EE389 Electronic Design Lab Report, EE Department, IIT Bombay, November, 2005

Temperature Sensing in an Artificial Limb

Group # D11

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Abstract

The project demonstrates the development of a temperature sensing circuit installed in the artificial hand of a bilateral amputee. The feedback of temperature sensed is given through vibrations to the skin by means of a vibrating motor. The report discusses the circuit used for the design, the components used in realizing it and the software aspects involved. Various patterns of vibrations suitable for conveying temperature information are devised and the response of human sensitivity to these patterns is discussed. The report also mentions the final specifications of the product designed and its limitations.

1. Introduction

Bilateral amputees often find it difficult to adjust to the surroundings. An artificial limb attached to their body does help them to manage with some basic operations but it is no good a substitute to a human hand. Our hand has a capability to sense, with or without touch, the temperature of the object we are touching or that of the surroundings. A problem often faced by bilateral amputees is the inability to sense the temperature (hotness or coldness) of the object they are touching. A simple example may be that of amputee who is holding a cup of coffee in his artificial hand but cannot sense how hot the coffee really is. The endeavor here is to develop a temperature-sensing device, which could be fitted in the artificial hand developed by IIT Bombay and CMC Vellore (Fig.1). The feedback mechanism designed should be effective, unambiguous, and adaptive to surrounding changes and must be able to attract the attention of the bilateral amputee, without him putting any conscious efforts. The project envisions designing such a device preferably at low cost and thus aid the amputee to lead a life one step closer to that of a normal person.

2. Problem Statement

The aim of the project is to design a circuit for sensing the temperature of the object held in the artificial hand of the bilateral amputee and provides feedback through vibrations. PT100 based temperature sensor would be fitted at the tip of the finger of the artificial hand of the bilateral amputee. The information about the temperature sensed is provided through vibrations of a miniature vibrating motor. Various patterns of vibrations created by frequency modulation and varying the average current drawn by the motor are demonstrated to come up with the most effective feedback scheme.

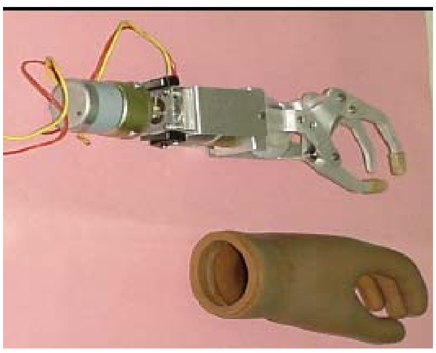

Fig 1: A Picture of the Dual Motor Prosthetic Hand and Glove,
developed at *IIT Bombay* and *CMC Vellore [1]*

3. Design Approach

The feedback about the temperature sensed could be given in a numerous ways, which may include sound, light or touch. A small speaker producing sound at frequencies proportional to the temperature can also be thought of as a feedback mechanism. The idea behind the project has always been to help the bilateral amputee in coping with the surroundings and to provide a feedback by means of sound may attract attention of people in the vicinity of the amputee, which could sometimes be embarrassing to the later. The second option could have been a digital display in the form of an array of LEDs or a small LCD screen attached to the artificial forearm. This display would not attract attention of the people in the vicinity but it would demand the attention of the amputee towards the screen in order to read the temperature. It is clear that providing the amputee with the exact temperature of the object he/she is touching is inconsequential. The amputee only requires knowing the approximate hotness and coldness of the object. Taking these specifications in mind, feedback through vibrations seems to be the most effective way of conveying information to the amputee. Vibration feedback is noiseless and does not attract the attention of the person in the vicinity of the amputee. Secondly, the amputee does not have to engage his/her attention to the vibrating device fitted on his body, as the change in the vibrating pattern may itself divert the amputees attention and guide him in judging the temperature of the object being touched.

Having realized the necessity of using a vibration feedback, the sensor designed at a block diagram level as shown in Fig. 2.

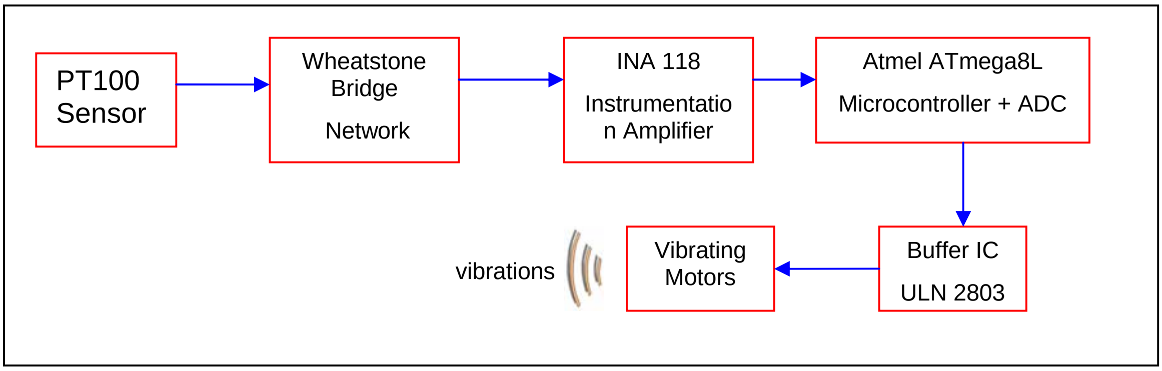

Fig 2: Block diagram for the temperature sensor

The project uses a Wheatstone bridge network to sense the temperature in terms of voltage using a PT100 temperature sensor, which has a linear variation of the resistance as temperature changes. The voltage sensed is then amplified using an instrumentation amplifier INA118, which makes it suitable for an analog to digital voltage change. The ATmega8L microcontroller senses the voltage developed at the output of the instrumentation amplifier and generates a pattern for vibration of the motor.

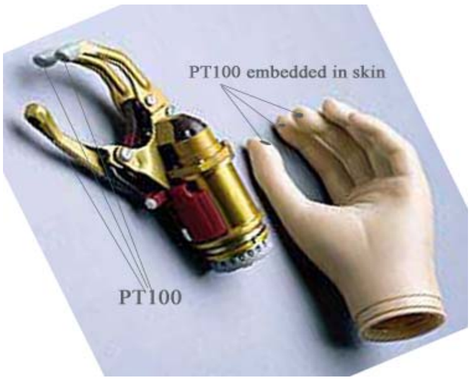

Fig 3: Artificial hand showing PT100 position

Human skin and sensitivity to vibrations

Eyes and ears are the most active senses. Skin is also an excellent sensory organ, because it can be stimulated to provide sensation in a number of ways, for example with electricity, temperature or mechanical signals. Among the various signals to which the skin is sensitive, vibrations appear to be the most effective way to offer information to this *untapped sense*. The skin is particularly receptive to vibrations between 100 Hz and 300 Hz, and has difficulty detecting frequencies below 50 Hz and above 600 Hz. The skin can also easily localize the source of these frequencies. For example, when a midge has landed, you know exactly where it is. Given this, it is possible to offer information locally via the skin. This prompts us to use the vibrations as the feedback to the amputee.

Study done on human sensing to vibrational feedbacks

a. During a research [10], tests have been performed on a hand based tactile device for response to different types of signals. Interestingly, when the signal was varied by amplitude and frequency, the quality of perception of the instructions increased. So, intensity could be the measure of the frequency of the vibrations, such that increase in frequency of vibration leads to a greater intensity in sensing it. The amplitude of vibration has no effect to play in determining the intensity of sensation and it is only dependent on the inertia of the vibrating system.

b. In some experiments [18], the ability of subjects to identify patterns of vibrotactile stimulation was tested using tactile displays mounted on the *arm and torso*. The performance was also compared at both sites. The results indicated that identification of the vibrotactile patterns was superior on the torso as compared to the forearm, with subjects achieving 99-100% accuracy with seven of the eight patterns presented.

c. A study [19] has been conducted on the sensitivity of human beings to detect changes to tactile patterns presented sequentially on the body surface. The results of the experiment reported reveals that people are unable to reliably detect when even a simple tactile pattern (consisting of only 1-3 vibrotactile elements over the body surface) changes, provided that the interval between successive pattern presentations is at least 800ms long. This illustrates that there is a finite amount of inertia associated with sensing of any pattern and the perception of the next pattern is not identified if it does not last for 800 ms.

Some of the applications using the vibration as feedback are:

a. e-pill Vibrating Watch - The watch is used as a medication reminder [10].

b. Tactile Situational Awareness System (TSAS) - The objective of the TSAS is to inform pilots of their orientation in three-dimensional space, called situational awareness [10].

4. Circuit Design

Following are the fundamental block used in designing the circuit:

4.1 *Temperature Sensing Circuit*

A Wheatstone bridge network is incorporated to sense the temperature using a PT100 sensor, which has a linearly varying resistance with the changes in temperature. There are two possible ways in which we can connect the PT100 in a bridge configuration as discussed below.

A Wheatstone bridge is the most common approach for measuring an RTD, as shown in wire circuit 1 in Fig. 4. As R_T increases or decreases with temperature, Vout also increases or decreases. Use an op-amp to observe Vout. Lead wire resistance, L1 and L2 directly adds to the RTD leg of the bridge.

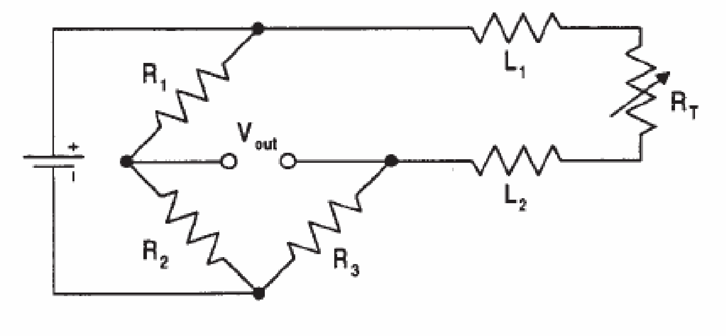

Fig 4: Wire Circuit 1 for Wheatstone bridge.

In Wire Circuit 2, L1 and L3 carry the bridge current. When the bridge is in balance, no current flows through L2 so no L2 lead resistance is observed. The bridge becomes unbalanced as R_T changes. The effects of L1 and L3 cancel when L1 = L3 since they are in separate arms of the bridge.

