, y, dat())
    y = 3
    PRINT #2, "new screen"
    FOR newdat = 0 TO 20
        dat(25 - newdat, y) = dat(659 - newdat, y)
    NEXT newdat

    CLS
    FOR l = 30 TO 330 STEP 30
        LINE (1, l)-(639, l), 4
    NEXT l

    x = 25


END SUB

SUB pause (graph)
    IF graph = 0 THEN z = 5000
    IF graph = 1 THEN z = 1
    FOR count = 1 TO z
    NEXT count
END SUB

SUB scrn
    SCREEN 9
    WINDOW (0, 0)-(639, 349)
    COLOR 7, 0
    FOR l = 30 TO 330 STEP 30
```

```
        LINE (1, l)-(639, l), 4
    NEXT l

    'LOCATE 25, 75

    'PRINT "time"

END SUB

SUB serial (quit, x, dat())
'
    y = 0
    count = 0
    PRINT #1, "r"

80  IF NOT EOF(1) THEN GOSUB 205
        IF INKEY$ = "q" THEN
            quit = 1
            EXIT SUB
        ELSEIF count > 200 THEN
            EXIT SUB
        ELSE
            count = count + 1
        END IF
    GOTO 80

205 data$ = INPUT$(LOC(1), #1)
    dat(x, y) = ASC(data$)
    IF dat(x, y) = 249 THEN EXIT SUB
    y = y + 1
    RETURN
END SUB



SUB time (graph, startTime)
    SHARED fs2$
    endTime = TIMER
    times = endTime - startTime
    IF graph = 0 THEN
        PRINT
        PRINT USING fs2$; times;
    END IF
    PRINT #2, USING fs2$; times;

END SUB
```