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Tactile Sensor for the UTAH/MIT Dexterous Hand

THESIS

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
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Master of Science in Electrical Engineering

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Preface

This thesis could not have been accomplished without the guidance of several (and help from dozens of) people. First of all, I have benefited from having two "most excellent" advisors, Dr. Mike Leahy & Dr. Steve Rogers. The fact that I've had two advisors manifests itself directly in this effort ; and its fruition can be described as a "fusing" between their respective fields; Robotics and Neural Network Pattern Recognition. Dr. Matt Kabrisky was a tremendous resource for broad-spectrum information and illuminating the slip-detection potential of the sensor. Paul Whalen certainly deserves mention for his readily accessable knowledge of the computer & software systems (without which I'd probably be a '93 graduate). Dr. Spenny's "big picture" talks were always insightfull.

Finally, I'd like thank Mom, Dad for the biological contribution , and my brother for the bowl and paper napkins.

P.S. " Now You'll have to get a *real* job!" *The Casual Observer*

Jeffery D. Nering

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Abstract

The Neural Tactile Sensor (NTS)is a high resolution, easily manufactured tactile sensor consisting of electrodes, a thin resistive "skin", and pattern recognition circuitry that is capable of resolving dynamic and static contact location, force, and slip throughout the continuum of the sensor's active region. The sensor operates by means of a resistive "skin" harboring the electric field generated when a current is injected into it, and a plurality of electrodes for taking measurements of said electric field. When current flows through the resistive medium from the location of tactile contact, an electric field within the resistive medium is established, with a voltage distribution pattern dependent on where the contact was made. The contact generated electric field is measured at a plurality of locations on or in the resistive medium by the electrodes. The outputs of these electrodes can be interpreted as a continuum of field representing voltage patterns that are unique, repeatable, and dependent upon the location that field establishing contact was made. The dynamics of said voltage patterns are related to contact trajectory and slip. These voltage patterns are then used as input to appropriate pattern recognizer circuitry, such as the multilayer perceptron Artificial Neural Network (ANN).

An Artificial Neural Network based Tactile Sensor for Robotic Applications

I. Introduction

Good men work hard-

Better men work smart-

- roboticist's credo (unofficial)

1.1 Motivation

The Air Force would like to employ robots as the means to reduce unnecessary personnel exposure to remote, hazardous, and tedious environments, as well as reduce general task cost and man-hour requirements. The present technology is inadequate to support these ends. The problem is that the present generation of robots have trouble dealing with the levels of work-space ambiguity arising from even the simplest unstructured object manipulation tasks. The robotics industry today seeks to create a new generation of robots capable of carrying out unstructured dexterous object manipulation tasks: the cognition-based, adaptive manipulation abilities routinely taken for granted by any human performing a task. As part of this search, robotics manipulation research has been on-going at the Air Force Institute of Technology (AFIT) for the past six years. One aim at AFIT is the development of technologies for autonomous and semi-autonomous robotic manipulation of objects in unstructured environments. These efforts are presently centered around experimentation with control schemes and technologies designed for the PUMA 560 [Unimation] robotic arm and the Utah/MIT Dexterous Hand [Jacobsen]. The two manipulators will eventually act in conjunction to form the cybernetic equivalent to the human arm. As a vital part of this continued effort, the Utah/MIT hand needs tactile sensors. Specifically, grasp contact resolution and slip detection are the two forms of tactile feedback deemed necessary for AFIT's continued research in object grasping/detection and dexterous manipulation. With a tactile sensing capability installed on the Utah/MIT hand, AFIT robotics

hopes to acquire the cognitive skills necessary to remove the ambiguity inherent in unstructured dexterous manipulation tasks: expanding the envelope of tasks suitable to robotic automation.

1.2 Background

Future improvements in robotic efficacy will most likely be rooted in the robot's ability to sense, interpret and compensate for variation and uncertainty in it's work environment. Many potential robot applications require some form of sensing together with computer control which can modify the robot's actions based on the sensory information. An important sensory skill that humans take for granted while conducting arbitrary object manipulation tasks is their sense of touch: the tactile sense. The incorporation of tactile information into robotic control systems presently lags other approaches (vision, force monitoring) to manipulation feedback. This lag is in part due to lack of an adequate sensor and remains a critical limitation to the adoption of robotic implementations for tasks possessing non-trivial levels of task ambiguity (i.e. locating, identifying, and manipulating arbitrarily oriented objects: detecting grasp engagement and onset of slip). Currently being studied at AFIT is an advanced manipulator designed to closely approximate the kinematic form and freedom of movement of the human hand, the Utah/MIT dexterous hand (Figure 1.1). The Utah/MIT hand is a 16 degree-of-freedom multi-fingered robotic manipulator that incorporates sensors in the joints and wrist to monitor the joint angles and tendon tensions of the whole hand (Figure 1.1). Presently missing in the Utah/MIT hand is sensory capacity in the form of tactile feedback: the hand has no sense of touch. In prior AFIT research, the Utah/MIT hand has sensed contact with objects in the work environment via indirect means (monitoring changes in tendon tension resulting from contact) as part of a force feedback control effort, but direct tactile sensing for the hand has yet to be obtained. In view of the lack of tactile sensors on the Utah/MIT hand and the hinderance this poses to future robotic manipulation projects at AFIT, there is a need to supply the hand with a set of fingertip sensors. These sensors will provide important grasp contact location and slip detection information. The acquired tactile information will then form the core of a cognition-based feedback control block to serve the larger scale tasks of interpreting and compensating for objects detected in the UTAH/MIT's

work-space. The control block will act through a suitable robotic control architecture like CHIMERA [Stewart] .

1.3 Objective

Robotic research with AFIT's Utah/MIT dexterous hand would benefit greatly from a tactile feedback capability. The goal of this thesis is to develop a sensor to 1), resolve contact location , 2) detect contact slip and, 3) resolve contact force and/or pressure.
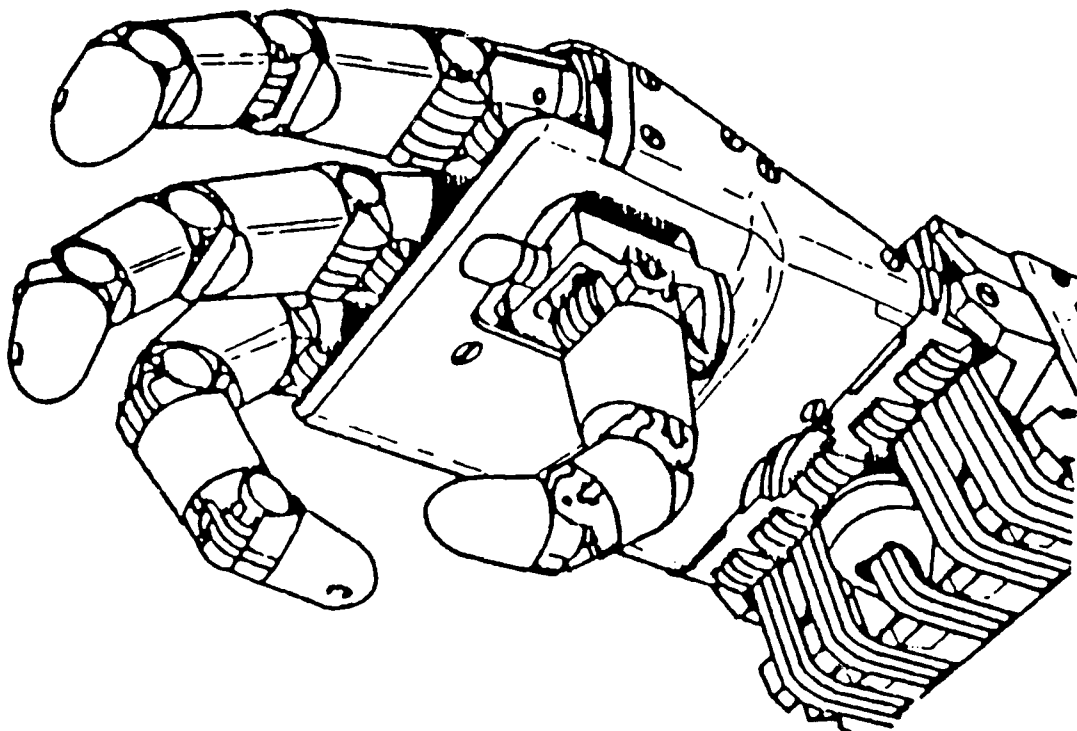
Figure 1.1   Line Drawing of the Utah/MIT Dexterous Hand [Jacobsen]

1.4 Problem Statement

This thesis concerns the development of a novel robotic tactile sensor, the Neural Tactile

Sensor (NTS). It seems logical that the combination of simple hardware generating a contact

dependent signal pattern for classification using ANN techniques can yield a sensor that is robust,

operationally sensitive, and flexible in design geometry. This research effort will explore several

specific tactile sensing criteria:

Contact Location Determination. The ability to resolve the location of contact on a

tactile sensor can be processed to ᵈetermine the orientation of the surface being contacted

(the contact normal). The NTS's continuous sensing surface possesses the possibility of

resolving contact location with accuracy unmatched by presently available sensors.

Slip Detection. An important ability for future manipulators is to recognize when its

grasp on an object is slipping. The direct interaction of the contact with the sensing area

on the NTS is conducive to specific dynamic phenomena associated with slip.

Force and/or Pressure Determination Knowing the force and/or pressure exerted on an

object is a valuable control variable. The relationship between the NTS's electrode

magnitude and the force applied will be investigated for utility as a sensor attribute.

1.5 NTS Concept

This thesis proposes a high resolution tactile sensor consisting of electrodes, a resistive

medium, and pattern recognition circuitry. The pattern recognition system must be capable of

resolving dynamic and static contact location, force, and slip throughout the continuum of the

sensor's active region. The proposed sensor (Figure 1.2) operates by means of an energized

object `1` coming into contact with the sensor's resistive skin `2`. Upon contact, electrical current

flows from the contact site to the ground reference (sink) electrodes `3`, via the resistive medium.

This current flow establishes a voltage field (dashed lines) within the resistive medium. The

Figure 1.2 Neural Tactile Sensor (NTS) Concept Schematic
for Resolving the Artificial Neural Network Interpreted Position ($\widehat{X}$) of the Actual
Contact Position (**X**)

voltage field created by the contact possess both static and dynamic characteristics and is measured by a series of electrodes [4]. The static components of the voltages read from these electrodes are interpreted as unique, repeatable, and position dependent voltage patterns created by the contact ; indicative of the contacting object's position (X) on the sensor. The dynamic components of the voltages read from the electrodes are indicative of contact integrity and are related to contact trajectory and slip. The static and dynamic voltage components are processed in different ways. The static voltage patterns are used as input to appropriate pattern recognizer circuitry, such as the Artificial Neural Network (ANN), which first "learns" the electrode voltage pattern/ contact position (X) mapping. Subsequently the ANN "recognizes" previously unseen voltage patterns and outputs (X), the network interpolated contact position. The dynamic (AC) voltage patterns from the electrode outputs are filtered to extractr elevant frequency content information . The resultant signal quantified into a measure of contact slip trajectory.

1.6 Method of Approach

The first and primary goal of this thesis was to develop a new contact sensor. Evaluating the NTS as a contact location sensor will be performed in three steps: development, validation, and refinement. Prototype development involves heuristically selecting an architecture, geometry, and materials; and constructing the appropriate software algorithms and hardware interfaces to facilitate operation and validation. Validation involved collecting and normalizing raw data at a variety of NTS contact orientations. The ANN was trained to associate a geometric interpretation of the orientation of the NTS as output with the normalized raw data as input. Comparing the network output to the actual orientation of the NTS when fed real-time, previously unseen data was the third step of the validation. The neural networks utilized in this effort used multilayer perceptron networks of varying dimensionality and backpropagation training variations. The refinement step involves repeating the previous two steps in a continual process constituting a development-validation loop seeking to optimize the sensitivity, durability, and practically of the NTS as a tactile contact location sensor technology.

A second NTS property evaluated was detecting the onset of slip. This was approached

through heuristic observation of the dynamic characteristics of the NTS raw output while slipping across a contacted object. A consistent, reliable signal frequency pattern indicative of the onset of tactile slip was isolated in the AC component of the NTS output during a slip condition. Next, appropriate electronic circuitry was constructed and refined to filter, extract, transform and quantify the AC frequency pattern observed on the scope into a DC contact slip probability potential.

The last NTS property evaluated in this effort was contact force measurement. Measurements of the aggregate magnitude of raw data samples were taken for a series of contact forces varying from 10 grams to 1000 grams. Results were repeated for varying contact orientations and correlations recorded and quantified.

In addition to the previously mentioned development, validation and refinement of the NTS, effort was concentrated on improving sensor construction, quality and robustness. Despite the NTS's simplicity, catastrophic failure occurred with numerous prototypes. Failed sensors were dissected and studied for clues as to the cause of failure, and improvements were proposed and implemented in subsequent NTS prototypes. An eventual total of 10 complete NTS prototypes were constructed. Via this method, steps were taken to:

■ Improve the NTS's Rubber Substrate

    ❏ remove bubbles created in finger injection molding process

    ❏ reduce finger warping caused during heat curing of the rubber

    ❏ increase consistency and hardness of rubber

■ Increase Electrode Robustness

    ❏ improve electrode/conductive skin interface bond and conductivity

    ❏ minimize required electrode depth in rubber finger

    ❏ minimize electrode surface area (increasing sensitivity) while maintaining interface

bond integrity

■ Optimize skin resistivity and consistency

     ❑ experiment with resistive paint's graphite mixture and standardize application process

     ❑ determine optimum resistivity requirements

In conclusion, these methods have attempted to optimize the functionality of the NTS. Efforts were concentrated on maximizing sensitivity to contact location while preserving output consistency. A functional slip-detection circuit was constructed, and the force to raw data vector relationship was investigated. Throughout this thesis effort, modes of sensor failure were addressed and steps were taken toward minimizing chances of reoccurrence, thereby maximizing the life and utility, of the sensor.

1. 7 Thesis Order of Presentation

This chapter introduced the NTS as a possible robotic tactile sensor technology. Chapter II provides a background of the present state in robotic tactile sensors as well as the theory of operation of the NTS. Chapter III provides documentation of the effort involved in the design, fabrication, and refining of the NTS. Chapter IV presents the performance results of the final form of the NTS. Chapter V concludes the significant findings of this research effort and makes recommendations for follow-on research. The Appendices include background and reference material concerning software created, hardware created, materials used, as well as supplemental and supporting data obtained while determining the performance of the sensor.

II. Background

2.1 Introduction

2.1.1 Motivation

The motivation for developing robotic tactile sensors is to advance robotic systems to operating unstuctured environments. This requires an external sensing capability. The majority of robots in use today use no external sensors and their motions consist of pre-computed sequences of trajectories that are repeated without variation [Barth:17]. This requires a well-organized, structured work-space for the robot to operate in. Advancing the robot's abilities to operate in less structured environments is critically dependent on enabling the robot to detect and compensate for the differences between the robot's internal, programmed model of how it's work-space is organized (specifically, the object's size, shape, position and orientation), and how the work-space is really organized. The ability to perceive and adapt to these differences is a skill humans take for granted when using their tactile senses. Providing this ability in robots depends upon the realization of a tactile sensor and its integration with control systems designed specifically to use tactile feedback. The "Air Force Studies Board 1989 Report on Advanced Robotics for Air Force Operations" [AFSB:2] states the present need for research and development in the areas of slip, force, and position sensing for robotic systems. Air Force robotic applications (aircraft refueling, armament loading, fuselage painting and cleaning, general flight-line maintenance) as well as NASA robotic applications (satellite repair, space-station assembly and maintenance) will require "intelligent" (semi-autonomous and autonomous) manipulation operations. Many of these operations are characterized by the need for a high degree of dexterity, achievable through the use of tactile sensors.