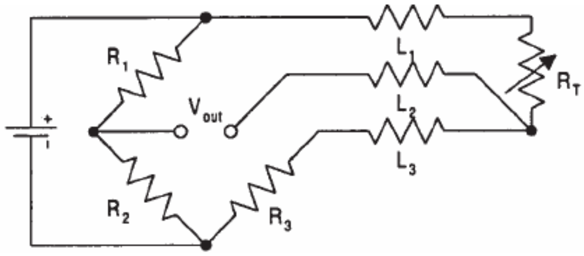

Fig 5: Wire Circuit 2 for Wheatstone bridge.

Design Justification

a. As shown above in Fig 4 and Fig 5, there are two Wheatstone bridge diagrams, but the former is used in the project. This is because accuracy and precision are not the sole requirement in our project. A few degree temperature variations are left unnoticed by human sensitivity and hence it is unnecessary to employ the latter, more precise method of observing resistive change.
b. $R_1 = R_2 = R_3 = 100\ \Omega$. At 0 °C, the ideal output of the Wheatstone network is 0 V. It is observed that by the increase in temperature leading to increase in the resistance of PT100 temperature sensor, the output voltage varies linearly with temperature. This happens primarily because resistances of 100 Ω at 0 ^{o}C balance the entire network. The output voltage reaches just about 400 mV at temperatures closer to 100 °C. High power consumption is the price to pay for using resistors of small values. So experiments were also performed using $R_2 = R_3 = 1000\ \Omega$. But it was observed that the output voltage bore a non-linear relationship with the temperature being sensed. So a compromise on power was decided to give preference to linearity in output voltage.

4.2 *INA118 - Instrumentation Amplifier*

The temperature sensed in the previous block using the Wheatstone bridge network provides a voltage output, which is very less in magnitude since it is of the order of few hundred millivolts. This double-ended output should be amplified before it can serve as an effective input to the ADC of the microcontroller. INA118 is a general-purpose instrumentation amplifier used in the design (Fig. 6).

The INA118 is a low power instrumentation amplifier offering excellent accuracy. A single external resistor sets any gain from 1 to 10,000. It operates with power supplies as low as ±1.35 V, and quiescent current is only 350 mA ideal for battery operated systems.

The output is referred to the output reference (Ref) terminal, which is normally grounded.

Gain of the Instrumentation Amplifier

Connecting a single external resistor, R_G, between pins 1 and 8, sets gain of the INA118, given by the formula:

$$G = 1 + \frac{(50\,\mathrm{k}\Omega)}{R_G}$$

Calculation of Gain and R_G

We need to keep the voltage output of the INA chip ≤ 5 V.

Maximum voltage output from the Wheatstone bridge Circuit = 410 mV

Therefore gain ≈ 12.5

Using the above formula, we get R_G = 4.4 KΩ

Design Justification

a. The voltage output from the INA118 is in the range of 0V to 4V, thus making it compatible to interface it with the microcontroller.

b. The INA118 is used in single supply mode at 5V. The limitation of the single supply voltage is that output voltage saturates at the values lower than the supply voltage. For 5V supply the maximum output saturates at 4.2V irrespective of gain.

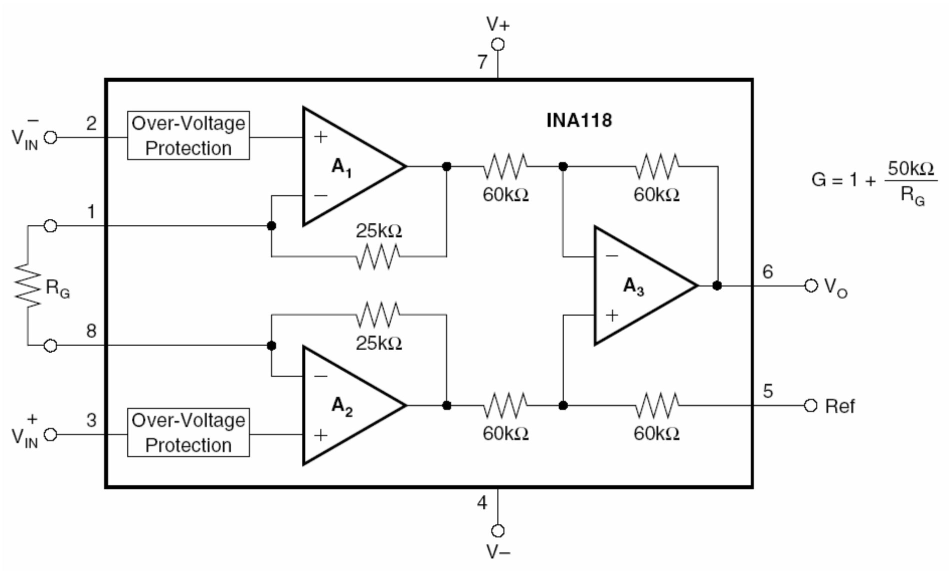

Fig 6: Circuit Diagram of INA 118

4.3 *Atmel ATmega8L – AVR Microcontroller*

The Atmel AVR controller ATmega8 is used in this stage. The output of the INA118 is fed as the input to one of the input channels of the built in ADC in the device. The controller generates vibration patterns of different frequencies and amplitude depending on the output of the instrumentation amplifier, which would be discussed in the following section.

Listed below are some features of the Atmel ATmega8L AVR controller.

a. Number of I/O Pins – 28
b. Operating Voltages – 2.7 – 5.5V
c. 6-channel ADC
d. Speed Grades – 0 - 8 MHz
e. Fully Static Operation
f. Up to 16 MIPS Throughput at 16 MHz
g. Programmable Watchdog Timer with Separate On-chip Oscillator
h. Three PWM Channels

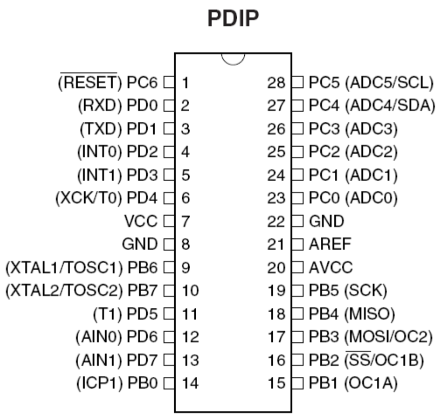

Fig.7: Pin-Diagram of ATmega8L

Estimate of Sensitivity

The in built ADC of the microcontroller is of 10-bit resolution. However, only the first 8 most significant bits are used in the design and the subsequent calculations, since the significant 8 bits ensure sufficient accuracy in the design. An 8-bit output limits the number of distinct levels of voltages sensed to be 255 between V_{REF-} to V_{REF+}, which are fixed at 0 V and 5 V respectively. The minimum difference in output voltage of instrumentation amplifier that is required to bring the change in the binary output of the microcontroller by 01H is termed as the sensitivity of the device.

Therefore, Sensitivity is $(S_V) = \dfrac{V_{REF+} - V_{REF-}}{256}$

We have suitably chosen $V_{REF+} = 5\,V$

$$V_{REF-} = 0\,V$$

$$S_V = \frac{5}{256} = 20\,mV$$

Hence a differential increase of 20 mV of the output of instrumentation amplifier would result in the change in the output of the micro-controller.

We define the sensitivity of the Wheatstone network (S_{WN}) as given below.

$$S_{WN} = \frac{S_V}{\text{Gain of the Instrumentation Amplifier}} = \frac{20\,\text{mV}}{12.5}$$

$$S_{WN} = 1.6\,\text{mV}$$

Therefore, 1.6 mV change in the output of the Wheatstone network will result in a change in the binary output pf the microcontroller

As previously discussed, it is reasonable to assume that the voltage output of the Wheatstone network is proportional to the temperature sensed in. ^{o}C Knowing the voltage output of the Wheatstone bridge to be 0 V and 400 mV at 0 ^{o}C and 80 ^{o}C respectively, we can calculate the change in output voltage of Wheatstone bridge per degree change in temperature C_D.

$$C_D = \frac{(400\,\mathrm{mV} - 0\,\mathrm{mV})}{(80^\circ\mathrm{C} - 0^\circ\mathrm{C})} = 5\ \mathrm{mV}/{}^\circ\mathrm{C}$$

Therefore, the theoretical sensitivity of the device with respect to temperature (S_T) is defined as minimum change in the temperature sensed that is required to bring the change in the binary output of the microcontroller. Alternatively it may be defined as the temperature change required bringing about a change in the voltage output of the Wheatstone bridge equal to its sensitivity (S_{WN}).

$$.\ S_{WN} = \frac{S_{WN}}{\mathrm{C_D}} = \frac{1.6\,\mathrm{mV}}{5\,\mathrm{mV}/{}^O C}$$

$$S_{WN} = 0.32^O C$$

Therefore, an increase in 0.3 ^{o}C would result in a change in output of the ADC register in the microcontroller. But this change when sensed through the vibration of motor may be beyond the scope of perception of human skin. This is illustrated later in micro-controller design section.

4.4 *ULN 2803*

The output generated from the microcontroller does not have the ability to drive a motor. A two-stage buffer is needed to drive the 25 ohm vibration motor. The first buffer is a single supply operational amplifier used in a voltage follower mode. The second current buffer is an IC, ULN2803, consisting of 8 standard Darlington arrays.

They provide for a high sinking current of 500 mA for driving devices that may need this current capability and will withstand at least 50 V in the off state. Table 1 shows the specification of ULN 2803 and Fig. 8 provide the pin diagram of the same.

Table 1: Specifications of ULN 2803

Parameter	Value
Output Voltage, VCE	50 V
Input Voltage, VIN	30 V
Continuous Output Current, IC	500 mA
Continuous Input Current, IIN	25 mA
Power Dissipation, PD (one Darlington pair)	1.0 W

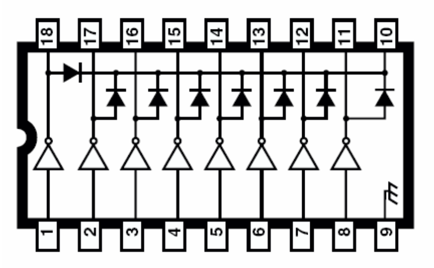

Fig 8: Diagram of ULN 2803

4.5 *Vibrating Motor*

Feedback of temperature variations can be given by a variety of tactile devices. Buzzers used in electric door bells, relays, linear solenoids, and vibration motors were the likely contenders. Door bell buzzers provide good vibrations but consume high power and are bulky. Relays fail to provide any sensation perceivable to human skin. Solenoids are used as tactile sensors for feedback in projects elsewhere. They are linear solenoids having a shaft which oscillates to and fro in a magnetic core on application of alternating voltage. Linear solenoids of dimension of the size of an inch which can be easily fitted on the human torso are not available commercially in India. Secondly, the frequency response of solenoids is sluggish in ranges of 100 Hz to 600 Hz [20].