2.1.2 Scope

In this chapter, a description and definition of tactile sensing will first be presented. Next, a review of current tactile sensing technologies and the latest literature pertaining to each

will be presented, providing a background to compare tactile sensing methodologies. Lastly, since the purpose of this thesis effort is to present and evaluate a new form of tactile sensor, the NTS, the properties of its planar resistive skin and the basic theory behind ANNs will be presented.

2.2 Tactile Sensing

Tactile sensors are devices designed to gather information from objects being contacted. Robotic tactile sensors act as the channel through which information on the robot's environment is transferred to its control system. Of the 5 senses, only vision and touch are required for a successful and adaptable robot,[Pennywitt:7] and touch is considered the single most important sense for humans and robots [Webster:13]. The present developments in robotic vision have overshadowed those in the area of touch and slip sensing. But as new and more elegant applications for robots are being conceived, tactile sensing is recognized as an increasingly important machine sense for detecting of contact and slip [Klafter:382]. The problem of tactile sensing can be hierarchically separated into three stages. At the lowest level of the hierarchy, there are the device level problems of designing a tactile sensory device and of designing a dexterous manipulator to be equipped with such sensors. It has been suggested [Harmon::11] that tactile sensors should be distributed in arrays on thin, flexible, compliant substrates; much like human skin. Also, since tactile sensing is based upon physical contact, it is required that the entire structure comprising the tactile sensors be mechanically durable and resistant to environmental variations and hazards [Pati:196].

2.2.1 Tactile Sensing Definition

Sensors are devices that convert information from one form into another [Regtien:195]. Tactile sensors provide an interface with the environment [Barth:17]. Tactile sensing may be viewed as a two-step process: (1) transduction and (2) data processing. Transduction occurs when the features of an object being examined are converted into signals of some usable form, as in the case of the translation of contact forces into electrical impulses. Data processing then

interprets these signals to obtain useful information about the features of interest [Pennywitt:178]
The ability to continuously sense the contacting exerted on an object over an area with spatial
resolution is defined as tactile sensing [Pennywitt:3]. Within this definition lie contact, force, and
slip sensing. Tactile sensing differs from simply force or torque sensing, which is restricted to a
single point [Barth:18]

Contact Sensing: A contact sensor can just detect, in a binary sense, when contact has
been made, or it can provide richer information as to the location of the contact on the
robot's skin .

Force Sensing: When a contact has been established, one important aspect of the
relationship is with what force is the contact being made. When we measure force, we
normally measure the force component perpendicular to the sensor contact surface.

Slip Sensing: With an established contact, it is sometimes desirable to measure the
tangential shear force. For example, when a robot gripper grasps an object, it must apply
enough perpendicular force so that the resulting tangential force exceeds the weight of
the object. If the tangential force is too low, slip will occur.

2..2.2 Continuous Versus Array Sensors

The NTS is a continuous tactile and slip sensor and therefore differs from all other known
tactile sensing methodologies, except biological. One expected benefit of a continuous area
tactile sensor are the non-existence of interstitial tactile "dead-zones". Another is that the output
would not contain, for a continuous contact trajectory across the sensor's surface, any jump
discontinuities in the output signal as a result of the center of contact moving from one distinct
tactile sensing site to another.

2.2.3 Binary Versus Analog Sensing

Some forms of tactile information are naturally binary, an example of such is contact, you are either touching the object or you're not, you are slipping or not, etc. But most tactile phenomena also have analog features. Force, temperature, texture, contact location, and trajectory all possess analog and continuously variable features not fully expressible as simply on or off.

2.2.4 Tactile Sensor Requirements

The most commonly stated requirement of a tactile sensor is that it should be skin-like [Pennywitt:182] Sskin-like sensors can accommodate tight space requirements and allow clearance for the tendons, actuators, wiring, and support structure of complex manipulators like the Stanford/JPL and Utah/MIT dexterous hands. A survey of researchers and industrial manufacturers by Leon D. Harmon led to the general requirements for tactile sensors listed below. The spatial resolution should be 1-2mm. This is approximately the spatial resolution of the human fingertip.

☐ The force sensitivity should be between 0.5-10 grams. Of course the degree of sensitivity depends upon the application. Mass, velocity, acceleration, response time, and strength of materials are mutually dependent design parameters relevant to sensitivity requirements.

☐ Dynamic range of 1000:1 is desirable, and often logarithmic response is satisfactory.

☐ The sensor bandwidth should extend from DC to at least 100 Hz. Some robotic applications require a bandwidth of up to 1kHz. The bandwidth determines the overall frequency response of a control loop. This can be considered a specification for sensing vibration.

❏ Linearity is desirable, but some non-linearity can be tolerated. As long as a sensor has good repeatability and stability, non-linearity can be compensated for.

❏ Hysteresis must be low. That is, the output should depend only on the input and not whether the input is increasing or decreasing.

❏ Sensors must be wear-resistant, especially with slip. They must also be rugged to withstand industrial environments. Specialized applications could require extra durability with exposure to heat, radiation, electrical interference, smoke, or mechanical abuse.

❏ Low-power consumption is important, especially for battery-operated devices

2.2.5 Human Sensors

It is often stated in the literature that a robotic tactile sensor should have capabilities similar to that of the human hand. Human skin is a sensory organ that is highly sensitive and resilient [Barth:18]. Since the specific requirements of robotic tactile sensing have not as yet been clearly defined, it is often useful to view tactile sensing in humans as a model for artificial tactile sensing [Pati:196]. The human is quite adept at grasping and manipulating objects, using touch alone as the feedback mechanism [Russel: 5]. Estimates of the spatial resolution of the fingertips vary from 0.8 to 3 millimeters depending upon the method of measuring [Pennywitt:180]. Imitation of human tactile sensory capabilities is recognized as the goal for research concerning tactile sensors [Dario:23].

2.2.6 Present Tactile Transduction Approaches

A wide variety of materials and techniques are presently employed to create tactile sensors that can at best crudely approach the sensitivity, range, flexibility, and performance of the human hand. At present, the most appropriate of these presently available sensors are chosen by determining (1) the task of the robotic system, (2) the type of sensing most required, (3) the

environment in which the robotic system operates. [Russel:14] There are two general types of tactile sensors: pure force sensors, which transduce the direct application of a force into an electrically measurable quantity (for example, the piezoelectric and piezoresistive effects) and deflection sensors, which measure a force-related displacement (for example, magnetic, capacitive, ultrasonic, and optical effects) [Regtein:94]. Sensors incorporating piezoresistive materials make use of its ability to transduce changes in applied pressure or strain into a change in the resistance, which is monitored electrically. Piezoresistive sensors include strain gauges, conductive elastomers, and carbon fiber sensors [Webster:7]. Piezoelectric materials generate an electric charge when deformed either by pressure or bending. Sensors employing these materials monitor the generated charge electrically. A big disadvantage with piezoelectric devices is that the material doesn't respond in the static condition, it's only the changes and/or bending that generate a signal. Capacitance based tactile sensors exploit the fact that contact pressure can easily vary the distance between two parallel plates, hence varying the capacitance between them. This technique has the advantages of being produced with very small size. The biggest problem with this type of sensor is its sensitivity to stray electric fields, dielectric loss, and parasitic capacitance [Suzuki:676]. Optoelectronic tactile sensors monitor changes light intensity resulting from transmissions or reflections that vary off a flexible intervening material in accordance to an applied pressure [Begej:481]. Other sensing methodologies employed in tactile sensors include Hall-effect, inductive, fluidic, ultrasonic time-of-flight, and thermal. Hall-effect sensors monitor current deflection as a result of an interfering magnetic field. Inductance can be varied by varying the geometry, the reluctance in the magnetic path, or the magnetic coupling in the inductive transducer. Fluidic techniques serve to isolate the pressure sensing sites from the actual pressure receiving sites. Ultrasonic pressure transducers measure the distance a compliant surface has deflected as a result of pressure. Thermal sensors operate by monitoring the amount of heat flowing out of the sensor into the object being touched.

2.3 The Neural Tactile Sensor (NTS) Background

The NTS is a novel concept born out of frustration with presently existing tactile sensing techniques. Presented in this section are the NTS's two principle principle component : 1) a resistive skin transducing contact into a voltage pattern and 2) ANN circuitry interpreting the voltage pattern.

2.3.1 Concept Evolution

In an earlier effort to provide the Utah/MIT hand with tactile sensors, AFIT attempted to install sensors on the pads of the fingertips of the Utah/MIT Dexterous Hand. A commercially available resistive force sensor, the Force Sensitive Resistor (FSR), was chosen. The FSR is a sheet of resistive material deposited (painted) on top of a network of two interleaved conductive grids. Current flows from one grid, through the resistive layer, to the second grid. The amount of current flowing between the grids is in direct relation to the force placed upon this sandwich. These devices are currently employed in cheap keypads for calculators, buttons for automated teller machines, microwave ovens, etc. It was the properties of the FSR's intermediate layer of resistive material that inspired the concept of this thesis. The NTS concept involves using ANN pattern recognition techniques to first learn and then recognize the voltage gradient patterns generated by a contact. These patterns are represented through a distribution of electrodes embedded in a resistive layer that is energized by a voltage from an arbitrarily established contact. Understanding the operation of the NTS depends primarily on understanding it's two primary components, a planar resistive sheet and the Artificial Neural Network (ANN).

2.3.2 Resistive Sheet Properties (Pattern Creation)

The initial hypothesis was that a series of electrodes embedded in a resistive sheet would give location-dependent resistance measurements from an arbitrary established contact (operating like a thick-film potentiometer, with the wiper acting analogous to the contact and the rails acting like the electrodes, but in a two dimensional arena). The first model of the sensor was constructed out of a strip of an FSR's resistive layer and an electrode placed on each end. This

RESISTIVE SURFACE GEOMETRY
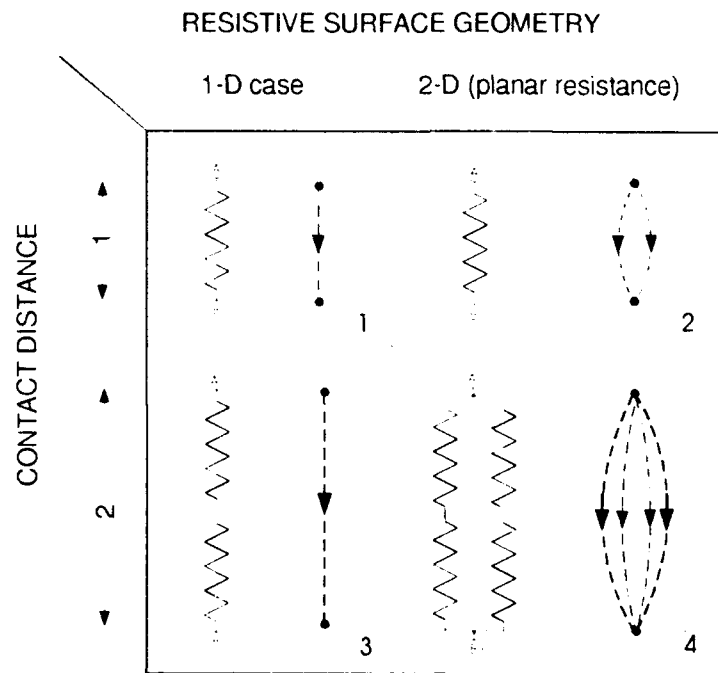
Figure 2.1   Schematic Comparason Between 1-Dimensional (conventional)
and 2-Dimensional Resistors

first concept specimen (which shared the appearance and linear distance/resistance relationship of

a thick film potentiometer) encouraged further development. A wider (2-dimensional) prototype

was constructed over a cylindrical surface (the cap off a prescription medication bottle) using

commercially available graphite impregnated resistive paint used for ElectroMagnetic

Interference (EMI) suppression and wire electrodes. Tests of this first 2-D prototype were

unexpected. Unlike a simple extrapolation of the 1-dimensional (potentiometer) case that was

2-8
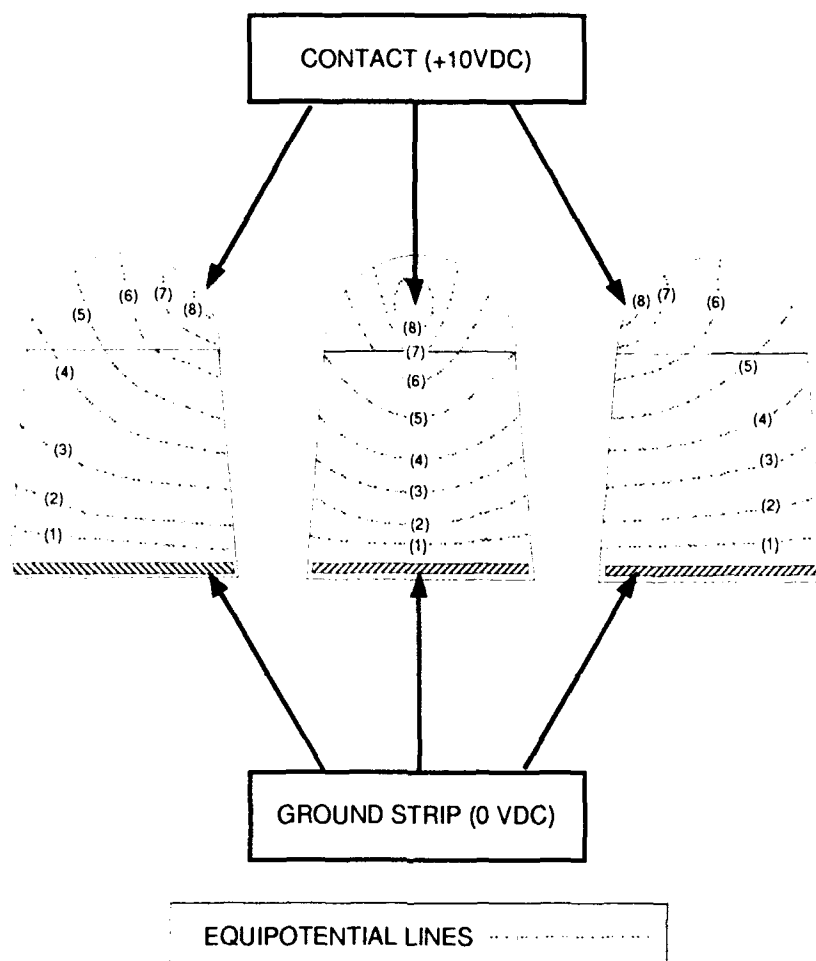
Figure 2.2 Representative Electric Field Distributions illustrating the
Contact-Location Dependency of the Field Pattern.

first explored , the 2-D sheet resistance measurements were not at all linearly related to the

distance of the contact and the reference electrodes (measurements show an uncorrelated

resistance/ distance relationship).   In the 1-dimensional case, increasing the distance between the

contact and the reference electrodes increased the linear length of the resistive medium (and

therefore the resistance). In the 2-D case, increasing the electrode distance increases the width of

the current path as well.   The resistance change due to the distance change the electrons have to

travel through the resistive medium is completely offset (ignoring edge effects) by the change in

path width of the electrons flowing from one electrode to the other. In the case of increased distance between electrodes, the path distance will increase (increasing the resistance), but the width of the current path has increased as well (reducing the resistance). For decreased distance between electrodes, the current path decreases (decreasing resistance) ,but the width of the current path has decreased as well (increasing the resistance). These two simultaneous, opposing effects of path length and path width in a planar (2-D) resistive layer combine to give a resultant resistance that is basically insensitive to the path length between electrodes placed on it. The planar resistive layer behavior compared to the strip (1-D) resistor can be visualized in the context of a resistor network model (Figure 2.1). In the ideal 1-D case (1)a single strip resistor) the current has only one path to follow between points A and B. This is analogous to the series resistor network.(2)The current path is basically a single series chain (doubling the contact distance doubles the resistance). In the ideal 2-D case (3)(ignoring boundary effects) doubling the distance similarly doubles the resistance of each individual path, but also doubles the number of paths ; (4)analogous to simultaneously adding parallel paths between points A and B to the original network. The net result for the resistance measurements between arbitrary points A and B is that **the resistance measured between electrodes is largely independent of their distance apart.**

Due to the largely independent resistance/distance relationship in two-dimensional resistive layers, using resistance as the transduction method was abandoned. But in using field equipotential lines to help visualize the inadequacy of using resistance as the method of transduction, the field lines themselves exhibited very interesting features. The voltage pattern created by current injected into a resistive sheet is contact dependent in nature. This can be shown as an electric field distributed throughout the resistive surface, peaking at the contact point and terminating at a ground strip (Figure 2.2). The exact pattern of the electric field is unique to the location of current injection into the resistive skin (the contact location). This field pattern is consistent and repeatable for a given contact location on the NTS's resistive sheet].

HIDDEN LAYER

OUTPUT LAYER

PROCESSING ELEMENT (NODE)

CONNECTION (LINK)

CONNECTION GAIN (WEIGHT)
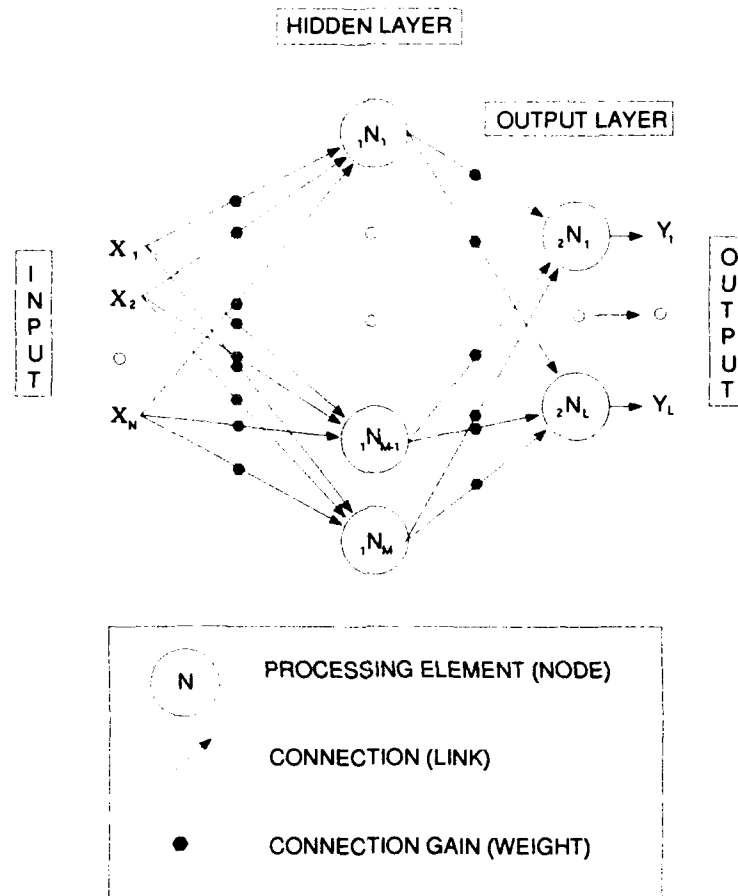
Figure 2.3 Typical Architecture for a Multilayer Perceptron (One Hidden Layer)

N Input Measurements
M Hidden Layer Nodes
L Outputs

2.3.3 Artificial Neural Networks (Pattern Interpretation)

Definition of a Neural Network: Robert Hecht-Nielsen has defined a neural network as a parallel

distributed information processing structure in the form of a directed graph, a geometrical object

consisting of a set of points (called nodes) along with a set of directed line segments (called links)

between them. Included in this definition are the following sub-definitions and restrictions. [Nielsen:22]

1) The nodes of the graph are called *processing elements.*

2) The links of the graph are called *connections.* Each connection functions as an instantaneous unidirectional signal-conduction path.

3) Each processing element can receive any number of incoming connections (input connections)

4) Each processing element can have only one output, but this single output signal can be fanned out to any number of outgoing connections.

5) Each processing element (node) possesses a *transfer function* which can use the input signals to create an output signal.

6) Input signals to a neural network from outside the network arrive via connections that originate in the outside world. Outputs from the network to the outside world are connections that leave the network

Figure 2.3 shows a typical network architecture.

The artificial neural network (ANN) is a pattern recognition system. Pattern recognition is used in this thesis effort to correlate the voltage patterns generated on the NTS's resistive sheet to the locations where these pattern generating voltages were applied.

Artificial neural networks, like many of the biological neural networks they were

modeled after, are computationally parallel in nature. Many simple computing elements, called nodes, are arranged in layers and receive input signals (either by other nodes from a lower layer or the input vector) and perform a basic mathematical activation function upon the weighted input sum. The activation function that operates on the weighted input sum can be linear, sigmoidal, gaussian, or a hard limiter. The node's many inputs are received, combined and transformed into a single output by the activation function. This single output is then either fed as input to each node in the next higher layer of nodes, or interpreted as an output of the neural net.

Artificial neural networks are not programmed or calibrated like computers or instruments, they are trained by example. Training is usually accomplished by introducing input patterns of known classification while simultaneously representing this classification as the desired output. Training schemes exist such as backpropagation [Werbos], and the principle idea is to selectively inhibit or enhance the inputs reaching each of each of these nodes in an "intelligent" manner that makes each node sensitive to a particular pattern (feature) of the inputs fed into it. The "intelligence" is represented as a series of gains (weights) that are adjusted by the training scheme and selectively sensitize each node in the network to a specific pattern of input signals received from the previous network layer.

Because ANNs learn to recognize input patterns by training with raw example data, there is no need to describe and algorithmize the desired recognition task. Under rules defined by a training scheme, networks are allowed to adjust their internal parameters, known as weights, to allow the network to "learn" the features needed to perform learned recognition tasks.

2.3.4 The Backpropagation Neural Network

A neural network category useful to this thesis effort is the Hyperplane classifier. Hyperplane classifiers form regions in the multidimensional input (feature) space that are trained to be identified as the desired output. The multilayer perceptron neural network is a popular and well studied hyperplane classifier. [Rogers:44-63] and best known implementation of the multilayer perceptron is the backpropagation neural network. The backpropagation neural network is one of the most important historical developments in neuro-computing. It is a

powerful mapping network that has been successfully applied to a wide variety of problems

ranging from credit application scoring to image compression [Hecht-Nielsen:124]

The NTS, although novel, is not the first tactile sensor to utilize neural interpretation

techniques. A review of the current literature revealed research involving neural techniques to

interpret low-level tactile sensor data,[Pati] and characterize surface texture using neural network

classification [Brenner], but these papers cover dynamic and theoretical aspects primarily, and

neither use neural techniques to resolve contact location. Contact location is an important tactile

sensory capability. It has been shown that contact location in conjunction with orientation

information (kinematics can be combined to utilize tactile sensors to determine the axis of a

Surface of rotation [Berkemeier] . Slip detection, a dynamic capability of the NTS, is a well

identified requirement in tactile sensing [Tomovic:567].

2.4 Conclusion

The need for tactile sensing in robots has been discussed. A definition of tactile sensing

and and a brief review of the wide variety of transducing techniques used for tactile sensing has

been reviewed. The tactile sensing capabilities of the human hand were reviewed and serve as a

base-line upon which to compare artificial tactile sensing capabilities. Lastly, a background of

the resistive two-dimensional sheet and the ANN interpretation scheme that comprise the NTS

was discussed. Before a more detailed report on the performance capabilities of the NTS can be

developed, the NTS sensor as it presently stands will be introduced in greater detail.

III. The NTS Sensor

3.1 Introduction

The NTS is a novel approach to imparting a sense of "touch" to just about any 2-dimensional surface. The NTS consists of two principle components: 1) a resistive sheet providing transduction and 2) ANN circuitry providing data interpretation. The generality of structure inherent in each of these two components allows for an implementational freedom that grants almost unlimited variation in NTS design geometry Furthermore, the NTS's thin "skin-like" geometry allows NTS implementations on surfaces previously too cramped or complex for installing a tactile sensing capability.

The most promising present application for the NTS is in robotics. It is widely accepted that the next major advance in robotics will be the robot's ability to sense, interpret, and compensate for variation and uncertainty in its work-space: the ability to work in unstructured environments [Dario:251]. Robots require tactile feedback to do this. The NTS provides an inexpensive, extremely adaptable form of tactile feedback for robots (the instant of contact, the location of contact, slip , and the force through which the contact is being applied).

This chapter describes the NTS sensor concept inception, implementation and capabilities in detail.

3.2 Biological Analogy

Bionics is the design and construction of artificial mechanisms based on study of similarly functioning biological systems [Ency. Britannica]. The NTS concept can be shown to be analogous in part to the sensing of the crustacean order *Decapoda*, the common crab . The chelae (pincers) of decapods in many ways resemble the robotic manipulators of today. The degrees of freedom of a crab pincer are very rigidly constrained with only one degree of freedom (DOF) allowed per joint. The claw is composed of a hard load-bearing shell and (like a robotic

arm) possesses no intrinsic sensory capacity. But this is not to say the crab doesn't possess a tactile sensory capability. Protruding from the surface of the crab's shell are dimples/spines of raised exoskeletal material. Emerging from the centers of these raised areas are receptive hairs that pierce through the crab's exoskeleton to the living tissue below. Under the shell, the hairs are connected to nerve cells, presumably not unlike the hairs on our bodies. It must be very expensive (metabolically) and compromising (structurally) for the crab to install these hair sensors on its body, for evolution has made the crab very stingy with them. The raised hair sites represent an obstacle to the moulting process and the holes created for the sensory hairs represent structural weak spots in the crabs armor. For this reason one can argue that evolution has optimized the crab's sensory mechanism to exact as much possible tactile information for the crab from as few as possible tactile sensing sights. Two observations that support this:

1) Each raised spine on the claw terminates with a tactile receptor. Geometrically, the raised tactile receptor sights represent the most probable area to be touched when an object comes in contact with the animal, and represent the only contact sites if the object contacted is more obtuse (less pointed) than the crab's body

2) The hairs from areas of the claw devoid of raised spines (i.e. the smooth areas near the pincers) extend unsupported and appear to grow normal to the shell surface. This would optimize the probability of tactile contact with objects in the proximity of the claw and could fully represent a light contact without ever touching the unreceptive chitin shell.

Observations 1 and 2 support the claim that the crab's limited number of tactile sensors are located in optimal areas for sensing its environment.

The limited number of tactile sites on the crab seem to belie the dexterity with which the crab goes about its business. At the business end of a claw (the pincers), the spines disappear and are replaced by hairs that protrude from the chitin shell without support. But these hairs too, like

the sensors on the tips of the spines, are spaced apart in patches, leaving most of the pincer tip without tactile representation. This would leave a control engineer expecting to see "limit-cycling" in the crab's motions as contact with objects it manipulates continually shifts from one tactile hair patch to another. Casual observations of crabs dexterously negotiating rock formations or collecting food morsels do not support this. Blind, cave-dwelling decapods exhibiting dexterity in their actions exclude the possibility they achieve this via visual assistance. Consistent with these observation would be that the crab possesses the ability to interpolate between hair sites, possibly using force applied to the hairs, or number of hairs contacted as feedback to accomplish this tactile site interpolation.

With the idea of tactile sensors resolving contact location beyond the density of these individual sensors, with finite tactile sites providing continuous tactile feedback, the NTS exhibits similarities to the sensing mechanism of crab-claws. The analogies are as follows:

1) The use of a resistive skin instead of protruding hairs to provide an interpolative tactile transfer medium between the contact location and the limited tactile sensing sites (making the tactile receptive area continuous for locations between the actual tactile receptors). The limited number of tactile sensing sites (hairs for the crab; electrodes for the NTS) are compensated for because the hairs/electrodes are sensitive to contact phenomena extending beyond the hair/electrode's specific location. Magnitude information is extracted from the sensing sites (the force with which the hair is contacted/the magnitude of the excitation voltage) to provide this interpolation capability.

2) Using a neuron-based pattern recognition technique to process the raw sensory data. No single tactile site tells the whole story, only when all the data from all the hairs/electrodes is interpreted as an ensemble whole are any conclusions drawn as to exactly where the contact location is being made.

3.3 NTS Description

The NTS uses Artificial Neural Networks (ANNs) to interpret the raw electrical data. Using this "learning by experience" pattern interpretation technique as an integral part of the sensor allows for design and manufacturing freedoms in the form of:

❏ No precise machining of components

❏ Freedom to use geometrically complex, analytically intractable sensor geometries

❏ No need to ensure homogeneousiy applied resistive sensing surfaces

❏ No need to ensure exact electrode placement within the resistive surface

The reason for these freedoms is that any inconsistencies in manufacturing or complexities in design are automatically identified and compensated for during the training phase of each sensor's creation. The sensor automatically calibrates itself during the network training phase.

3.3.1 NTS Concept

The concept is to embed a number of electrodes into a resistive sheet that covers the surface (of arbitrary geometry) of an object (robotic arm, gripper, etc.) that one wishes to imbibe with the sense of "touch" (contact lo ation & force applied). The output of the electrodes become the input to an Artificial Neural Network that, through training by example, has learned the the arbitrary, non-linear relationship between the electrode output voltages and the position on the resistive sheet where current has been applied.

Once a contact has been made on the sensor, a potential (voltage) is created , causing a current to be injected into the resistive sheet at the point of contact. This current flows through the resistive sheet in a LOCATION DEPENDENT DISTRIBUTED PATH toward the reference (ground) electrode, which is usually located along the periphery of the resistive skin. The injected current generates a field (voltage gradient) across the entire resistive skin. Electrodes

embedded in the resistive skin directly measure this voltage distribution caused by the current injection. The resulting voltage readings taken off the electrodes provides a UNIQUE, CONSISTENT and NON_LINEARLY MAPPABLE voltage vector (of dimension equal to the number of electrodes) that can be interpreted as belonging to a specific location on the sensor. This interpretation is accomplished with a non-linear pattern vector recognition scheme such as the ANN.

3.4 NTS Attributes

The NTS concept is a very simple one that can be extended and varied to accommodate the needs of a wide range of applications. Attributes that contribute to this generality of application include:

SIMPLE HARDWARE: (extendable to any object) The design methodology of a simple array of conductors embedded in a resistive skin is simple to manufacture and the process can be extended to cover an infinite variety of surfaces. (no other sensor can be implemented and built so easily)

MINIMAL SIZE REQUIREMENT: (smallest of any known sensor) Because the sensor design occupies only the outer skin of the object it is to supply with the sense of touch, (analogous the the nerves in the skin of the human hand) very little space (just the thickness of the skin) is required for the sensor. Skin thickness is presently under 0.01".

INEXPENSIVE : Because of its simple manufacture using few components, electrodes and a resistive skin, the physical sensor itself can even be "disposable"

ENVIRONMENTALLY ROBUST: Although the resistive medium used in the NTS may have a thermal drift coefficient, it is an ensemble pattern that is used and not an individual reading. Consequentially the device needs no thermal compensation.