Vibration motors are small, cheap and provide a decent response to current variations through them. Hence, they have been used to provide feedback to the amputee by adequate vibrations.

4.5.1 *Working of the motor*

The base unit contains a magnetic shaft surrounded by conductive wire wrappings. As a current is passed through the wires, the magnetic forces between the wire and shaft cause the shaft to rotate. The vibrating motor is characterized by an off-center weight located at the end of the shaft. As the shaft rotates, the off-center weight creates a centrifugal force that is transmitted through the entire motor as a vibration.

4.5.2 *Motor used*

This is a normal DC stepper motor with an unbalanced shaft (as shown below) is distributed by Alcom Computer Systems and is used in Nokia 3210 cellular phone devices. Its input resistance is 30 Ω. These vibrations vary linearly with the voltage and maximum 4 V to 5 V can be applied to them.

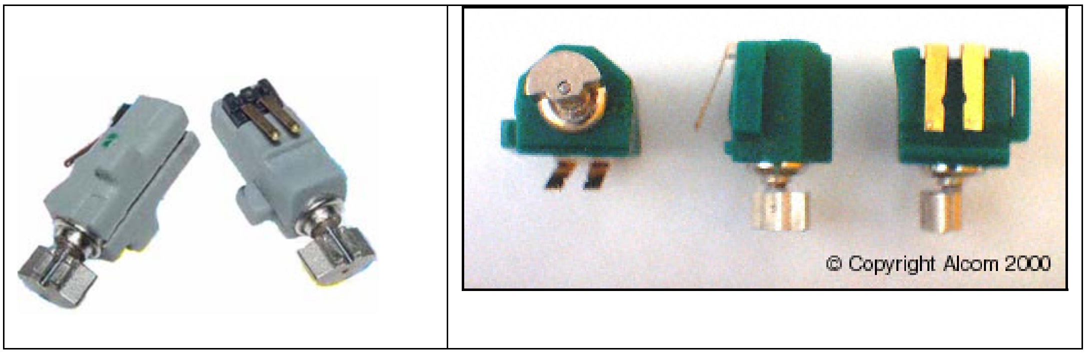

Figure 9: Vibrating Motor used in cellular phone devices
(Note: The Alcom motor has a soft rubber casing that can be easily removed)

4.5.3 *Response Time of the Motor*

If the voltage across the motor rises sharply from 0 V to 5 V, there is finite amount of delay associated with the motor, which prevents it from rotating the shaft at the required speed immediately after a step change in the voltage. This delay in time is referred to as the response time of the motor or the switch ON/OFF time of the motor. It is documented that this time is approximately 6 ms to 10 ms.

Consider the switch on and off time of the motor to be 8 ms each. This means the motor takes 8 ms each to turn on and turn off. So, if a square wave of 0 V to 5 V applied across the motor has a frequency greater than 62.5 Hz, the motor would never completely turn on or turn off. In other words, the motor will switch on and switch off completely in every cycle of the applied square wave only if its frequency is less than 62.5 Hz.

4.5.4 *Speed of the motor*

The rated speed of the motor is 7500 rpm at 5 V. Assuming a linear speed vs. applied voltage characteristics with an offset of 1 V as the switch on voltage; we can estimate the vibration of the motor at any intermediate voltage level. Note that the vibration frequency of the motor then becomes 125 Hz at rated voltage.

Advantages of vibration motor are as follows [9]:

a. The motors are extremely small in size and light in weight.

b. The vibrating motors consume much less power compared to buzzers and solenoids.

c. The motors are significantly quieter; a proper casing can make the vibrations noiseless.

Disadvantages of vibration motor include:

a. Unlike the buzzers and solenoid, these motors are not robust. The unbalanced shaft must have isolation from human interaction.

b. A simple solder connection to extension wires is difficult and imprecise

c. Motor is sluggish with the turn on voltage being 1 V.

d. A custom housing has to be designed to prevent unintentional contact with the motor.

We have referred to a project done by students at Berkeley [9]. The goal of the project is to develop a functional, as well as aesthetic, wireless tactile vest. In fact, the project focuses on the design and development of the mechanical and electrical systems of the tactile vest.

5. Experiments with the vibrating motor

Here we illustrate some of the most important finding on human sensitivity and response to vibrations offered by the vibration motor used in the design.

A simple experiment was conducted in which a 0-5 V square wave was applied across the motor with varying frequency and a constant duty cycle of 50%.

Table 2: Touch sensitivity to vibrations offered by vibrating motor

Frequency (Hz)	***Time Period (s)***	***Motor Response***	***Human Sensitivity to vibrations***
0.5	2	The motor switches ON for 1 s and switches OFF for 1 s	The motor switching ON and OFF is identifiable. It is possible to count the turning on and off of the motor precisely in every cycle
3	0.33	The motor switches ON for 0.16s and switches OFF for 0.16 s	The motor switching ON and OFF is identifiable. It is possible to count the turning on and off of the motor precisely in every cycle
5	0.2	The motor switches ON for 0.1 s and switches OFF for 0.1 s	The motor switching ON and OFF is identifiable. It is difficult to count the individual turning on and off of the motor precisely in every cycle
5-25	0.04-0.2	The motor switches ON and switched OFF completely in every cycle	The motor switching ON and OFF is identifiable. It is however impossible to count the individual turning on and off of the motor in every cycle. The change in frequency is sometimes identifiable by change in the sensation perceived
25 – 62	0.04-0.016	The motor switches ON and switched OFF completely in every cycle	The motor switching ON and OFF is not identifiable. The entire pattern seems like a single sensation and there is no change in perception observed on changing the frequency in this range
> 62		The motor does not switch ON and switch OFF completely in every cycle. It draws an average current from the supply proportional to the duty cycle	The motor switching ON and OFF is not identifiable. The entire pattern seems like a single sensation and there is no change in perception observed on changing the frequency in this range

As shown in the Table 2 above, human beings can easily count the distinct turning on and turning off of the vibration motor for frequencies of the square wave less than 5 Hz. For ranges of frequencies greater than 5 Hz and less than 25 Hz, perception of change in the applied frequency is possible, but one cannot distinctly recognize the individual turning off and turning on of the motor in every cycle. In other words, the change perceived after varying the frequency in this range cannot be quantified and hence is useless when it comes to generating patterns. At frequencies greater than 25 Hz, it is not possible to recognize individual turning off and turning on of the motor, nor is the change in frequency of the square wave perceivable. It should however be noted that till the frequency of 62.5 Hz, the motor turns on and turns off completely in every cycle of the square wave, as discussed in the sections above.

6. Software Design Approach

The motor is known to have a finite turn on and turn off time. This feature of the motor is exploited by applying a 0 - 5 V square wave at frequencies much above 62.5 Hz. This assures that the motor does not completely switch on and switch off in every cycle of the square wave and draws an average current from the supply which is directly proportional to the duty cycle of the square wave. Also the rotational speed of the shaft depends on the average current drawn by the motor. The intensity of vibration is perceived through the rotational speed of the shaft. i.e. a less intense vibration is distinguished from a more intense vibration through the difference in the rotational speed of the shaft of the motor.

The design synthesized here applies a modulating square wave of varying duty cycle and a fixed frequency of 500 Hz. This high frequency assures that the motor never completely turns on or turns off but draws an average current through the supply depending on the duty cycle. The duty cycle would be varied with temperature, thereby assuring the change in intensity of the vibrations with change in temperature. For example, a 0 - 5 V square wave and a frequency of 500 Hz with 75% duty cycle has an 'on' time of modulation to be 1.5 ms and 'off' time of modulation to be 0.5 ms. By varying the duty cycle of the 500 Hz square wave to the motor, we are varying the average supply over the range of 0 - 5 V and hence the rotational speed of the motor from 0 to 7500 rpm. So, if the square wave has a duty cycle periodically switched between two values, the motor will be switched between two rotational speeds, resulting in a pulsed frequency modulation.

It was observed that application of simple square wave to the motor was inadequate to provide a useful feedback to the amputee for the following reasons:

a. Applying a constant feedback causes insensitivity to that intensity of vibration after some time.

b. Changing the duty cycle of the square wave yields perceivable variation in vibrations in the range of 20% to 80% only. Variation of duty cycle beyond 80% does not yield any perceivable change in the vibration rate. Considering the range of temperatures to be sensed is from 0 ^{o}C to 80 ^{o}C, just providing temperature information by varying the duty cycle is inadequate.

c. The continued constant application of square wave also means that the motor always draws a heavy current from the supply, which is undesirable.

Hence it was therefore concluded that varying the duty cycle of the square wave alone would not be sufficient to provide temperature information.

As mentioned above, human skin can easily perceive the rate of vibration if the frequency is less than 5 Hz. The idea here is to switch off the motor completely for some time so that the intensity of vibration is perceived more accurately. Hence, on-off vibration patterns are used. During the 'on' time of the pattern, the motor is run on a square wave of frequency 500 Hz and a duty cycle, which depends on the temperature. Further this 'on' time itself depends on the temperature sensed. The 'off' time of the pattern is defined as the time when zero voltage is applied to the motor or the motor is completely switched off and there are no vibrations. This 'off' time is also made a function of temperature.

The on and off time of the pattern are greater than 250 ms and hence, can be easily perceived. So, a typical pattern for a temperature sensed could be explained as follows. During the 'ON' time of the pattern, the motor will vibrate with intensity proportional to the temperature sensed. This 'ON' time would be in the order of 0.5 s to 2 s. It will then be followed by a pattern 'OFF' time when the motor will be completely switched off for time of the order of 0.5 s - 2 s. This pattern will then repeat itself until the temperature is changed. Note that the pattern frequency is assured to be less than 2 Hz because the on and the off time for the patterns are at least 0.5 s. This pattern frequency of less than 2 Hz can be perceived distinctly by human skin. A very large 'off' pattern time (of the order of seconds) assures that the motor is completely switched off.

For testing we devised four different schemes of patterns. The symbols used for various parameters varying with temperature are discussed below.

a. Pattern on-time: T_{pon}

b. Pattern off-time: T_{poff}

c. Pattern Time Period: T_p

d. Square Wave on-time: T_{mon}

e. Square Wave off-time: T_{moff}

f. Square Wave Time Period: T_m

g. 8 – bit ADC output in decimal: b

After the temperature is sensed, the voltage equivalent of the temperature is converted to a 8-bit binary number, whose decimal equivalent is 'b'. So, effectively 'b' controls all the other parameters mentioned above. Theoretically the value of 'b' lies in the range (0, 255], but for the output it is limited to (0, 250]

Having described these parameters, we proceed to discuss the various schemes of patterns implemented to come up with the best pattern for the final design. Hence forth, in this section, reference to temperature will be made with the decimal equivalent output 'b' for simplicity in calculation.

Scheme – 1

Tm = Tmon + Tmoff = 2 ms (constant and independent of temperature)

Tmon = 8 X b μs,

Tmoff = 8 X (250 - b) μs,

Tp = Tpon + Tpoff = 2500 ms (constant and independent of temperature)

Tpon = 2 X 4 X b ms,

= 8b ms (ranges over [0, 2000] ms)

Tpoff = 2 X 4 X (250 - b) ms + 500 ms (ranges over [500, 2500] ms)

Following observations can be made for this scheme

a. The average current drawn by the motor increases with temperature. This can be perceived by the fact that the vibrations tend to get more intense as the temperature increases.

b. Also, the time for which the pattern remains off gradually decreases as the temperature rises. So for b = 250, the vibration is highly intense and last for time of 2 s and the pattern is vibrations are 'off' for 0.5 s. When b = 128, the vibrations are lesser intense and last for the time of approximately 1 s. Also, the off time of the pattern here tends to get longer to about 1.5 s.

Scheme – 2

This pattern is the cascade arrangement of two patterns, namely pattern1 and pattern-2 each existing for time T_{p1} and T_{p2} respectively. The idea is to give vibration feedback corresponding to temperature sensed in time T_{p1} and to give feedback of the surrounding temperature in time T_{p2}. By judging the intensity difference in two patterns, the amputee can estimate the deviation of temperature from the surrounding temperature. We define T_{p1} = 2 s & T_{p2} = 1 s (constant and independent of temperature). During pattern-1, existing for time T_{p1}, a square wave of 500 Hz is applied across the motor, the duty cycle of which varies linearly with temperature.

T_{m1} = Time Period of the square wave in pattern -1

T_{m1on} = ON time of square wave in pattern -1

= 8b μs,

T_{m1off} = OFF time of the square wave in pattern -1

= 8 (250 - b) μs,

Tm1 = Tm1on + Tm1off = 2 ms (constant and independent of temperature)

As mentioned above, the controller displays pattern-2 for the time Tp2. In this time interval, the motor is driven by a square wave of frequency 500 Hz, the duty cycle of which depends on the surrounding temperature. Suppose 'c' is temperature equivalent to the surrounding temperature sensed, then 'c' varies in the range of (0, 250].

T_{m2} = Time Period of the square wave in pattern-2

T_{m2on} = ON time of square wave in Tp2

= 8 c μs,

T_{m2off} = OFF time of t square wave in Tp2

= 8(250 - c) μs,

T_{m2on} + T_{m2off} = T_{m2} = 2 ms (constant and independent of temperature)

Here, 'c' was chosen to be 128.

Following observations can be made for this scheme

a. The motor is observed to vibrate with two different intensities.

b. The intensity for which the motor vibrates for 2 s corresponds to the temperature being sensed by the sensor and the other intensity corresponds to the ambient temperature of the surroundings.

c. The endeavor here is that human skin can detect the change in the intensity of vibrations faster than judging the temperature by sensing one particular intensity. So, if one observes a high intensity pattern for 2 s followed by a change to a very low intensity pattern for 1 s, then one understands that the object being touched is at a much higher temperature than the ambient temperature. Conversely, if the intensity pattern sensed for 2 s is weaker than the one sensed for the preceding 1 s, then one realizes that the object being touched is at a lower temperature than the ambient temperature.

d. The intensity change observed between pattern-1 and pattern-2 can thereby give the measure of the difference between the temperature of the object being touched and the ambient temperature.

Scheme – 3

This pattern gives short pulses of vibrations each lasting for over 250 ms and interspersed with the time lag of 250 ms. The number of pulses generated will be proportional to the temperature sensed by the sensor and the entire range of temperatures sensed is divided into 8 parts, in order to quantize the pulses from 1 to 8 in number. The pulse is generated by applying 5 V to the motor or in other words, no duty cycle variation is generated.

We define the number of pulses 'n' as shown below:

$n = 1+\text{int}(b/32)$

$n = 1$ if b is in the range of [0, 31]

$n = 2$ if b is in the range of [32, 63]

…..

$n = 8$ if b is in the range of [225, 250]

As mentioned above each pulse would be of the duration of 250 ms followed by a complete turn off of the motor for 250 ms. This pattern would be continued ‘n’ times where ‘n’ is controlled by the temperature being sensed.

The total time taken for these n pulses is $(n\times 0.5)$ s = (n/2) s.

After the specified number of ‘n’ pulses is given to the motor, the motor is switched off for 1 s indicating the completion of the pattern. To give an example, if b = 53, corresponding to n = 2 the following sequence of events will take place in one cycle of the pattern.

a. The motor is turned on at 5 V for the time of 250 ms, and then completely switched off for next 250 ms.

b. The motor is again turned on at 5 V for 250 ms, followed by a complete switching off for 250 ms. By the end of this event, the total time elapsed in the pattern is 1 s.

c. The motor will continue to be switched off for another 1 s which indicates the pattern cycle is over. The entire cycle then repeats itself.

Following observations can be made for this scheme

a. The motor is sensed to turn on and turn off in about half a second, which can be easily perceived by the human skin. The number of such pulses depends on the temperature sensed and lies in the range of 1 to 8.

b. The drawback of this scheme is that it is incapable of changing the feedback until the change in the temperature enters another level of quantization. To give an example, if b = 48, then the pattern generates 2 pulses as discussed above. Now, any temperature deviation not strong enough to push the b out of the 32 - 63, will not result in trigger any change in the pattern.

c. The motor draws large current as it is always turned on at the voltage of 5 V.

Scheme – 4

T_m = 2 ms (constant and independent of temperature)

$T_{mon} = 8b\ \mu s$,

$T_{moff} = 8(250 - b)\ \mu s$,

$T_{pon} = T_{poff} = (n/2)$ s

where,

$n = 1 + int (b/32)$

$n = 1$ if b is in the range of [0, 31]

$n = 2$ if b is in the range of [32, 63]

…..

$n = 8$ if b is in the range of [225, 250]

$T_p = T_{pon} + T_{poff} = n$ s.

Following observations can be made for this scheme

a. The pattern typically gives low intensity vibrations at low frequency for lower temperatures. The frequency of repetition of the pattern increases with temperature which is coupled with the increase in the intensity of the vibrations given by the motor.

b. This scheme by far conveys the temperature and also the change observed quickly and effectively than any other scheme.

Out of the 4 schemes developed, scheme-4 promises to convey the temperature sensed effectively and quickly than the other schemes. Hence, this scheme is used in the final implementation of the design.

Every scheme discussed so far, gives a vibration output at every possible temperature sensed. This would mean that the person using this sensor will always feel the vibrations corresponding to the surrounding temperature, even if he does not intend to hold or touch any object in his hand. These vibrations are unnecessary for two reasons, one being that vibrating motor consumes a very large amount of power (average of 0.5 W) and secondly, human skin tends to get numb or insensitive for persistent vibrations. The ideal design would be that the motor sets itself to the reference temperature, i.e. it provides no vibrations at this temperature. There are two ways in which one can accomplish this:

a. Constant detection of surrounding temperature

To realize this idea assume that the bilateral amputee using this feedback scheme is not holding/touching anything with his artificial hand. This means that the temperature sensor embedded at his finger tips would be sensing the approximate surrounding temperature. Let us also assume that we implement Scheme-4 as discussed above in conveying temperatures through vibrations. Also assume that the current reference temperature stored in the microcontroller is in fact the surrounding temperature. Lastly, all the vibration patterns would be given proportional to the deviation of the temperature sensed from the reference temperature, i.e. a small deviation of temperature sensed from the reference temperature would give less intensity vibrations of Scheme-4 and a bigger deviation of temperature sensed from the reference temperature would give high intensity vibrations of Scheme-4. Having established this it is evident that the person using this sensor would not get any vibrations at times he is not using his hand, because the sensor constantly senses the surrounding temperature and the controller has already updated its reference temperature to this surrounding temperature. But as soon as the bilateral amputee touches a hot/cold object the temperature sensed is high/low than the reference temperature. This deviation from reference temperature is detected by the controller which in turn triggers the motor to vibrate, the vibrations of which are proportional to the deviation from the reference temperature. The controller simultaneously samples the rise/fall in surrounding temperature and raises/lowers its reference temperature accordingly. Now, after one pattern of Scheme-4 is generated and the new temperature sensed is recorded. Assuming that the new temperature sensed is the same as the previously sensed temperature, the deviation this time is lesser due to the rise in the reference temperature of the controller. This will lessen the intensity of vibration and also the frequency of the pattern displayed according to Scheme-4. Also, a repeated contact with a hot/cold object at constant temperature would raise the reference temperature of the controller close enough to the temperature of the object being touched. This will result in vibrations dying away and the motor would cease to vibrate after displaying a few patterns, with decreasing intensity.