Furthermore, because any resistive skin can be used (ceramics, nicrome plating, resistive metallic alloys) the NTS has the ability to be used in environments too hostile or corrosive for previous sensing methods. (i.e. welding condition surroundings, inside furnaces, under acid baths)

SELF- DIAGNOSING (fault detection) Analytic techniques have been developed that can test and recognize the erroneous readings associated with broken electrode wires or torn skin; alerting to when the sensor skin should be replaced. Work is still ongoing to identify a suitable neural technique)

Fault Detection Technique:

Individually disconnect an electrode from the A/D and connect it to a positive voltage source. This has the effect of creating a voltage distribution on the NTS as if a contact were just established at the current injecting electrode. (a separate, test electrode could be dedicated to this task instead) The readings of the remainder of the electrodes should indicate a contact at the position of the charge injecting electrode. If not , a fault condition can be presumed to exist.

THE RESISTIVE NATURE OF THE SENSOR DESIGN MEANS NO BIASES OR OFFSETS IN THE RAW ELECTRODE OUTPUTS.

NO MOVING PARTS MEANS NO HYSTERESIS IN VOLTAGE OUTPUT.

MULTI-SENSING (slip, force, and position)

THE OUTPUT IS NOT MULTIPLEXED (no timing requirements or cross-talk)

PASSIVE (RESISTIVE) AND CONTINUOUS DEVICE: The outputs are continuous and in real-time (no quantization error usually associated with array-type sensors and device is micro-second fast). This continuous, non-multiplexed output is particularly suited to present feedback control systems.

GEOMETRIC FLEXIBILITY: Although this sensor was demonstrated as a fingertip sensor for a state of the art robotic manipulator (the UTAH/MIT dexterous hand) the concept (electrodes embedded in a resistive skin, with position dependent current injection interpreted with an artificial neural network) can easily be extended to any arbitrary surface and a number of different operating modes.

NO SIZE LIMITATION:: NTS sensors can be made for manipulators small enough to dexterously handle delicate instruments or large enough to cover steam-shovels. Because electric field generation takes place at the atom/electron level, only quantum field effects limit resolution, leaving the door open to microscopic sized tactile sensors. As long as the resistive medium is able to harbor an analog, continuous field pattern, the NTS concept holds. On the other side of the size spectrum, the NTS's ease of manufacture can allow for sensors that cover manipulators the size of houses. The design can also be repeated identically, in an array architecture, to standardize implementation and increase resolution over larger surfaces.

TRANSDUCTION METHOD FLEXIBILITY: In the first generation NTS implementation, the sensor concept was demonstrated with the contacted object acting at the current injector to the resistive layer, which was directly exposed to the contact environment. Alternative methods of injecting current to the resistive layer (Figure 3.1) have been proposed that eliminate the need for the contact to be electrically charged.

3.5 *NTS Variational Approaches*

A nun.ber of possible sensor variations have been proposed but not yet attem~ud due to time and materials constraints. These variations involve 1) allowing the NTS to detect non-conductive, non-charged objects 2) altering the NTS to detect tangential shear forces and 3) imparting to the NTS a multi-contact sensing capability

3.5.1 Arbitrary Object Sensitivity

The NTS prototypes demonstrated thus far have required the contacting object itself to act as the current injector. An alternative method is proposed (FIG 3.2) that eliminates the need for the contacted body to also be the charge injector, but this variation is just an extension of the basic NTS concept. Figure 3.2 illustrates the proposed alternative to the present NTS design requiring the contacting object to inject current into the NTS's resistive layer. This modification allows the NTS to detect non-charged contacting objects. The modification requires three additional layers in addition the the original resistive layer: 1) an insulating and resilient outer skin 2) a pliable conductive layer , and 3) a force (compression) sensitive conductive layer. The job of each layer is detailed below:

Insulating outer skin: This outer skin's job is to protect and electrically isolate the NTS from the work environment. One requirement is that the skin be durable. Because the force of contact has to he transmitted through this layer, it should be compliant and soft. To be rubbery and slip resistant in texture could be an additional characteristic.

Pliable conductive layer: This layer would be just below the insulating outermost layer. Its job is to supply the entire surface of the sensor with an equally available current supply regardless of location. Candidates for composition of this layer include conductive paints, aluminum or gold foil, fine metallic mesh, etc.

Pressure sensitive variably conductive layer: This is the most critical of the three layers.

ORIGINAL NTS CONCEPT:

EXHIBITING REQUIREMENT FOR
A CURRENT INJECTING CONTACT
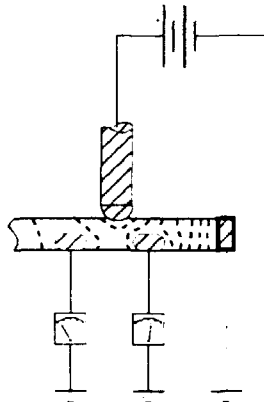
NTS CONCEPT VARIATION:

EXHIBITING INDEPENDENCE FROM
CONTACT ELECTRICITY VIA CURRENT
INJECTING INTERMEDIATE LAYERS

FORCE (COMPRESSION)
SENSITIVE CONDUCTING
LAYER

CONDUCTIVE MATERIAL

INSULATING "SKIN"

RESISTIVE SENSING
MEDIUM -w- EQUAL-
POTENTIAL LINES

Figure 3.1 Comparason exhibiting the Modifications Required to Liberate the
NTS from Receiving Injection Current Directly from the Contact

This layer provides the contact location dependent current injection that is critical to the basic NTS concept. This layer is sandwiched between the pliable conductive layer above and the NTS's resistive layer below. The conductive layer above provides a equipotential surface on top in which to draw current and the resistive layer below stands ready to receive current. The principal idea is that this pressure sensitive layer acts as an insulator between the conductive and resistive layers during a no contact condition that degenerates locally into a current transmitting medium as a direct result of force being applied from a contact condition.
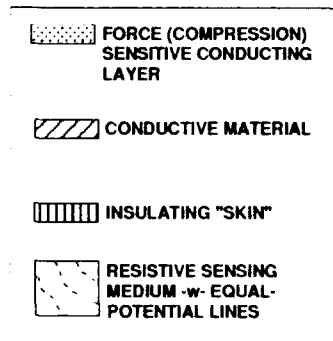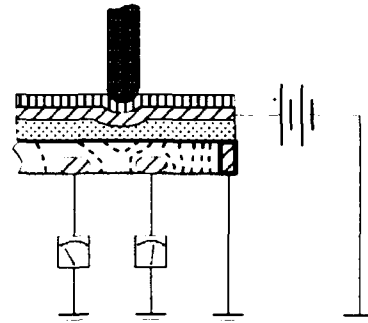
This proposed modification is just one approach to solving the problem of enabling the NTS to detect non-charged, non-conductive contacting objects. Additional variations involve reversing the order of the electrically conductive, pressure sensitive, and resistive layers to remove the pliability requirement of the conductive layer. The expected benefit with this reshuffling of the three layers would be increased sensitivity because the important resistive and pressure sensitive layers are less hidden in the stratification. The concern with this approach is that the electrodes now have to float above the substrate, creating construction concerns.

Regardless of how the layers are organized, this NTS variation would have the expected benefit of heightened pressure sensitivity due to the pressure sensitive variably conductive layer. Preliminary investigation of commercially available pressure sensitive layers [Acheson] show high consistency in these layer's pressure/ conductivity relationships. This form of transduction can be exploited in the form of a direct force to current flow relationship for NTS variations employing this kind of pressure sensitive material.

One drawback of enabling the NTS to detect non-charged, non-conductive contacting objects would be the possible loss of the present approach to slip detection. The slip detection capability in the NTS is recognized as resulting from the dynamic current fluctuations resulting from a dynamic contact condition, the current path from contact to resistive layer is direct and dynamic during slip. With the modification, the current is no longer being injected from the

contact but through an intermediate pressure sensitive layer that only responds to the force applied. With the contact no longer supplying the current, contact properties (slip) that previously relied solely on current injection dynamics cannot be exploited. But, a possible alternative would be to mold ridges, not unlike the ones on the human fingertip, onto the insulating surface of the modified NTS to provoke a slip to vibration dynamic pressure relationship with a bandwidth and magnitude detectable by the pressure sensitive layer.

3.5.2 Shear Force Detection

There presently exists commercially available materials that exhibit stress and strain dependent resistive natures. Resistive skins constructed from such materials would exhibit patterns when tangentially stressed distorted from the patterns created from a non-shear force contact at the identical location. (This scenario assumes the substrate is compliant enough to transmit the tangential stresses to the resistive layer)

3.5.3 Multi-Contact detection and decomposition

Preliminary work was begun on trying to establish distinguishing characteristics indicative to a multi-contact situation. Results thus far have been inconclusive using a neural detection scheme based upon voltage pattern novelty and magnitude. Alternative, analytic schemes appear feasible. One such scheme would be a geometry directed electrode scan that would trace voltage gradients. Under a single contact scenario, only one voltage peak would exist (at the point of contact) and all voltage levels would decrease radially away from it. A multi-contact contact situation would lead to multiple peaks that would be detectable if the distance between contacts was appreciable as compared to the distance between electrodes.

An interesting and potentially very useful characteristic of the NTS when the multiple contact interstitial distance is small when compared to the interstitial electrode distance is that the network decomposes this situation and yields a interpreted contact location that experimentally has been shown to closely approximate the centroid of the multiple contacts. The experiment

involved using three needles to inject current into the NTS at 3 different locations corresponding to an equilateral triangle approximately 1mm to a side. The NTS interpreted this condition as a single location resting approximately at the centroid of the three contacts

3.5.4 Medical Possibilities

One of the most interesting possibilities of the NTS concept is in medical applications. The fact that the interpretation scheme used for the NTS is in itself an interpretation of how animals process sensory information gives it an inherent advantage in the "Machine-to-Meat" interface that would inevitably have to be constructed before prosthetic sensors could replace those lost from amputated or paralyzed human limbs. It is even possible that a human could "train" himself to recognize the multi-channel simultaneous pattern interfaced with his severed nerves (after appropriate signal conditioning, of course). Someone did a similar thing on V1 with a blind guy (I don't have the reference).

3.6 Artificial Neural Networks

With the contact generated electric field providing a unique, consistent, and contact dependent suite of electrical signals, processing the signals was approached using artificial neural network (ANN) techniques. Electrodes embedded in the resistive sheet sample the voltage field pattern created by the contact and present them in a systematic manner as input to a ANN. The primary reason for choosing this approach was its simplicity. With an ANN first learning, then recognizing the voltage patterns (feature vectors) associated with specific contact locations, the difficult task of creating a voltage-pattern-to-contact-location transfer function was eliminated. Training a separate neural net for each separate sensor carries the additional benefit of learning (hence compensating for) any inconsistencies and variations in the resistive skin's resistivity, uniformity, and geometry, eliminating the need for calibration.

Neural networks were used in the NTS primarily for the following reasons: 1) because of the non-linearity of the contact location to electrode output relationship of the NTS, a

deterministic, analytic interpretation of the NTS transduction was not known. Neural networks learn to classify by example, and therefore the exact relationship doesn't have to be known. 2) Neural networks are actively being investigated and are proving to be efficient, robust methods to solving complex pattern recognition tasks.

The ANN technique chosen for verification was backpropagation . The reason for this choice was backpropagation's proven efficacy in classifying patterns that are unique and repeatable for a given output class.

The backpropagation neural network, used for the NTS, has been compared to a degenerate Kalman filter, and this is basically a confirmation that backpropagation uses all the information available to it in order to minimize the error of the final answer. [Ruck:686] Because each electrode of the NTS is somehow affected by the location of contact no matter where it is on the resistive skin, each electrode individually contains information relevant and contributive to the accuracy of the final result. Exploiting this fact to the NTS's advantage is that backpropagation is an interpretation scheme that uses all the electrodes as an ensemble.

Since the voltage distribution created on the resistive sheet of the NTS is a continuous gradient of two dimensions minimum. The first task is to reduce this pattern into a tractable group, or vector, of voltage measurements. these measurements become a degenerate approximation of the original field distribution, a representative measurement.

3.7 Conclusions:

A tactile sensor comprised of a electrodes embedded in a simple resistive layer and ANN interpretive circuitry was designed and constructed. A biological comparison to crab-claws was made, followed by a description of the unique implementational freedoms that using a neural interpretation technique provides. Next, a description of the NTS concept was given and the

attributes of this new sensor technology were detailed. Finally, proposed but yet unverified variations of the first generation NTS were considered. The next chapter details the design and fabrication of the first generation NTS.

IV. NTS Design and Fabrication

4.1 Introduction

With the NTS, software is as integral to operation as hardware. The raw electrode output is multidimensional and only a loose heuristic relationship between the geometric contact position and electrode output can be made. Using artificial neural networks to interpret the complex electrode pattern frees one from having to define this complex I/O relationship. This methodology also offers unique flexibilities in its use. This chapter reviews the components of the NTS on a piece by piece basis: first hardware, then software.

4.2 Hardware

4.2.1 Sensor Geometry

The NTS was designed from the onset to be installed on the Utah/MIT dexterous hand. Accordingly, the outer geometry of the sensor was derived from the original equipment fingertips that came witn the hand. This approach was taken because: (1.) the small size of the original fingertips allowed for the dexterous manipulation of small objects. (2.) the surface geometry of the original fingertips is approximately a conic section terminated with a hemispherical tip. Observing (1) ensured the NTS installation wouldn't interfere with the hand's original freedom of movement. Observing (2) yields kinematic benefits by allowing the unique mapping of a contact location on the surface of the NTS to a contact vector useful for deriving elements of the contact force vector C. which relates to the generalized force vector F and the grasp matrix W by the relationship:

$$F = WC \tag{4-1}$$

Fingertip geometry measurements obtained from an original fingertip of the Utah/MIT hand yielded the following dimensions (Figure 4.1): The fingertip measures 0.655 inches in diameter at the base and narrows linearly to a diameter of 0.545 inches at the hemispherical tip. The tip is a hemisphere, 0.545 inches in diameter. Piercing through the conic section &
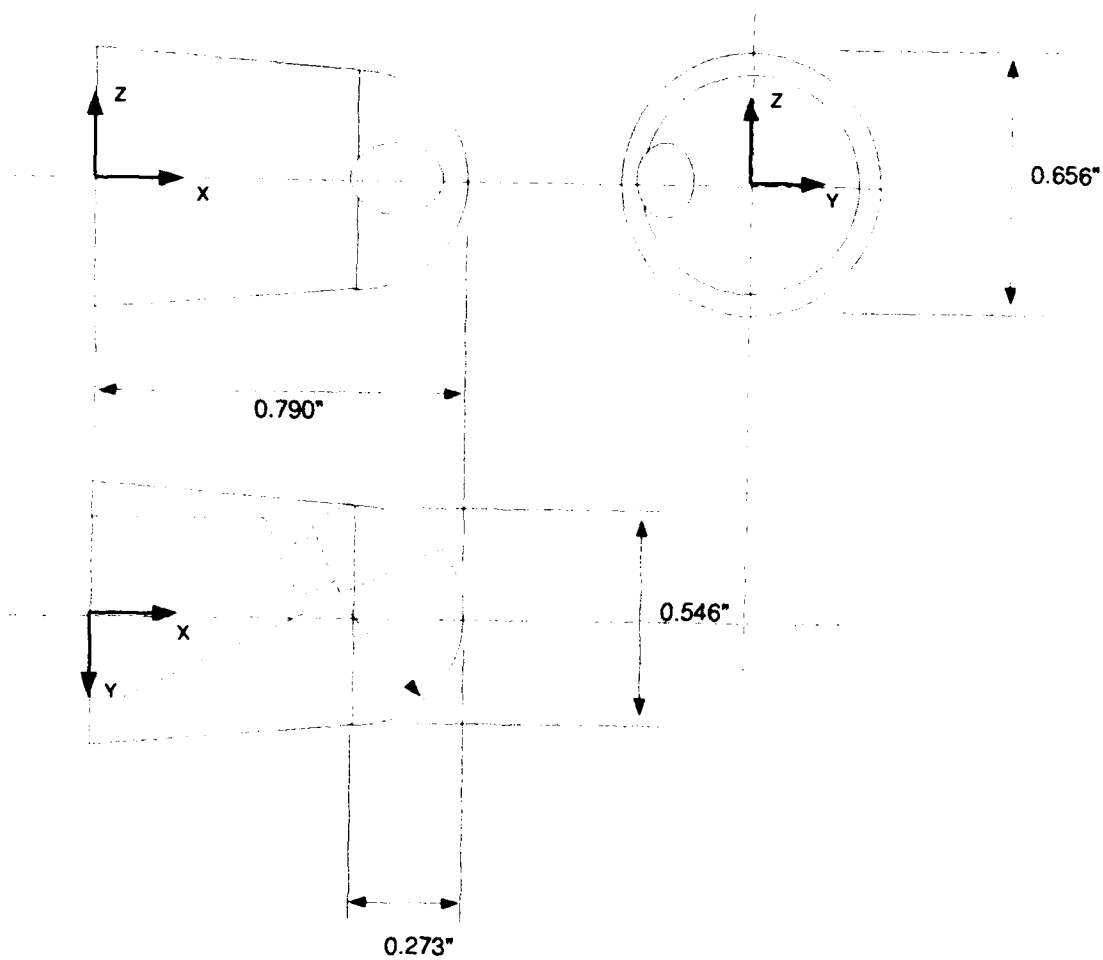
Figure 4.1 Physical Dimensions of the NTS Prototype for the
Utah/MIT Dexterous Hand

hemispheric tip is a hole to allow access to the mounting screw. The interior dimension of the NTS was created by taking a mold of the original fingertip mounts of the Utah/MIT hand. This piece can be described as a cylinder with two planar regions at different angles milled into it, with a threaded hole drilled into it for securing the fingertip.