This design seems good in constantly updating itself to the surrounding temperature. Few issues regarding the settings of reference temperature within the microcontroller are needed to be discussed. The amount by which the microcontroller changes the reference temperature after it has sensed the surrounding temperature needs to be varied. A simple illustration of this issue is given below. Suppose that the current reference temperature set be the microcontroller is 30 ^{o}C. The bilateral amputee touches a hot tea cup of 70 ^{o}C. Now the first time the controller senses the temperature, it observes a 40 ^{o}C deviation in the positive direction and sends vibrations proportional to this deviation according to Scheme-4. But now the question arises about what value should the reference temperature within the microcontroller rise to? Any guess of 5, 10, 15 ^{o}C is a matter of perception. Suppose the microcontroller raises the reference temperature by 5 ^{o}C to set it to 35 ^{o}C. The next time it senses the temperature of the hot tea cup, it observes a deviation of 35 (70 - 35) ^{o}C and sends vibrations proportional to this change by Scheme-4. This would go on for a total of 8 cycles, until the reference temperature touches 70 ^{o}C and the deviation of surrounding temperature with the reference temperature is negligible. There is still a large amount of ambiguity associated with the amount of raise/fall that needs to be given to the reference temperature, each time a surrounding temperature is sensed. The issue here also becomes highly subjective as vibrations could get repetitive and less attention seeking to one person and absolutely inadequate to the other. Hence this design is unsuitable for mass scale manufacturing of the product. This urges us to look at a rather simple but effective design given below.

b. Fixed reference temperature and varying ambient temperature

The inspiration for this design goes with the fact that the amputee should be given the correct vibration corresponding to the temperature sensed for a very short period of time followed by a complete turn off of the vibrations. This is to say in reference to the earlier design where the user received vibrations of decreasing intensity until then ceased completely, which could be rather irritating to some people.

The design implementation goes as follows. Figure 10 shows the block diagram of the design flow. Let us consider that the reference voltage of the microcontroller is hard coded to 30 ^{o}C and kept constant thereafter. When the temperature sensing circuitry is switched on, the microcontroller senses the temperature for the first time and stores this temperature as the ambient temperature in its memory. Further, it sends out vibrations (Scheme-4) to the motor proportional to the deviation of this ambient temperature from the reference temperature. Once the complete cycle of vibrations is sent, the controller senses the temperature again. It records the newly read temperature and compares with the ambient temperature. If this newly recorded temperature happens to be in the range of 3 ^{o}C of the ambient temperature, the controller ignores this recorded temperature and senses the temperature again. If the newly recorded temperature is outside the range of 3 ^{o}C from the ambient temperature, the controller updates the ambient temperature to this new value of recorded temperature. Further it sends out vibrations of Scheme-4 corresponding to deviation of this new ambient temperature from the same old fixed reference temperature. After the complete cycle of Scheme-4 vibrations is complete the controller reads the new surrounding temperature and the entire procedure is repeated endlessly. This concept can be illustrated by the same example taken above.

Suppose that a bilateral amputee, with his artificial hands free from doing any work, is present in the environment with the surrounding temperature of 35 ^{o}C. The hard coded reference temperature in the microcontroller is 30 ^{o}C. When the temperature sensor is switched on, the controller records the new surrounding temperature, sets its ambient temperature to this surrounding temperature (35 ^{o}C) and send out vibrations of Scheme-4 proportional to 5 ^{o}C (5 ^{o}C is the positive deviation of ambient temperature from the reference fixed temperature). After the set of vibrations are provided and supposing the amputee still does not engage himself

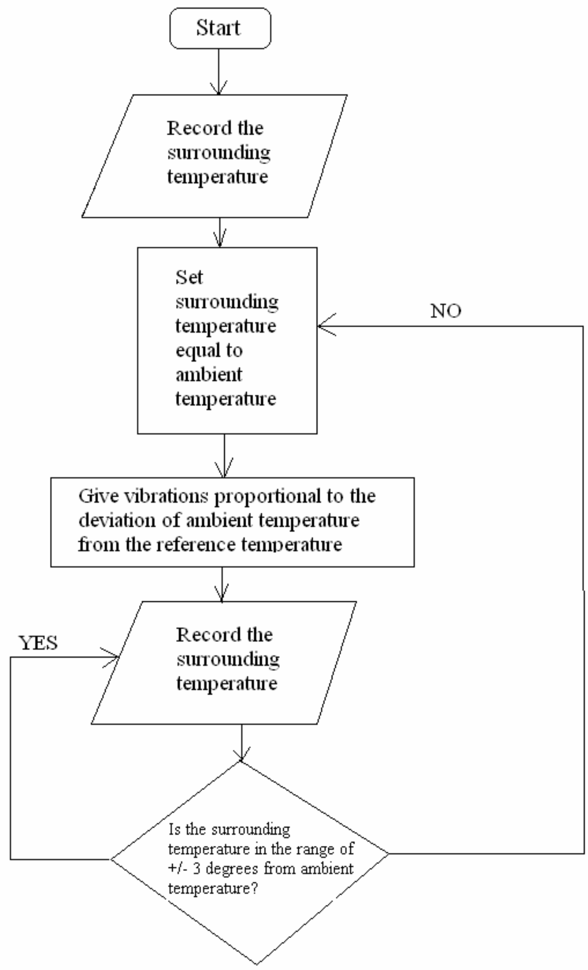

Fig. 10: Flowchart for "Fixed Reference temperature and variable ambient temperature" design

in any change in his previous activity, the further temperatures recorded would be 35 ^oC. But now, the ambient temperature within the microcontroller having set at 35 ^oC, no further vibrations are given out. The controller silently keeps recording the new temperature sensed, which happens to be approximately equal to the ambient temperature. Now when the amputee suddenly touches a hot tea cup at 70 ^oC, the new recorded temperature does not happen to lie in the range of 3 ^oC of the current ambient temperature (35 ^oC). So the controller updates its ambient temperature to this new recorded temperature of 70 ^oC. It further sends out vibrations of Scheme-4 proportional to the deviation of the new ambient temperature from the reference temperature. This deviation happens to be 40 ^oC (70 – 30). Once this cycle of sensing and displaying vibrations is complete, no further vibrations are given out by the controller, as the sensed surrounding temperature is close to 70 ^{o}C which happens to lie in the range of 3 ^{o}C from the ambient temperature (currently close to 70 ^{o}C).

It is evident that this design is simple, unambiguous and hassle free. It is relatively easy to adapt to and also draws the attention of the amputee as quickly as possible due to its sheer suddenness of response (the vibrations start as soon as any new temperature is sensed, and the motor ceases to vibrate after giving a couple of vibrations corresponding the deviation of the temperature from the fixed reference temperature). Hence, this design is used in the final implementation of the circuit. However, the reference temperature of the controller is set approximately to 32 ^{o}C.

The idea is to depict the temperature deviations in both colder and hotter directions. It is necessary that the bilateral amputee get adjusted to a single scheme (Scheme-4, in this case) of vibrations so that perceiving the change in vibrations becomes his second habit. In other words, the amputee should put in the least amount of attention or effort in knowing the change in temperature or the deviation of temperature from the fixed reference temperature. The simplest way of conveying this information is employing the same scheme on two different motors, one of which would be used for deviations below the fixed reference temperature and other for deviations above fixed reference temperature. Both of these motors would employ the same vibration scheme, namely scheme-4, but at a time at most one of them would be sending vibrations and the other would be turned off. The endeavor has always been that the amputee should get a fair idea about the temperature of the object he/she is touching as quickly and unambiguously as possible. By placing these two motors at entirely two different locations on the body, it is assured that the information of the hotness/coldness and its deviation from the fixed reference temperature is conveyed effectively and conspicuously. The torso and the forearm are one of the most sensitive parts of human body with regards to perceiving vibration sensation. So the two motors would be fitted at these two places on the body of the bilateral amputee. It should be noted that if the amplitude of the positive and the negative deviation from the fixed reference temperature is the same, then the controller would generate the same vibration patterns but on two different motors fitted at two different parts of the body.

7. Circuit Diagram

The Fig. 11 shows the circuit diagram of the final product.

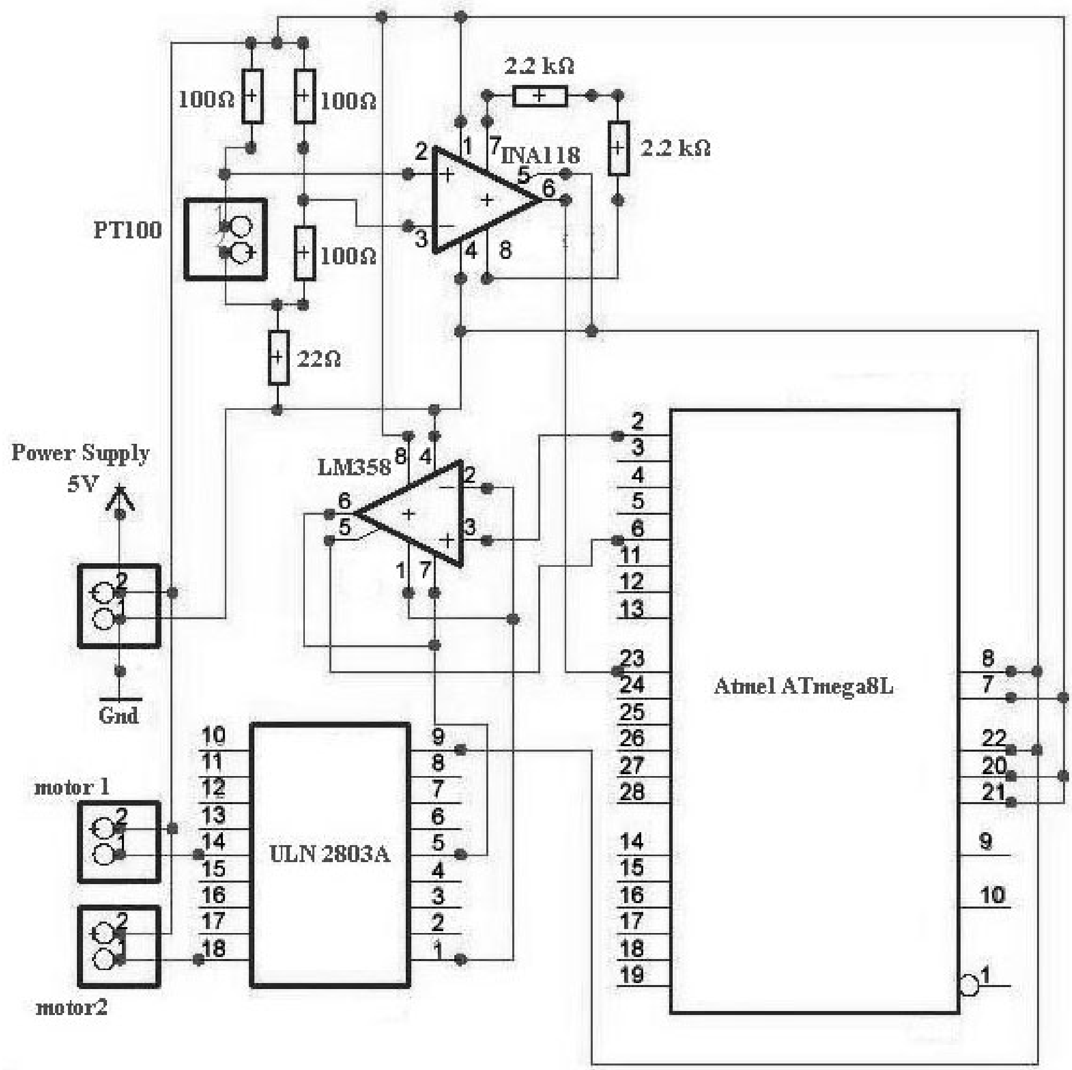

Fig. 11: Circuit Diagram of the final product

8. Product Design and Product Specifications

The final product consists of the following parts; the specifications for them are mentioned wherever necessary:

Controller Circuit

The designed product is a sub-system of a larger product, which is the artificial hand itself. Hence there are two ways of incorporating this product in the artificial hand.

a) Accommodate the PCB of the product inside the limb of the artificial arm.

b) The PCB of the product can be enclosed in a suitable casing. This casing can then be strapped around the artificial arm. This approach is adopted in this product.

The PCB is designed using surface mountable device packages of all ICs. The physical dimensions of the casing protecting the PCB are as shown in Table.

Table 3: Physical Dimensions of the casing

Dimension	Length (cm)
Length	3
Breadth	3
Height	1.5

The electrical specifications of the circuit are as shown in Table.

Table 4: Electrical Specifications of the temperature sensing circuit

Parameter	Min	Max	Unit
Supply Voltage	3.0	5.0	V
Supply Current (vibration motor switched ON)	30	200	mA
Supply Current (vibration motor switched OFF)	-	30	mA
Power (vibration motor switched ON)	90	1000	mW
Power (vibration motor switched OFF)	-	150	mW
Operating temperature	0	80	^{0}C

External Ports

Output Ports

The circuit has the following output ports

a. Vibration motor 1: This is a 2-pin output port to connect vibration motor to provide feedback at higher temperatures. This motor provides vibrations proportional to the positive deviation of the temperature sensed from the fixed reference temperature as discussed above.
b. Vibration motor 2: This is a 2-pin output port to connect to another identical vibration motor to provide feedback at lower temperatures. This motor provides vibrations proportional to the negative deviation of the temperature sensed from the fixed reference temperature as discussed above.

Input Ports

The circuit has the following input ports

a. Supply: Single supply voltage source must be connected at this port referring to the specifications in Table 4.
b. PT 100 Sensor connector Port: The PT100 sensor is externally connected this port

Vibration Motors

The two identical vibration motors discussed above are protected in a suitable casing and connected to the ‘vibration motor’ output ports. One of the motors must be mounted on the forearm of the amputee and the other must be fitted on his torso by strapping it through a suitable band.

PT 100 Sensor

The index finger is predominantly used for holding or touching objects. So, the temperature sensor must be mounted at the tip of the index finger of the right hand of the bilateral amputee, as shown in Fig. 3.

9. Results

Fig. 12 shows the interfacing on the temperature sensing circuit with the instrumentation amplifier. Instead of using the PT 100 sensor, resistors of different values ranging from 100 to 140 Ω are used. The approximate values for temperatures corresponding to every value for the PT 100 sensor are obtained from the PT 100 datasheet. Table 4 shows the outputs observed at the temperature sensing Wheatstone network as well as the INA 118 amplification stage for different values of resistances taken. Fig 13 and 14 show the approximate linear relationship between the outputs at each stage and PT 100 resistance.

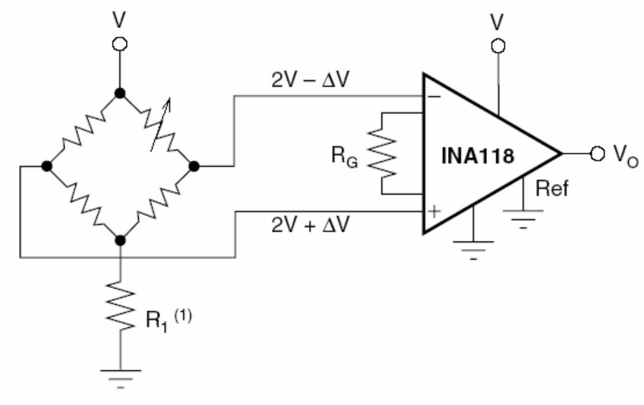

Fig 12: Interface between Wheatstone Bridge and INA 118

Table 5: Showing output voltage across the PT100 and INA as the resistance of PT100 varies due to temperature variations

Temperature(°C)	R_{PT100}(Ω)	$V_{out,PT100}$(mV)	$V_{out,INA}$(V)
0	100	0	0
10	105.5	50	0.6
20	111	100	1.2
50	122	204	2.5
64	127.5	300	3.7
80	133	324	4.0

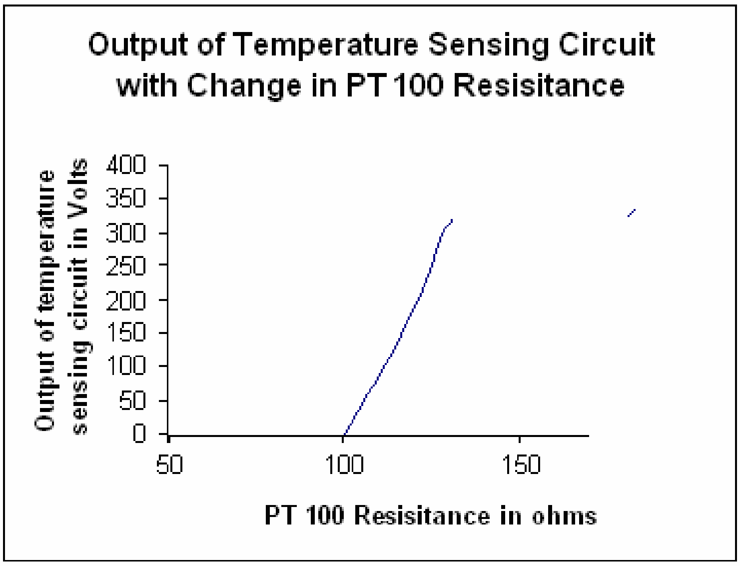

Fig 13: Graph showing output voltage against PT100 resistance

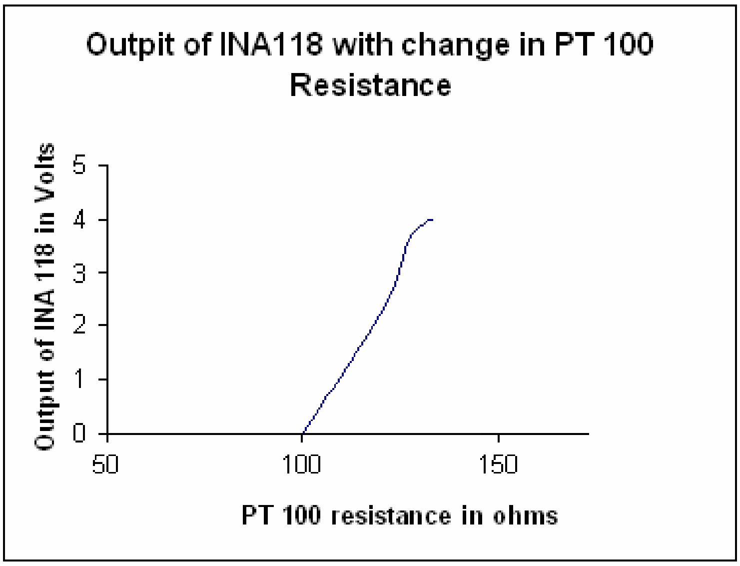

Fig 14: Graph showing output voltage at INA118 against PT100 resistance

Measurements of Human Sensitivity about Just Noticeable Difference

Perception to external vibration patterns is highly subjective and differs from person to person. A sudden change of vibrations perceived by one person is likely to go unnoticed to the other. Various types of experiments were devised in order to quantify the result obtained through subjective measurement. The three broad types of evaluation criterion are listed below:

a. **Ranking of two elements**: Here the subject in the experiment is presented with two closely spaced test samples and told to pick the better of the two samples according to his perception. From the ordered pairs generated, by carrying out this evaluation under the entire spectrum of test samples. It is possible to rank them according to the subject is perception.

b. **Scaling**: here the subject is presented with a set of test samples and told to scale his/her perception to the scale of 0-10 or 0-100 about each test sample.

c. **Sampling by Just Noticeable Difference**: Here, the subject is given a 'reference' test sample. Then a slight perturbation is made in this sample and the response of the subject is observed. For some minor perturbations, it is possible that the subject does not recognize a change in perturbation. Thus, a threshold of perturbation below which no change in perception is observed by the subject is determined. This perturbation is termed as "Just Noticeable Difference" (JND). The experimental setup consists of a vibrating motor which is driven by a 0-5 V square wave of frequency 500 Hz and a varying duty cycle. The duty cycle of the square wave is directly proportional to the DC input given to the microcontroller. The values of v_{base} range from 0.4 V to 5 V and perturbations are given for each value of v_{base} to note the response of the subject. A "hit" is considered if the subject recognizes the change, and a "miss" is considered when the perturbation goes unnoticed. The subject is stimulated with a particular v_{base} & $v_{\text{base}} + \Delta v_{\text{base}}$ five times, and the perturbation is said to be 'detectable' if 3 or more "hits" are observed in 5 stimulations. JND is the minimum Δv_{base} which passes the detection test. Table 6 shows the results of experimentation done on two subjects according to the setup discussed above and the JND values for every value of v_{base} were noted. The positive and the negative deviations are considered separately. Fig. 15 and 16 show the variation of Δv_{base} corresponding to JND with v_{base}.