4.2.2 Electrode Location Determination

The locations for the electrodes on the surface of the sensor were chosen heuristically. Criteria considered in the selection of electrode locations include:

1) A preference to be distributed evenly across the entire active surface area. This criterion simply reflects the preference for the NTS to accurately identify contact location across the entire surface.

2) A preference to have the NTS be most sensitive in the finger "pad" area; the area most sensitive in human fingertips.

3) To limit the number of electrodes to a maximum of eight, in order to allow multiple sensors being read simultaneously by the A/D card. Present hardware constraints in the AFIT robotics lab restrict analog input to 32 channels. Allowing only eight electrodes per sensor would allow a NTS to be installed on all four fingertips of the Utah/MIT

4) A number of geometric variations were constructed. Experimentation confirmed that signals received from electrodes placed near the ground strip were attenuated in the vicinity of this equipotential ground strip. For this reason, the largest expanse between electrodes was located near the ground strip.
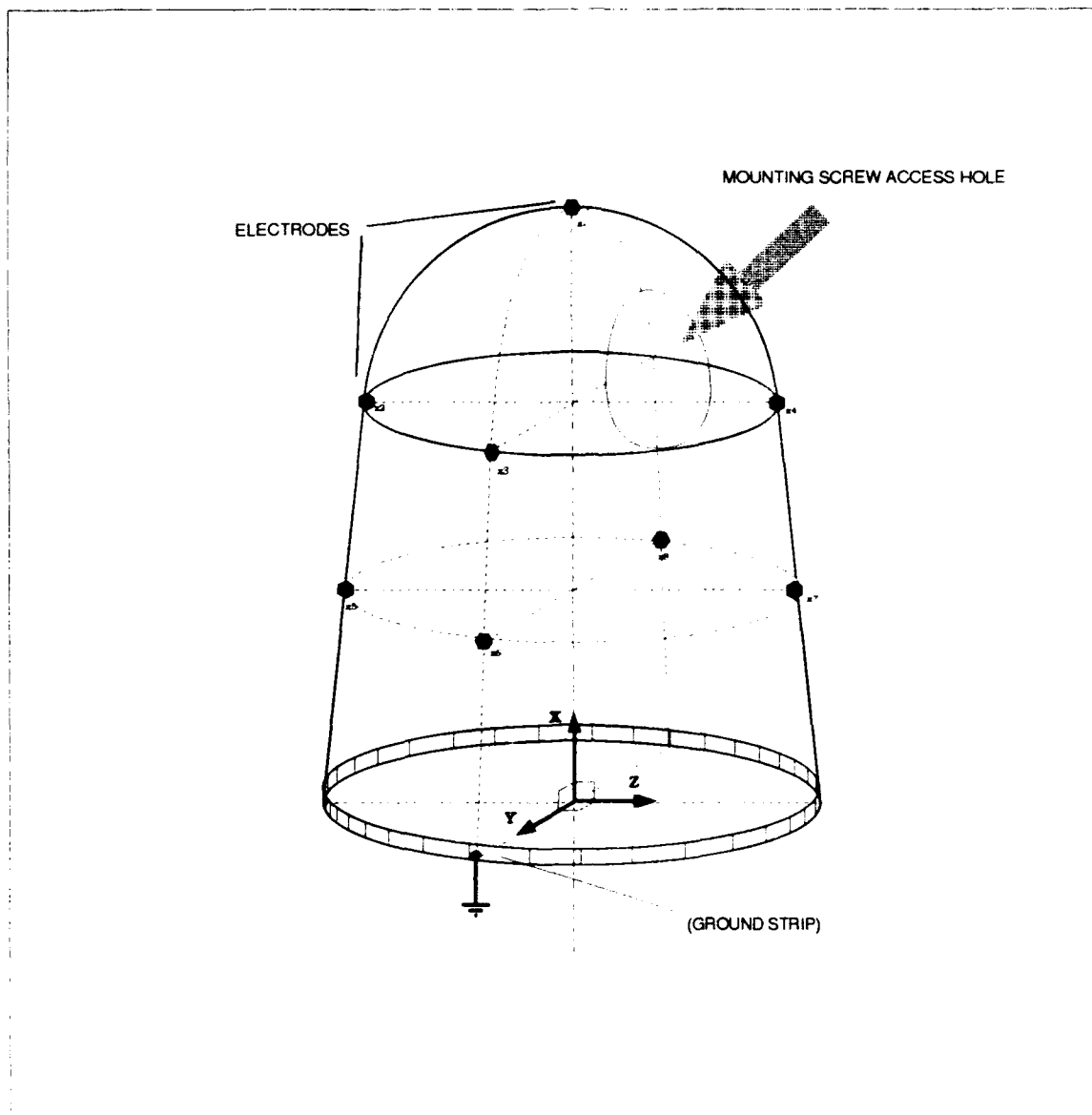
Figure 4.2 Aspect View of the NTS Exhibiting the Electrode and Ground Strip Locations

Using the above criteria, the chosen electrode locations for the Utah/MIT NTS are depicted in Figure 4.2

4.2.3 Sensor Materials

The NTS is very simple in construction. It is physically composed of 1) an elastomer substrate 2) conductive paint skin 3) electrodes and wires 4) metallic tape for a ground strip and 5) assorted connectors and protective hardware.

4.2.4 Substrate Composition

Two materials were procured as candidates for the substrate used to create the desired geometry:

1. DuraThane ™ polyurethane rubber compound

2. Ren-co:Thane™ Series 6402 polyurethane elastomer

The relevant difference between the two substrate candidates is their elasticity/ hardness. DuraThane's rubber is a softer material (Durometer reading: 63) and Ren:Co- Thane is harder (Durometer value: 90). The Durometer number is dimensionless and reperesents the hardness for compliant materials (analogous to the Rockwell Hardness scale for metals). DuraThane was the first substrate used for the NTS prototypes, but its difficulty to work with using injection molding, and susceptibility to irreparabe damage during training and operation prompted the use of the harder substrate, Ren-Co:Thane, for all subsequent sensors after prototype 6.

This switch was made for robustness reasons despite the indications that the softer DuraThane substrate bonded better with the resistive skin and created a more continuous interface, possibly stabilizing the resistive skin and making it more sensitive. For whatever reason, the DuraThane substrate NTSs performed better initially but failed later.

Manufacturing problems were prevalent to both substrate candidates. Improvements

were suggested with the aid of the AFIT model shop. Steps were taken to:

❐ Remove bubbles created in finger injection molding process

❐ Reduce finger warping caused during the curing of the rubber

❐ Increase consistency and hardness of rubber

4.2.5 Conductive Skin Composition

Microcircuits™ "NR2HF" Rubber EMI/RFI Shielding Paint was used for all NTS prototypes. The paint rubber based and impregnated with carbon particles. The carbon settles to the bottom, requiring mixing before use. Because the resistance value for a thoroughly mixed product exhibits too low a resistance, (approx. 5 Ω/ square) injection currents for this mixture become too high. The result is that the contact current "smokes" the coating when a current is injected into it

Heuristic experiments with varying rubber paint/carbon mixtures ratios yielded varying results and leave two desirable attributes fighting each other: consistency and sensitivity. It is optimal (for the data acquisition hardware) to keep the voltage gradient developed over the NTS surface as large a possible, so that discretizing errors in the field measurements are minimized. The Higher voltage also ensures a better (NTS to contacted object) current injection interface. Optimal voltage for the present A/D system is 10 volts DC. Unfortunately, when using paint/carbon mixtures that exploit the benefits of using 10VDC (approx. 6,000- 10,000 Ω/square), paint consistency and uniformity of conductivity diminish. It has been observed that injection currents in excess of 40 mA begin to cause heating in the localized area of current injection. currents over 100mA have caused irreparable damage: the current "smoked" the thin resistive paint skin of 2 NTSs (prototypes 2 & 3).

4.2.6 Electrode Composition

The electrodes of the NTS consist of thin wires terminated with a pad of conductive material to measure the skin field voltage and resist pulling through the substrate caused by stresses induced during mounting to the Utah/ MIT. The 8 electrodes that contact the resistive skin are subject to a number of mutually exclusive criteria. The electrode pads must be large enough to allow good electrical contact with the skin and resist being accidentally pulled through the substrate during installation and use, but small enough in surface area to minimize a loss in sensitivity that accompanies pad's equipotential surfaces "dead-zoning" patches of resistive skin directly above them, and thin enough as to not protrude from the substrate geometry, causing "dimples" that would compromise the kinematic benefits of the NTS's chosen geometry.

Solving the wiring problem was especially tedious, with a satisfactory combination of diameter, flexibility , and strength found after much effort and only through custom fabrication . The wires running through the NTS are subject to several forms of stress, and failures were frequent. A number of NTSs using a variety of available wiring candidates were constructed. Types of electrode wires tested include:

- ☐ Magnet wire (50 Awg. and 42 Awg.)
- ☐ Standard Wire-Wrap wire
- ☐ Commercially available multi-strand lead wire 12 strand (36 Awg.)
- ☐ Custom manufactured 42 Awg 65-strand wire.

The magnet wire was difficult to work with and 2 of the 3 prototypes failed during installation. However, the one that did survive exhibited the best experimentally recorded results before it failed. My hypothesis for this is that this prototype had the smallest electrode surface area embedded in the resistive medium, distorting the E-field the least with its minimal conductive area , maximizing sensitivity.

The Wire -Wrap is the standard single conductor solid wire used for connections when prototyping printed circuit (PC) boaids. This wire was more robust to work with, and no breakage during installation occurred. The problem with this wire was its stiffness. The sensor constructed with this material exhibited electrode pull-through and fatigue failure.

The 36Awg., multi-strand wire was the smallest commercially available. Nevertheless, it was too big for the application and sensors using this wire were too cramped for space, making installation impossible.

Custom manufactured 42 Awg. 65-strand wire was purchased. Only with this exotic wire specification were the simultaneous needs of flexibility, strength, and minimal diameter met. All NTS tests documented in this effort were constructed using this wire.

4.2.7 Ground Strip Composition

Current flowing from the contact location to the ground strip is what generates the desired electric field for detection by the electrodes. The ground strip defines the terminating boundaries for the E-field and sinks all current injected into the resistive medium by the contact. Durability and consistency is as important for the strip as it is for the conductive paint and electrodes. For the Utah/MIT NTS, the ground strip was located around the base of the NTS substrate, created from a thin metallic strip soldered together at the ends to form a continuous ring. This solder point also serves as the connecting point for the ground wire. A variety of conductive rings were explored. Testing included:

Brass shim stock: Although the hardest (therefore probably the most durable) of the materials tested for ground strip suitability, the Brass schim stock (used by mechanics for bushings raw material) was difficult to work with and had to be first fastened to a rig to be soldered into a ring shape. This was impractical due to difficulty in creating the correct the ring size tolerance. Due

to this difficulty, subsequent alternative ground ring candidates were procured in the form of a metallic adhesive tape. Using metallic adhesive tapes allowed the strip to be taped to the NTS substrate prior to soldering ,ensuring perfect size.

Aluminum adhesive tap: The aluminum tape was a great improvement over the shim stock, but soldering to aluminum is very difficult the prolonged application of the soldering iron heat damaged the urethane substrate.

Lead adhesive tape: Lead tape suffered just the opposite problem as the aluminum,: soldering had to be timed just right or the tape itself would melt and fail. Lead tape also is too soft, and was easily damaged.

Copper adhesive tape: copper tape was the last tape acquired, but was worth the wait. Copper bonds excellently with electronic-grade solder. Copper also bonds quickly enough so that the urethane substrate doesn't get overheated. The copper tape was strong enough to resist damage from routine stress, yet ductile enough to "roll with the punches" during high contact pressures that elastically deformed the substrate and ground ring. Copper provides an easily sanded and cleaned ground strip surface that forms a substantial bond interface with the conductive paint.

After evaluating all four ground strip candidates, the copper adhesive tape was chosen as best suited to the NTS requirements of strength, flexibility, solderability, and the ability to form a solid electrical bond to the resistive paint with no delamination.

4.2.8 Miscellaneous NTS Hardware

Because the NTS will be operating on the extremities of the Utah/MIT, finding supposedly simple things like a suitable wiring harness and pin connectors was an arduous task. After much hunting and experimentation, the following solutions were found.

Nylon (anti-pinch) protective sheath - Adapted from a child's toy novelty bracelet. The child's bracelet is a continuous coil of nylon that looks like a thin spring about five inches long. The electrode wires of the NTS are threaded through the middle of this nylon coil to prevent their getting caught and pinched between the finger joints of the Utah/MIT. The sheath's spring-like flexibility also contains the electrode slack that could otherwise get in the way of other fingers during flexing and extending the fingers.

Amp™ Micro connectors , 10-pin male and female quick connectors. This type of very high density connector allows quick-connect capability for 10 wires with a 0.25"× 0.1875" footprint. Conventional connectors would have proven too bulky for a device as small as a human hand.

4.2.9 Added Capability Hardware

Dr. Matthew Kabrisky of AFIT first postulated the NTS's detecting slip. One of the NTS's most potentially useful attributes is its ability to detect the onset of slip. When a contact slip across the NTS surface, a pronounced high-frequency AC component rides on the output electrodes , in addition to the raw position vector signal. Proper high frequency detection circuitry (installed remotely) is able to discriminate onset of slip from the normal contact signal. The high frequency nature of this signal is such that it is best detected with a dedicated analog circuit, rather than an A/D converter with digital signal processing (DSP) capability.

4.3 SOFTWARE:

As mentioned in the introduction of this chapter, the pattern training and recognition algorithms are as integral to the functionality of this device as any of the aforementioned hardware concerns.