Table 6: JND observed for two subjects for different values of v_{base} for positive and negative perturbations

	Subject 1		Subject 2	
V_{base} (V)	Δv_{base} (+) (JND) (V)	Δv_{base} (-) (JND) (V)	Δv_{base} (+) (JND) (V)	Δv_{base} (-) (JND) (V)
0.2	0.2	-0.2	0.4	-0.2
0.4	0.2	-0.4	0.4	-0.4
0.6	0.6	-0.4	0.4	-0.6
0.8	0.4	-0.6	0.4	-0.4
1.0	0.4	-0.4	0.6	-0.6
1.2	0.4	-0.4	0.6	-0.6
1.4	0.4	-0.6	0.6	-0.6
1.6	0.6	-0.4	0.6	-0.6
1.8	0.4	-0.4	0.6	-0.8
2.0	0.4	-0.8	0.6	-0.6
2.2	0.4	-0.4	0.4	-0.4
2.4	0.4	-0.6	0.6	-0.6
2.6	0.4	-0.4	0.4	-0.4
2.8	0.4	-0.8	0.4	-0.6
3.0	0.4	-0.4	0.6	-0.6
3.2	0.4	-0.4	0.6	-0.6
3.4	0.4	-0.6	0.8	-0.8
3.6	0.6	-0.6	0.8	-0.8
3.8	0.8	-0.6	1.0	-0.8
4.0	1.2	-0.6	1.2	-1.6
4.2	1.2	-0.6	1.4	-1.6
4.4	1.4	-0.6	1.4	-1.6

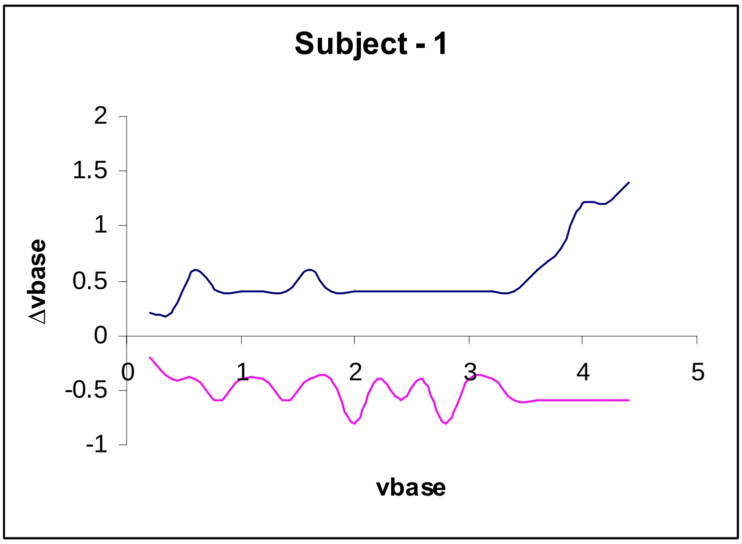

Fig 15: Graph showing the JND observed by subject 1.

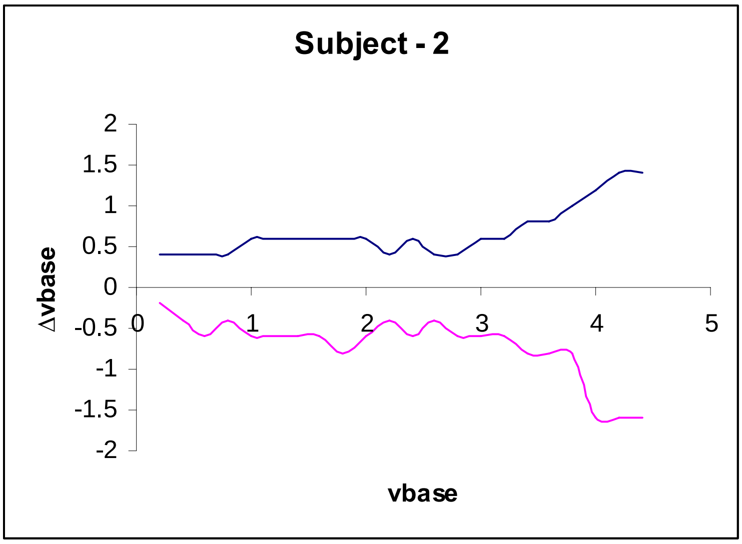

Fig 16: Graph showing the JND observed by subject 2.

Thus it has been clearly observed that test samples of low voltage inputs have comparatively low values of just noticeable perturbations. As the test base voltages increase, the minimum perturbation from the base voltage necessary to bring about a noticeable difference in perception also increases. This can primarily be reasoned out from the fact that once the human body gets accustomed to high intensity vibration, the slight perturbation on the lower side goes unnoticed and a relatively high deviation from the base intensity must be supplied to bring a change in the vibration sensation.

Measurement of Just Noticeable Difference for Scheme-4

We employ the same method used above to determine the JND for base voltages in Scheme-4. A reasonable approximation can simplify things and give us a fair estimate of temperatures being sensed. We assume that we employ design-2 discussed above, “fixed reference temperature and variable ambient temperature” in the final design. At the room temperature of 32 ^{o}C, which is set as the fixed reference temperature, the output of the difference amplifier is 1.6 V and it varies linearly with temperature change. We also know that the output of the difference amplifier is very close to 0 V at 0 ^{o}C. We can now make a reasonable estimate of output of the instrumentation amplifier at any temperature by assuming a linear relationship between the two quantities. Also, the output is known to saturate at 4 V which happens at 80 ^{o}C. Hence, an approximate relation between the temperature sensed and the output of the operational amplifier is given by:

Output of difference amplifier (V) = temperature sensed (^{o}C) / 20

From the above inputs we can calculate the JND from the point of view of temperature sensed as well as the voltages applied (Table 7).

Table 7: JND observed for two subjects for different values of v_{base} (and temperature), for positive and negative perturbations in Scheme-4

	Temperature	**Subject 1**		**Subject 2**	
v_{base}	(^oC)	Δv_{base} (+) (JND) (V)	Δv_{base} (-) (JND) (V)	Δv_{base} (+) (JND) (V)	Δv_{base} (-) (JND) (V)
0.2	4	0.4	-0.2	0.4	-0.2
0.4	8	0.2	-0.4	0.4	-0.4
0.6	12	0.2	-0.4	0.2	-0.2
0.8	16	0.2	-0.4	0.2	-0.4
1.0	20	0.4	-0.4	0.6	-0.4
1.2	24	0.2	-0.2	0.6	-0.4
1.4	28	0.4	-0.6	0.6	-0.2
1.6	32	0.4	-0.2	0.4	-0.4
1.8	36	0.4	-0.2	0.4	-0.4
2.0	40	0.4	-0.2	0.4	-0.4
2.2	44	0.2	-0.4	0.4	-0.4
2.4	48	0.4	-0.4	0.2	-0.4
2.6	52	0.4	-0.4	0.4	-0.2
2.8	56	0.4	-0.4	0.2	-0.4
3.0	60	0.4	-0.2	0.4	-0.6
3.2	64	0.4	-0.4	0.6	-0.4
3.4	68	0.4	-0.4	0.4	-0.4
3.6	72	0.2	-0.6	0.4	-0.4

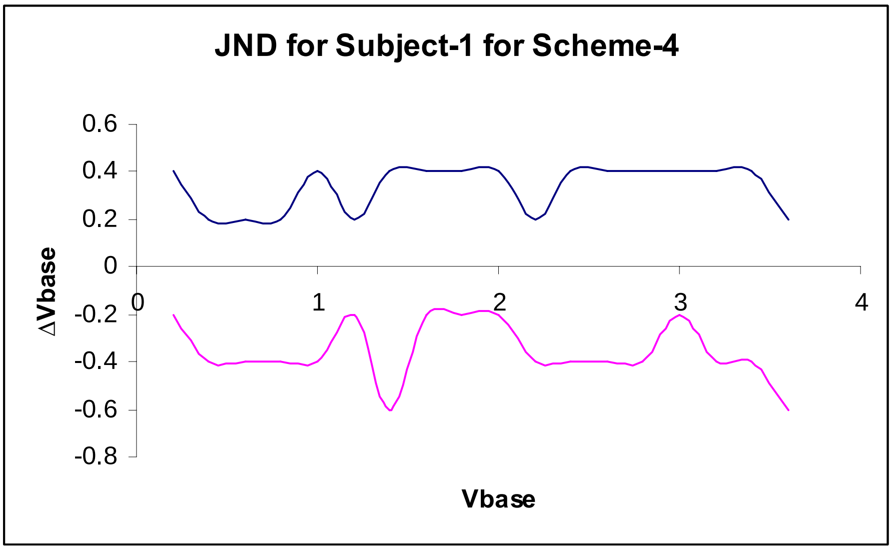

Fig. 17: Graph showing the Just Noticeable Change in Subject 1 for Scheme-4

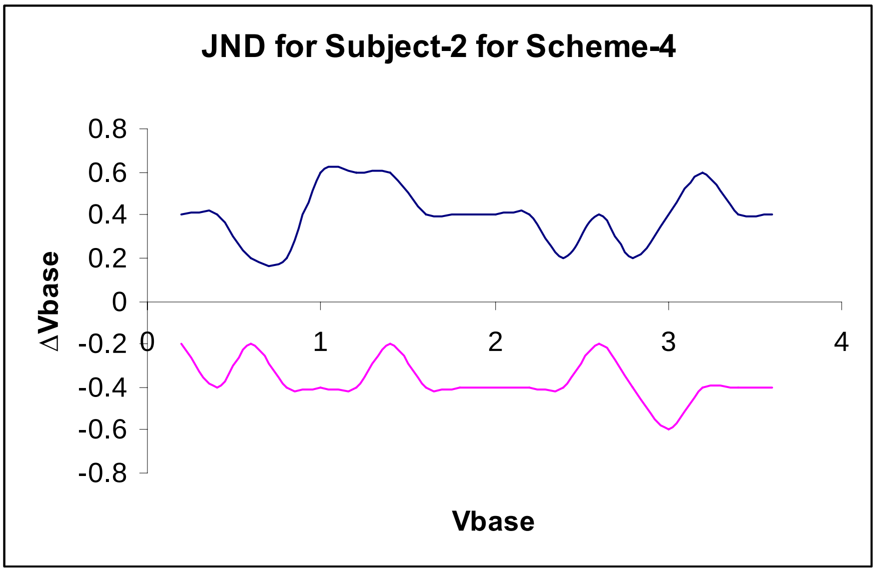

Fig. 18: Graph showing the Just Noticeable Change in Subject 2 for Scheme - 4

As observed in Fig. 17 and 18 the JND in Scheme-4, has the maximum magnitude of 0.6 V. Ordinarily, this magnitude is 0.4 V. This means that, in a worst case, a 0.6 V change in the output of the instrumentation amplifier, INA 118 would bring a change in sensation perceived. Now, a 0.6 V change corresponds to 12 ^{o}C change in the temperature sensed, as discussed above. So, it can be said alternatively that, in the worst case, a 12 ^{o}C change in the temperature sensed is required in order to bring about a change in sensations perceived. However, a 8 ^{o}C perturbation in temperature (corresponding to +/- 0.4 V) is sufficient for changes in vibrations to get detected, and hence we consider 8 ^{o}C to be the JND for the temperature sensing circuit.

Comparing the results obtained for Scheme 4 from Fig. 17 and 18, with those obtained by applying simple square wave with changing duty cycle, in Fig. 15 and 16, it is clear that Just Noticeable Difference for Schem-4 is smaller and more uniform across all values of V_{base}. Thus Scheme-4 must prove effective in conveying the temperature sensed with JND of 8 ^{o}C.

10. Conclusion

A stand alone temperature sensing circuit for the artificial hand of a bilateral amputee was developed. The feedback of the temperature sensed by PT 100 resistor was given through vibrations of vibrating motor. Various vibration patterns were devised and their utility in providing unambiguous and quick response was studied. The final product incorporated the most effective pattern scheme and it provided feedback by two independent vibrating motors, one for temperatures below reference temperature and the other for temperatures above the fixed reference temperature. The reference temperature for the microcontroller was fixed at 32 ^{o}C. The 'Just Noticeable Difference' in temperature obtained by experimentation was 8 ^{o}C. A compact, easily mountable PCB was made for the circuit from surface mountable packages of all ICs. The circuit board was covered with casing for protection.

Following are the photographs of the PCB designed and the final product developed

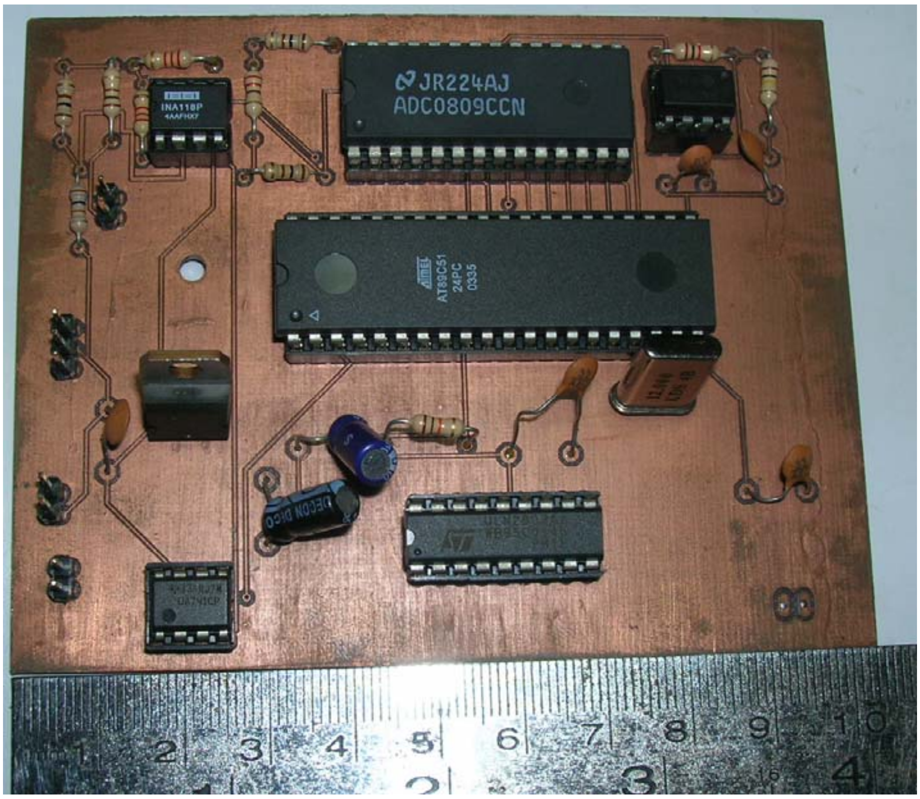

Fig. 19: PCB designed at the initial stage of the project in April 2005

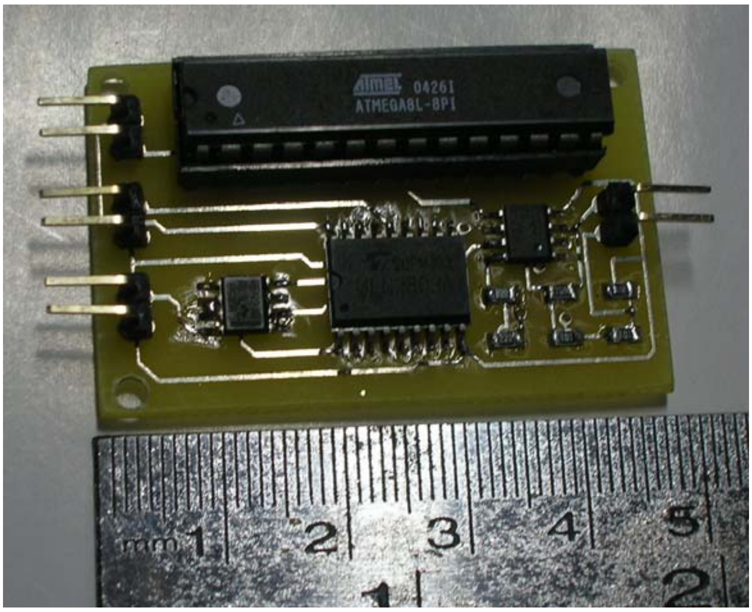

Fig. 20: PCB designed with Dual Inline package of microcontroller in November 2005

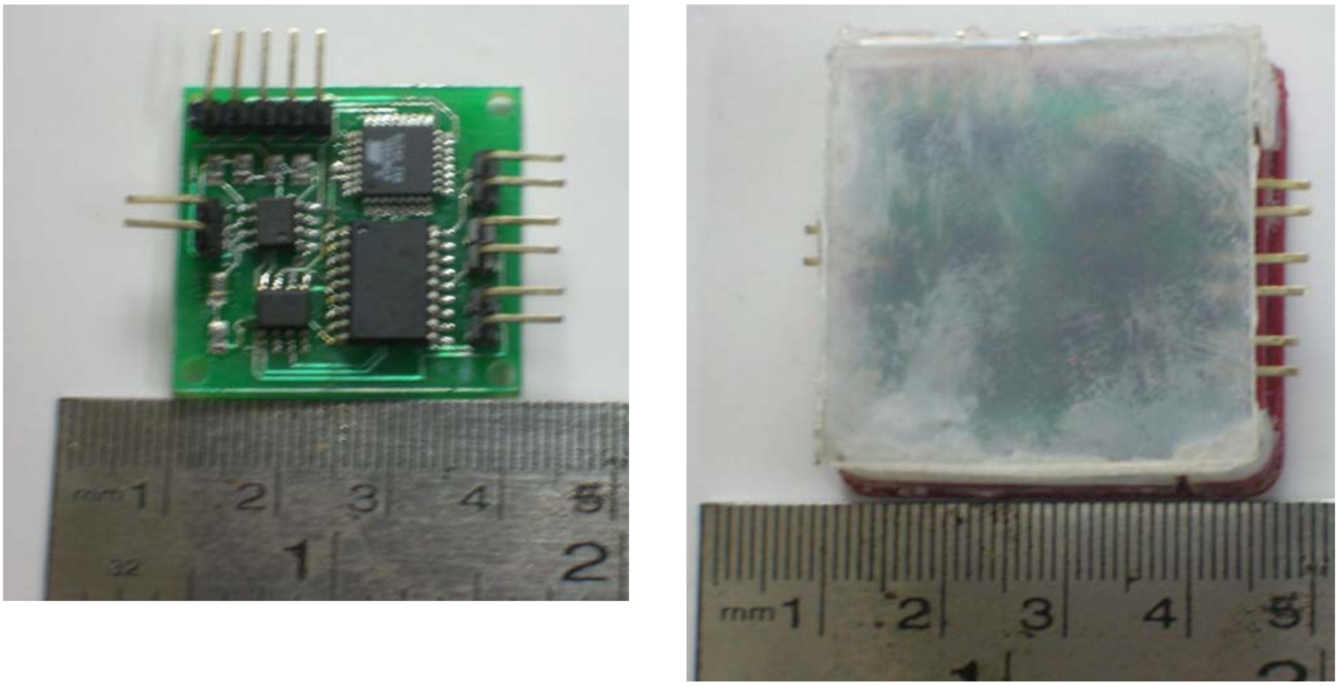

Fig. 21: PCB designed with surface mountable package of the microcontroller with a prototype of the external casing in November 2005

References

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19. Design of a wearable tactile display

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20. A Shoulder Pad Insert Vibrotactile Display

Aaron Toney; Lucy Dunne; Bruce H. Thomas; Susan P. Ashdown; Seventh International Symposium on Wearable Computers, October 21 - 23, 2003

Appendix

PT100:- A Pt-100 is a temperature dependent resistor. The resistance at 0°C is 100ohm. The temperature coefficient is approximately 0.38 Ohm/K. Pt-100's are used to measure temperatures of -200...+850 °C. Platinum resistance thermometers (PRTs) offer excellent accuracy over a wide temperature range (from -200 to 850 C). The principle of operation is to measure the resistance of a platinum element. There are also PT25 and PT1000 sensors that have a resistance of 25 ohms and 1000 ohms respectively at 0 C.

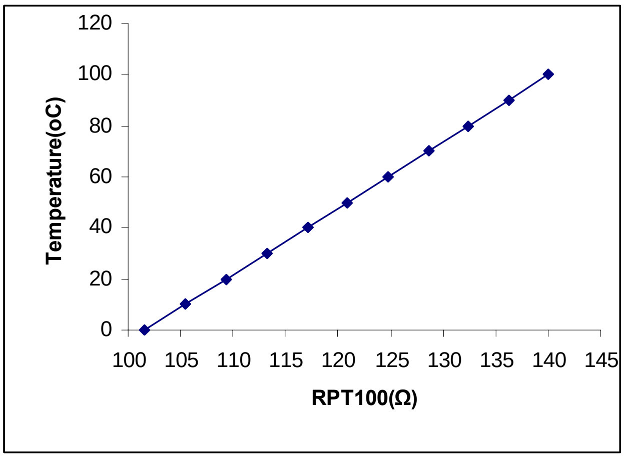

Fig. 22: Graph plotted for values taken from PT100 datasheet