4.3.1 Raw Input Vector Processing

For the NTS models created for the Utah/MIT dexterous hand, an 8-dimensional input vector (8 electrodes) design was chosen to: 1). demonstrate the NTS's ability to interpolate contact positions between electrode sites; 2) limiting the NTS to 8 electrodes per sensor allows for future experiments with sensors placed on all 4 fingers of the UTAH/MIT observing the present AFIT Robotics A/D channel capacity of 32 channels. In the present NTS configuration, 8 electrodes leads are patched from the fingertip electrodes through a miniature connector directly to the VME A/D board (no signal conditioning or buffering used). The NTS ground strip is connected to the VME A/D board analog ground (the A/D is configured for single-ended, common-ground referenced operation) and the floating common of a Hewlett-Packard 6236B power supply. The supply voltage is set to just less than +10VDC with respect to common so that the A/D converter selected range of 0-10VDC is utilized to it's fullest extent. These electrode voltages are fed into the A/D board and converted to digital. The A/D presents to the VME bus an 8-dimensional voltage vector that is subsequently read and processed with software routines running on an Ironics IV-3230 Single Board Computer (SBC).

4.3.2 Voltage Vector Processing

Once the eight electrodes of the NTS are read into the computer, the resulting voltage vector from the NTS can , like any other vector, be represented as a magnitude and a direction. Each of these two vector properties has a distinct physical interpretation useful to tactile sensing.

4.3.3 Magnitude Interpretation

Experiments have shown [Ref Figure 5.5] the magnitude of the voltage output vector to be directly (although not linearly) related to the pressure of the applied contact. Vector magnitude is also directly, linearly related to the contact potential selected at the power supply.

Energy normalization is performed on the voltage vector read in from the A/D. The

8-dimensional direction of the voltage vector is a function of the contact location on the sensor. The magnitude of the vector varies with contact voltage and pressure. Because the magnitude of the voltage vector is independent of the contact position, the voltage vector is normalized to unity magnitude for position measurement All contact location sensing and training is done with a normalized vector.

Inspection of the electrode's geometric locations produce insights on how to possibly combine and manipulate the outputs of selected electrodes into "higher order features"; new features created from mathmatical manipulation of one or a combination of "basis" features. One commonly created feature is the aggregate energy of the input vector; the vector magnitude. A proposed NTS higher order features combines NTS electrodes lying in X, Y or Z geometric iso-planes (with respect to the NTS coordinate system). Averaging the electrode outputs along a deliberate geometrical path can desensitize the created feature to input variation along that geometrical path.

For example:

Voltages from electrodes corresponding to positions in an X-Y iso-planes thought the NTS could be summed and averaged to give a high order feature independently much more sensitive to Z than any other individual electrode output. Similarly, electrodes intersecting planes that incorporate the Z axis (perpendicular to the X-Y plane) could be combined in a similar way to maximize sensitivity to X and Y.

4.3.6 NTS Software Interpretation Scheme

Because of the non-linear contact position to voltage pattern relationship inherent to the resistive skin of the NTS, pattern recognition techniques using neural networks for interpolation was a logical choice.

all require "training"

The use of neural network based pattern recognition techniques necessitated the gathering of representative "training" data. This can be considered an extended case of the calibration usually necessary with most sensor technologies.

4.4 NTS Coordinate systems

One interpretation of how trained neural networks operate can be described as a mapping from the network input vector (of dimensionality equal to the number of inputs) to the output vector of a specified dimensionality. In an attempt to maximize the performance of the NTS, three different coordinate systems were created for use as the desired output vector. The four coordinate systems evaluated include:

☐ Pitch and Roll

☐ Normalized and Offset X-Y-Z

☐ NTS Contact Location Vector

☐ Subnormalized and Offset X-Y-Z

4.4.1 Pitch and Roll

The pitch and roll coordinate system was the first and simplest of the position coordinate systems used to train the NTS. Pitch and roll are the two operating degrees of freedom designed into the NTS training rig to control NTS training and testing orientation (Figure 4.3). The problem encountered with using pitch and roll is the discontinuity when the roll angle. θ_1 (measured in degrees or radians) , is simultaneously equal to both 0° and 360° (or 0 and 2π radians). Neural networks have consistently shown difficulty training on data with sharp membership differentiation (i.e. the XOR problem). This angular jump discontinuity also violates

the Lipschitz' criterion , which infers that vectors close (as measured by the dot product of two normalized vectors) in the input space of the network should correspond to vectors close in the output space. The use of pitch and roll as a NTS coordinate system violates the Lipschitz' continuity condition at this point and results in long training sessions and large network output errors at and around $\theta_1 = 0° = 360°$.

4.4.2 Normalized X-Y-Z

To create a training orientation coordinate system better suited to the neural network's recognized preference for Lipschitz constrained training data, the original pitch and roll angles recorded from the training rig were converted into a degenerate Cartesian coordinate system, normalized XYZ, using simple geometric coordinate transformations. Specifically, the θ_1 and θ_2 coordinate system from the NTS training rig:

$$\theta_1 = \text{Pitch Angle (in degrees)}$$

$$\theta_2 = \text{Roll Angle (in degrees)}$$

are converted into a normalized Cartesian system, via the transformation:

$$X = (\ \text{Cos}(\theta_1)\ \text{Cos}(\theta_2)\ )$$

$$Y = (\ 1.0 - (\text{Cos}(\theta_1)\ \text{Sin}(\theta_2))\ )$$

$$Z = (\ 1.0 - (\text{Sin}(\theta_1))\ )$$

These equations transform NTS training rig pitch (θ_1) and roll (θ_2) into continuous and unique X, Y, and Z cartesian vector.

As can be seen in the above three equations involving two variables , removing the jump discontinuity necessitated including an additional degree of freedom. The X, Y, and Z
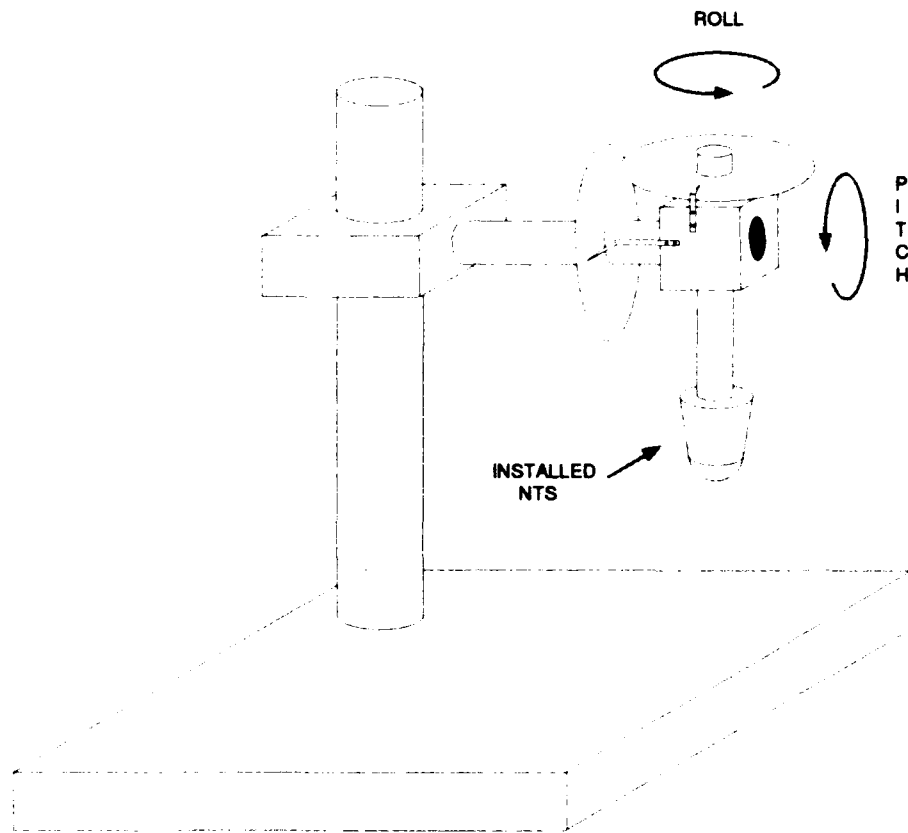
ROLL

PITCH

INSTALLED
NTS

Figure 4.3 NTS Training and Testing Rig

coordinates describe, for a given θ_1 and θ_2, a position on the surface of a sphere of unit radius. This geometry for the coordinate transformation was chosen because the tip of the NTS for the Utah/MIT hand is also a hemisphere. The unity spherical scaling was chosen heuristically in order to fully utilize the magnitude zero to magnitude one output capability of the neural network's sigmoidal output layer.

4.4.3 NTS Location Vector

The next chosen training coordinate system involved scaling and offsetting the previous XYZ system in order to directly map the output of the NTS to it's surface. This involved taking into consideration the NTS' conic segment in the geometry, which creates an offset of 0.790" for the Z term. This effort resulted in the augmented equations:

$$X = (0.273(Cos(\theta_1) \, Cos(\theta_2)))$$
$$Y = (0.273 - 0.273 \, (Cos(\theta_1) \, Sin(\theta_2)))$$
$$Z = 0.790 - 0.273(1.0 - Sin(\theta_1))$$

4.4.4 Subnormalized and Offset X-Y-Z

The last coordinate system was formulated in order to explore the possibility that that the NTS's neural network would be able to detect input patterns grossly deviant to anything encountered in the training data (i.e input patterns resulting from multiple contact location conditions, broken electrodes, ripped skin). The idea is that an additional constraint were to be "subconsciously" placed upon the network output; a constraint that can be independently tested for aberration. The constraint was geometric and already chosen with the choice to go XYZ, but the scaling and offsetting were attenuated to allow the network to "overload" or exceed the trained bounds. This was accomplished by not fully utilizing the full-scale range of the neural network's sigmoidal outputs. By scaling and offsetting the coordinate original transformation to yield:

CALIBRATED MASS

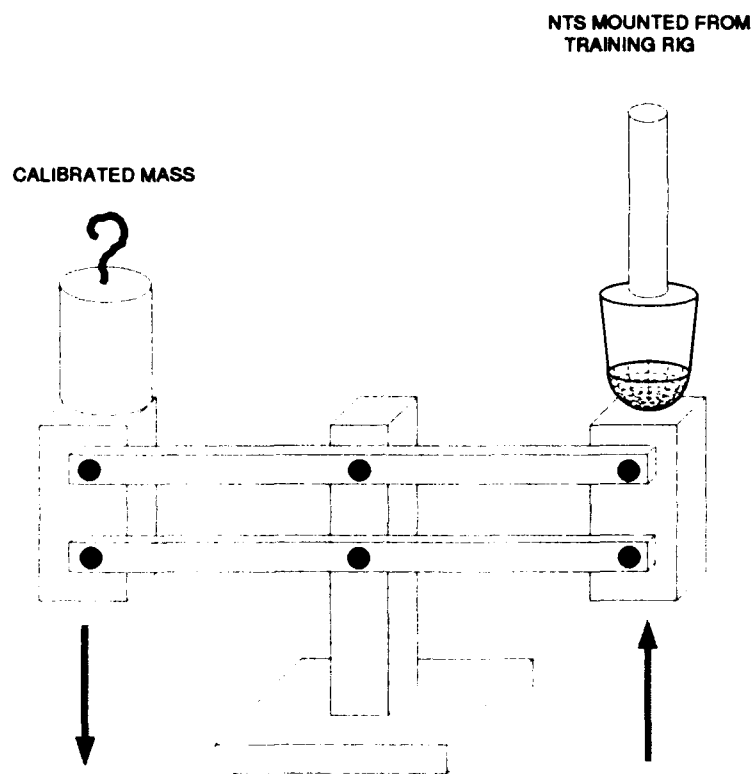**NTS MOUNTED FROM TRAINING RIG**

Figure 4.4 Force Application Scale

$$X = 0.5 - 0.25(\cos(\theta_1) \cos(\theta_2))$$

$$Y = 0.5 + 0.25(\cos(\theta_1) \sin(\theta_2))$$

$$Z = 0.5 - 0.25(1.0 - (\sin(\theta_1)))$$

This has the effect to constraining the full-scale range of the ANN desired output between 0.25 and 0.75. keep in mind that this is a desired subset of the 0.0 to 1.0 value range capable of the ANN's sigmoidal outputs. The idea is that if the net is trained under nominal conditions (only one contact) with the aforementioned scaling in effect, the possibility exists that under previously unseen conditions (multiple contacts) that the ANN output nodes might fall outside of their artificially constrained thresholds and indicate that a non-nominal (fault) condition exists with the E-field pattern. The initial guess is that for multiple contacts, the E-field created on the NTS skin will be contorted. A probable possibility would be that more than one E-field peak would exist for each contact location, creating more electrode magnitude than the net was used to, the previously extablished norm of a single peak electrode would no longer exist, and the network response would generate values outside the artificially imposed training data constraint.

4.5 NTS Training Rig

The NTS Training Rig was constructed to provide a rigid, calibrated platform upon which to collect training data for the NTS sensors and verify trained sensor accuracy. The sensor mount of the platform possesses two rotating degrees of freedom, pitch and roll, upon which rotational scales have been installed to give the rig an orientation resolution of 1° for each degree of freedom (Figure 4.3). The rig is presumed to be sufficiently rigid and has been stressed to 3 Kg. applied to the sensor mount with no detectable bending. In addition to providing full orientational supervision over the sensor, the training rig also provides a base through which to control and monitor the force through which the sensor contacts are made. To facilitate this force calibration capability, a force application scale was designed and constructed (Figure 4.4) to sit upon the base of the training rig. The force scale is constructed as two free-floating platforms

connected through parallelogram arrangement of pivoting cross members to a fulcrum base . The

parallelogram connection constrains the two floating platforms to be orientationally constant. A

desired mass is placed upon one of the platforms and the NTS contacts the other. Like a

playground "see-saw", the weight of the mass on one platform is transferred to the other platform.

When the force scale is used in conjunction with the training rig, they provide an orientationally

fixed, position and force calibrated contact surface to interact with the orientation calibrated,

position fixed sensor mount to provide complete and independent orientation and force control

over contacts applied to the sensors.

4.6 CONCLUSIONS

This chapter has described the design and fabrication of the NTS sensor. The next

chapter details the specific results for constructed, trained, and tested NTS prototypes.

5.1 Introduction

Probably the two most important question to be asked concerning this thesis are: does the NTS work? and if it does, how well? This chapter details the methods employed in training the NTS, the tests designed to verify the functionality of the sensor and gauge its resolution, and the experimental results obtained from testing trained sensors.

5.2 NTS Contact Position Training

The NTS's input/output relationship between contact position and the voltage vector output is highly non-linear. Add the inhomogeneity introduced via resistive skin inconsistencies and electrode placement inaccuracies and this I/O relationship for practical purposes become analytically intractable. For these reasons, training a neural network to learn the complex electrode voltage input - contact location output mapping is an integral part of the NTS concept. With this approach, a major factor of concern is that the NTS's input vector be unique and consistent for a given output.

In the NTS's case, ANN training effort is focused not on distinct classes but a continuum of contact locations. The ANN "collapses" an eight-space voltage vector into a three-space contact location vector. The X, Y, and Z outputs of the NTS neural network are interpreted geometrically as a contact normal vector for the spherical tip of the sensor. Unlike networks utilizing the output nodes in a binary (YES or NO) sense by assigning each output node to a single independent class (tank, jeep, truck, etc.), the NTS's neural network is exercising all the outputs for a given input. The ANN is trained as an analog, continuous interpreter; not a pattern classifier.

5.2.1 Utah/MIT NTS Prototype Training

Training the NTS fingertips for the Utah/MIT Dexterous Hand was accomplished using
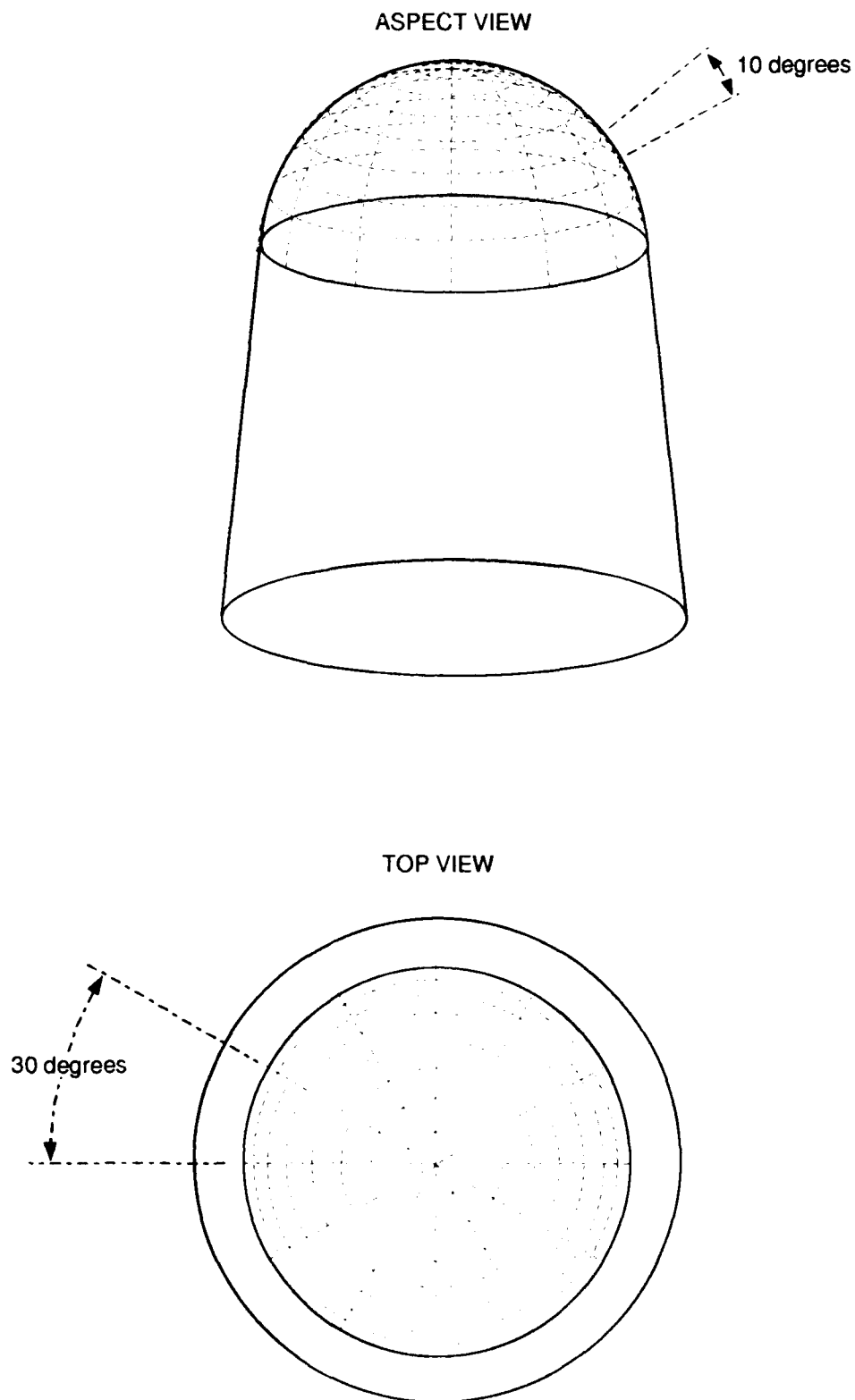
ASPECT VIEW

10 degrees

TOP VIEW

30 degrees

Figure 5.1 Training Map for Spherical Tip of the NTS prototype for the
Utah/MIT Dexterous Hand Showing The 10° Latitude and 30° Longitude spacing
between Training Data Sites. (Dotted -line Intersections represent Training Data Sites)

the training rig (Figure 4.2) and force scale (Figure 4.3) described in chapter IV. The NTS

training rig was constructed by the AFIT mouel shop in order to provide the NTS with a rigid,

calibrated platform from which an orientation ensemble of repeatable position readings of the

sensor could be consistently taken and monitored. Using the training rig's pitch and roll

coordinate scheme, a series of 90 exemplar network training contact locations were assigned

across the spherical tip of the sensor in a longitude/latitude fashion (Figure 5.1). These 90

locations create a grid-like array of points, placed at 30° longitude and 10° latitude intervals

around the hemispherical tip. Data was collected from each of these 90 locations for each of the

sensors trained. To minimize the possibility of not accurately recording an "exemplar" vector for

the 90 locations, training data for each of the 90 locations was collected in three sweeps of

10,000 samples each. Averaging the electrode outputs for three different contacts for each

location allows for variation in contact dynamics resulting from different contact forces. Forces

used for each of the 3 data collection sweeps were 20 grams, 50 grams, and 100 grams. For each

contact, 10,000 samples were averaged together to make each of the three contacts itself an

average of approximately 10 seconds of sampling (the A/D used samples at around 1000 samples

per second). Data resulting from this operation became the exemplar training data, used to train

the ANN portion of the NTS.

ANN training was successful, typical and uneventful. Using Mean Squared Error (MSE)

as a measure of training success, the typical training curve is represented in the graph of Figure

5.2. This training curve exhibited in Figure 5.2 is representative of of the ANN progress despite

randomized vecto introduction and training weights.

MSE error is enumerated in the equation below with p equal to the number of output

nodes, which in the case of the NTS is three.

$$\text{M.S.E. Error} = 0.5\sum\nolimits^{p}_{i=1}(\mathbf{d}_i - y_i)^T(\mathbf{d}_i - y_i)$$
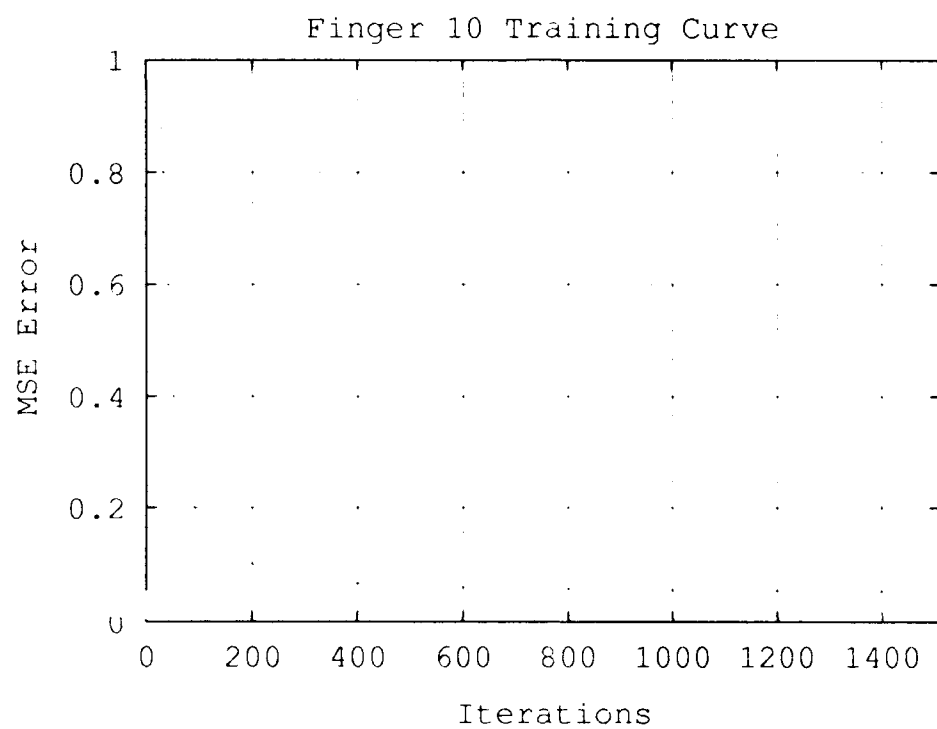
Finger 10 Training Curve

Figure 5.2 Representative ANN Training Curve
8 input nodes
12 hidden nodes
3 output nodes

The training data was applied to a number of variations to the Backpropagation Neural Network algorithm. Variations attempted included:

- ❏ Basic Backpropagation algorithm

- ❏ Backpropagation with a Momentum function

- ❏ Linear and Arc-Tangent output nodes

- ❏ Various numbers of hidden nodes

As a result of many comparisons made between various network's training speed and final accuracy, a heuristically chosen architecture for evaluation was arrived at. The chosen ANN architecture consists of 8 inputs (corresponding to the eight electrode voltages of the NTS), 12 hidden layer nodes, and 3 output nodes (corresponding to the X, Y, and Z dimensions of the contact location vector). The criterion for choosing 12 hidden layers was that this architecture was consistently the first one to finish in a race to train to 0.05 MSE . This architecture was racing against ANNs with 8, 10, 16 and 21 hidden nodes. Linear activation functions were tried without any success: the outputs never converged.

Because of the success of the NTS with the Backpropagation algorithm, additional planned network training using Radial Basis Functions as a network learning scheme were suspended and effort was concentrated on improving sensor construction and quality. This approach was taken because experiments were showing backpropagation to be performing as well as could be expected, given the data fed to it. The inaccuracy of the network in determining the location of contact was traced to an inability of the NTS to give an identical output vector for an identical input location. The problem was the generated electrode pattern vector, not the network interpretation. More rigorous network consideration was unjustified because the present resolution limitations of the NTS have been traced to the inconsistency inherent in the electric field pattern. This conclusion is supported by a test conducted to simultaneously evaluate the network interpretation ability and the consistency of the resistive skin's voltage pattern. The

dot product between the desired and actual output of the NTS was compared with the dot product

between the training data and test data for several *a priori* trained locations. This test can be

considered a utilization of the Lipschitz' condition. Lipschitz' condition is basically a measure of

function continuity [Apostol:122]. Lipschitz is a useful measure to this effort because it can be

used in describing the continuity of the output (the contact location), which is a multivariable

function of the input (the electrode voltage vector). Lipschitz states that for similar inputs, you

should have similar outputs. The test (Figure 5.3) shows how dot product comparisons of both
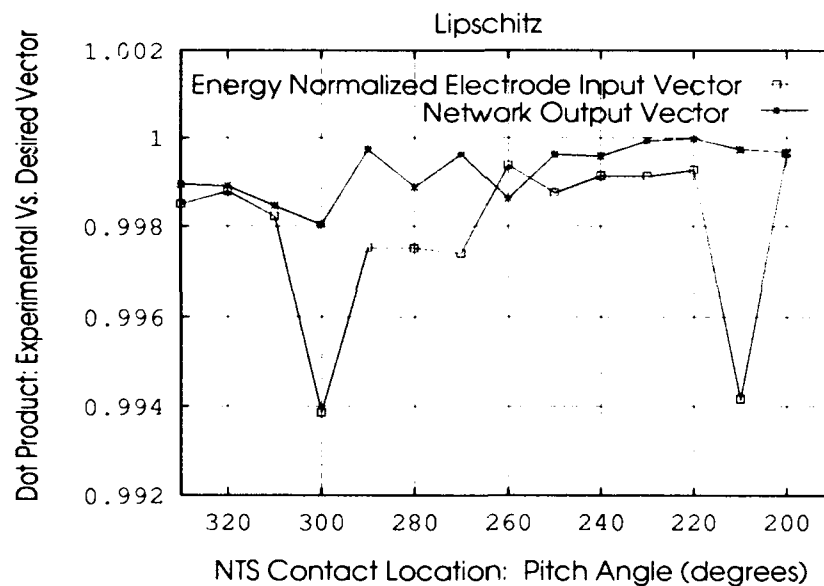

Figure 5.3 Plot showing how the the ANN Output Vector
and the ANN input vector deviate from desired in accord with each other

input and output vectors vary with each other. This test revealed that the problem was not with the network interpretation of the input vectors, but the consistency of the input vectors themselves. Because the output of a neural network can be no more accurate than the input that it receives, improving the consistency of the of the electrode vector is the logical approach to improving NTS resolution.

Contact location is the only NTS feature presently interpreted via artificial neural network training. Force and slip determination are resolved more conventionally with no network training.

5.3 Testing Results

Considerable effort was spent on developing NTS variations before arriving at a sensor that was robust and sensitive. In this thesis effort, a total of 10 NTSs for the Utah/MIT dexterous hand were built. Three of the Ten were never trained because they failed mechanically before or during training data could be fully collected. Three of the seven left failed sometime thereafter. Of the remaining four, fingertip #10 (the latest incarnation) was chosen to be evaluated here . The reason is that it's resistive skin exhibits the most isotropic behavior. (as judged by heuristically inspecting the raw training data). The following section details tests conducted and results obtained from fingertip #10.

5.3.1 Contact location

Determination of contact location was the primary goal of this effort. In determining the efficacy of the NTS in interpreting contact location, repeatability, resolution, and interpolation abilities will be exhibited.

5.3.2 Repeatability

This was the first test conducted when a new NTS was "hooked-up" to the A/D. Repeatability is measured here two different ways, depending on the number of electrode vector

readings taken per contact, single and multiple. Single and multiple contact vector repeatability are measured in first and second order statistics. The running mean, standard deviation, and covariance values are computed for both examples. The single contact statistics were collected from a single contact and 5,000 samples of the electrodes were taken. The multiple contact statistics were collected by establishing a contact, taking a single reading, removing and then re-establishing the contact, taking another reading, and continuing this for 300 contacts. The mean, standard deviation and covariance were computed for the data compiled for each of the two tests.

This repeatability test is only shown for the raw electrode data, since the trained network is a deterministic non-linear function derived directly from this data.

Single Contact Repeatability (single contact; 5,000 reading taken; force varying)

Mean Vector:	0.1177	0.2526	0.4590	0.6593
Std. Dev. Vector:	9.748e-04	1.861e-03	4.247e-03	4.818e-03
Avg. Covariance:	1.443e-05	6.412e-05	2.3902e-04	4.873e-04

Multiple Contact Repeatability (300 readings, 1 reading per contact; force varying)

Mean Vector:	0.1165	0.2451	0.4437	0.6437
Std. Dev. Vector:	5.564e-03	1.177e-02	4.126e-02	4.498e-02
Avg. Covariance:	3.016e-04	1.348e-03	4.993e-03	1.053e-02

The data exhibited here represent electrode voltages chosen to give a variety of magnitude values.

Other than the passing comment that the statistics look tight, a potentially useful characteristic is that the variance in the statistics appear directly related to the magnitude of the respective mean. Assuming these statistics can be described as second order, the fact that the spread magnitudes

are related to the mean values have potential in statistically optimizing the output.

5.3.3 Degenerate Lipschitz Analogy

Because the magnitude normalized voltage vector output is a pattern that is completely dependent on the contact location, it can be argued that one is a function of the other. One can make a case for the continuity of the input/output mapping by showing that for two inputs that are spatially close, the corresponding outputs (which are functions of the inputs) are spatially close as well. This characteristic is of critical importance to the location detecting ability of the NTS because functional continuity is essential to the validity of interpolation and extrapolation of contact locations to extend between and beyond the locations specifically included in the training data of the NTS ANN. To confirm this continuity in the NTS's resistive layer, pattern vectors were correlated to vectors in its vicinity by taking the dot product between the two and plotting this as a function of the spatial distance between the contacts (figure 5.4). This plot confirms the claim that there is continuity between the 8-dimensional input space and the 3-dimensional ANN output space.

5.3.4 Network Resolution

Here defined as a measure of how accurately the network output reflects the contact location and measured as a vector dot product between the actual and desired vectors.

location	ANN Output			dot product with desired
1	0.990108	0.507107	0.476686	0.998610
2	*0.993060*	*0.520881*	*0.504098*	*0.999076*
3	0.994067	0.523224	0.517336	0.999759
4	*0.991755*	*0.547311*	*0.577198*	*0.999453*
5	0.989197	0.563597	0.609841	0.999628

Dot Products between electrode vectors taken from varying pitch angles and an electrode vector taken at an NTS Pitch anle of 270 degrees
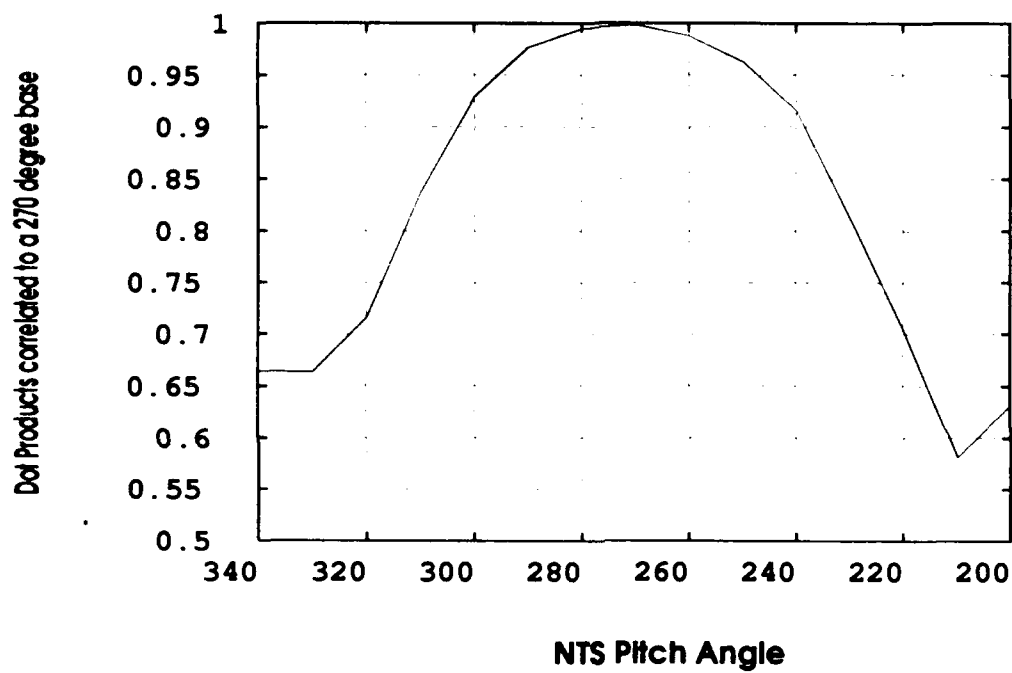
The italicized rows represent network interpretations of contact locations NOT represented in the training data. The even numbered locations lie exactly between the odd numbered locations, 5° from either of its neighbors. The dot products at the ends of the rows shows how close each network output came to its desired, geometrically derived, location. The dot products comparison show that the interpolated contact are comparable in accuracy as the contact locations explicitly trained for. One can also see that the interpolated ANN outputs are in between (in terms of magnitude) their neighbors. This observation shows that the network acts in a consistent manner relative to itself, if not absolutely. This kind of relative continuity is more accurate than the mapping to the trained exemplar locations and this leads to the possibility of using output differences with respect to time that can give an ANN output vector trajectory indicative of the contact location trajectory on the surface of the NTS. Because this data only has to be consistent with the data taken at the last sample instant and not with "exemplar" training vectors recorded long ago, in contains the capability of being much more accurate. This kind of data, a contact derivative vector, has many potential uses in control theory where a continuous tactile derivative has yet to be mentioned in the literature

5.4 Force Detection

Force detection capability has received the least development attention because it is poor. As it now stands, all that can be said about the force/electrode magnitude relationship is that it is direct and non-linear. Attempts to map the relationship to a power law have also been dismal. Figure 5.5 exhibits a representative test measurement. The relationship appears to be related to the contact electrical voltage drop. The higher the force, the more the NTS substrate flattens at the point of contact, the more resistive surface area contacted with the contact, the more efficacious the contact, the more current flows, the more voltage measured at the electrodes, the higher the vector magnitude. This operational mode was arrived at by observing the steeper initial curve exhibited by the earlier NTS prototypes made with the softer, more deformable DuraThane substrate. This relationship is also location dependent and less sensitive at locations that are more obtuse, also supporting the hypothesis.
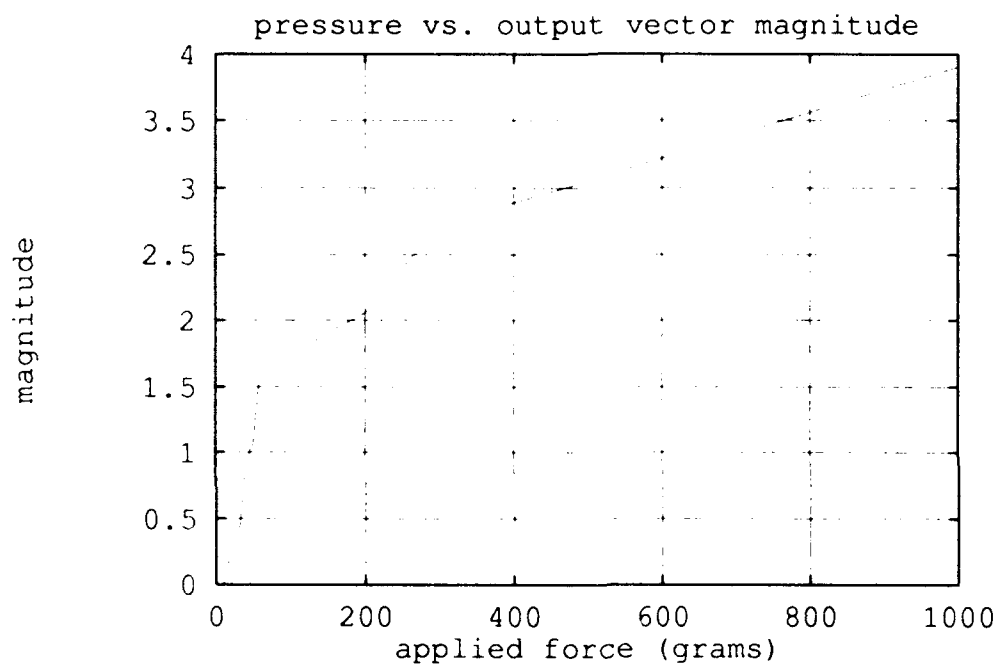
Figure 5.5 Force vs. Vector Magnitude Plot Representative
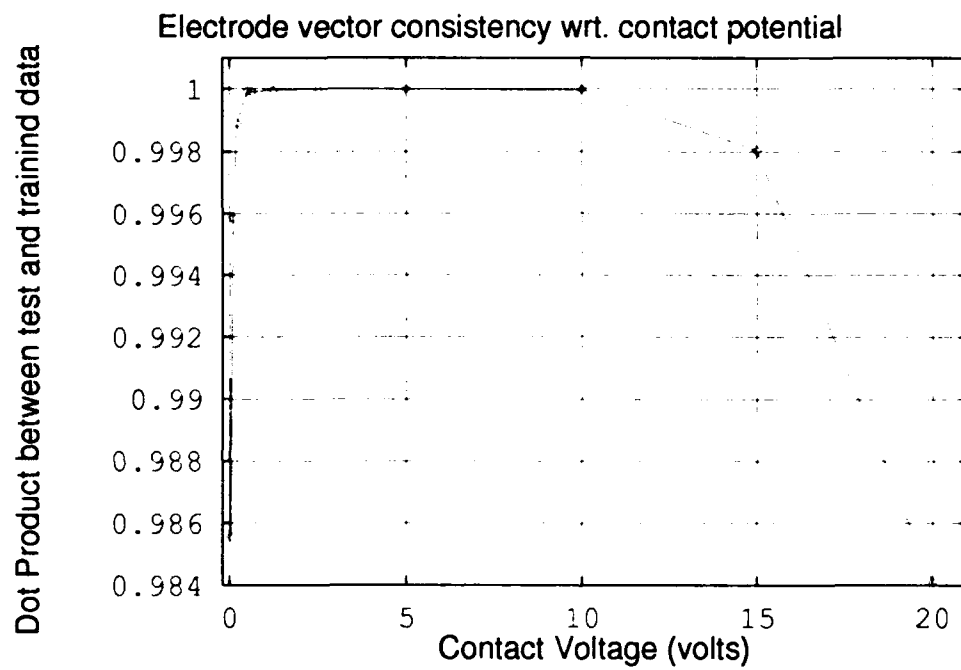of NTS sensors using Ren:co:Thane Substrate

Figure 5.6 Plot consistency of the electrode vector
over the range of the A/D (1-10 volts) by means of the dot product with an exemplar
vector recorded previously.

5.5 NTS Insensitivity to Voltage Variation

Figure 5.6 exhibits a demonstrated insensitivity of the normalized voltage vector to voltage variation for a range between 0.5-10 Volts. The ability of the vector to accurately reflect the contact pattern is diminished at the low voltage (0.04 volts) end by discretizing errors in the A/D and at the high voltage (over 10 Volts) by the A/D inputs being over-driven.

5.6 Slip Detection

Slip detection is accomplished via dedicated analog filtering, quantification, and thresholding. Three observations are made concerning this ability.

- ❏ Slip detection is detected and interpreted as a DC voltage threshold.
- ❏ All I can say is that it works, but can sometimes be set off by contact rolling.
- ❏ The circuit is more sensitive to rough surfaces than smooth ones, but slip so far has always been detectable

5.7 Conclusion

This chapter presented experimental results representative of the typical behavior observed with the NTS. The method for collection training data was outlined. Representative results briefing the location determination accuracy was presented. A Lipschitz-like case for the continuity of the ANN input and output vectors was argued. The relationship between the input magnitude and the force applied was discussed. The interpolative ability of the NTS (which relies on pattern continuity) was demonstrated. Finally The NTS's insensitivity to voltage variation was demonstrated.

VI. Conclusions and Recommendations for Further Research

6.1 Conclusions

The goal of this research effort was to design, fabricate and characterize a tactile sensor concept consisting of electrodes embedded in a resistive skin, artificial neural network circuitry, and slip-detection circuitry. To this effect, a continual loop approach was taken toward development that targets the optimization of NTS robustness, sensitivity, and consistency. This loop consists of four stages: design, fabrication, testing, and evaluation. Through this method, problems arising in the NTS's evolution could be identified early in the testing phase and compensated for in subsequent prototypes.

This thesis effort was successful in designing, fabricating, and characterizing the performance of a novel tactile sensing technology. For the first generation NTS prototype designed created for this thesis effort, three categories define its performance as a tactile sensor. The three categories are location, slip and force detection.

Location Detection: The ability to detect the location of a contact made with the NTS was the first and primary goal of this sensor. It is also the only aspect of the sensor presently employing neural techniques for information interpretation. Contact location resolution exhibited vector accuracies to within 10°; this translates radially across the surface as 0.05 inches of the desired location. This resolution is better than any other sensing technology to date.

Slip Detection: In the strictest sense, detection of slip is a binary piece of tactile information; the object is slipping or it is not. Dedicated NTS circuitry has exhibited the ability to detect the onset and steady-state slip phenomena and has done this for a wide range of surface textures ranging from milled titanium to aluminum foil. In

addition, the characteristics of the signal used in detecting slip contain frequency information found to be related to the texture of the contacted object and the rate with which the contact is sliding.

Force-Pressure Detection: Nothing inherent in the design of the NTS was ever focused upon toward the detection of force or pressure. Nevertheless, a direct relationship between the NTS output and the force/pressure applied has been identified. Study of this phenomena revealed the relationship to be non-linear and dependent on the curvature of both the contact and sensor surfaces. For this thesis effort, the relationship has been reported as existing and not much else.

6.2 Recommendations

As can probably be said with any first generation prototypes, there are many promising variations and extensions of the original technological theme that are still unexplored. Although this thesis effort successfully designed, realized, and characterized a novel form of tactile sensor, there are still advances, variations, and changes which should be pursued to facilitate higher NTS performance and a wider range of potential uses.

Recommendations for further development fall into two general categories: 1) those aimed at improving the present performance of the NTS, and 2) those focused upon expanding the envelope of the sensors present capabilities.

Performance Enhancement:

1. Increased Contact Resolution: A number of modifications to the existing NTS design would facilitate even better contact position determination. Although the NTS presently provides unprecedented contact resolution, attempts to increase resolution even further can be justified in view of its potential uses as a continuous contact normal vector indicator. Information of this This signal would play an

integral role in object shape recognition and grasp optimization. Two immediate steps that could be taken are:

1) The use of a larger spherical diameter on fingertip for increased surface area. Because the NTS neural output is contact location, the use of a larger spherical surface on the NTS fingertip would have a direct effect on the quality of the contact location to contact normal vector geometric transformation.

2) The use of more electrodes for greater resolution. Earlier tests with partially damaged NTS prototypes (broken electrodes) were trainable, but the resolution was diminished. Therefore, it is reasonable to expect that increasing the number of electrodes will accordingly increase the resolution for a given sensor geometry.

Capability Expansion: The first generation NTS has one serious limitation, its dependency on the contacted object to also supply the charge for the sensor to operate. A second generation NTS has been proposed (Chapter III) that eliminates this dependency, but no prototypes have yet been constructed. Another potential windfall of the 2nd generation NTS would be the ability to build an intrinsic force sensing capability with a transduction method potentially more tractable than what is presently observed.

If the NTS sensor has an Achilles heel, it is undoubtedly in i   present inability to resolve multi-contact conditions. This effort has centered on a neural solution to this problem, simultaneously training subliminal constraints on the output, but has been unsuccessful. An analytic approach has been proposed in chapter III but has yet to be tested.

Force or Pressure Sensing: Little access was obtained in this area and the ANN approaches were complete failures. Resolving force with the NTS is an area requiring further investigation.

These recommendations provide a path for improvement in the present NTS system, with the goal of providing a multifunctional, multi-application tactile sensor.

A the sensor presently stands, the completion of the objectives for this thesis represent a significant contribution to AFIT's dexterous object manipulation and gross motion control studies. The newly acquired tactile sensing capabilities enable continuing dexterity and semi-autonomous manipulation studies on the Utah/MIT hand at AFIT. The performance characteristics of the NTS will also serve as a base-line in evaluating the BONNEVILLE tactile sensor presently being developed commercially through contract with AAMRL/BBA.

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Vita

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REPORT DOCUMENTATION PAGE

4. TITLE AND SUBTITLE

An Artificial Neural Network based Tactile Sensor:
The Neural Tactile Sensor (NTS)

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11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

The Neural Tactile Sensor (NTS) is a high resolution, easily manufactured tactile sensor consisting of electrodes, a resistive medium, and pattern recognition circuitry that is capable of resolving static and dynamic contact location, force and slip throughout the continuum of the sensor's active region. The sensor operates by means of a resistive medium harboring the electric field generated whin current is injected into it, and a plurality of electrodes for taking measurements. The outputs of these electrodes are used as input to appropriate pattern recognition circuitry, such as the multi-layer perceptron artificial neural network.

14. SUBJECT TERMS

ARTIFICIAL NEURAL NETWORKS, ROBOTICS, TACTILE SENSING, SLIP DETECTION,SENSORS

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17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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