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Filip Fuma
University of Pennsylvania

John Bradley
University of Pennsylvania

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A Procedure for Characterizing Tactile Sensors

Abstract

We describe a methodology for the characterization of tactile sensors. We address the questions of verification of manufacturer's claims about the output of a sensor, reliability of the output and robustness of the sensor over time.

In our work with tactile sensors, it has become apparent that there is a need for a rigorous methodology of characterizing sensor quality.

We implement this as a procedure which is specific for the Lord LTS-200 sensor [ref 1] With some modifications, this methodology could be applied to other tactile sensors.

Comments

University of Pennsylvania Department of Computer and Information Science Technical Report No. MS-CIS-88-102.

A PROCEDURE FOR CHARACTERIZING TACTILE SENSORS

*Filip Fuma and
John Bradley*

**MS-CIS-88-102
GRASP LAB 171**

**Department of Computer and Information Science
School of Engineering and Applied Science
University of Pennsylvania
Philadelphia, PA 19104**

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Introduction

We describe a methodology for the characterization of tactile sensors. We address the questions of verification of manufacturer's claims about the output of a sensor, reliability of the output and robustness of the sensor over time.

In our work with tactile sensors, it has become apparent that there is a need for a rigorous methodology of characterizing sensor quality.

We implement this as a procedure which is specific for the Lord LTS-200 sensor [ref 1]. With some modifications, this methodology could be applied to other tactile sensors.

The Sensor

The LTS-200 actually consists of two sensors: (see [ref 1, fig 1-1] for dimensions)

- a 10 x 16 tactile array, which measures displacement (or deflection) via optical technology. [ref 6]
a 6 degree of freedom force/torque module using strain gauge technology. The force/torque module is mounted under the tactile array. This is not an array, its output is scalar.

The interface and signal processing circuitry is located in an external box.

The Hardware

A special testing fixture has been fabricated. (see Fig. 1B) The fixture consists of a press mechanism for applying force, a precision strain-gauge-based load cell for measuring the forces applied [ref 2], and a dial indicator for measuring the deformation of the sensor under load. The press mechanism was previously part of a mechanical comparator. It is very rigid and can be adjusted very precisely. The load cell is threaded to allow for different end effectors. We used two different end effectors. (see Fig. 3) The round flat effector was used for the activation of multiple sites. Its face has been machined to be flat within 0.0001", and it is parallel to the reference surface within 0.001". Its dimensions were chosen based on the dimensions of the LTS-200. The point effector can be used for the activation of individual sites. (It was only used in experiment 9.)

The load cell, model SM-25-8, is connected to a model 8320-13 interface and digital readout. These are both manufactured by Interface Inc. The load cell and its readout can display force in increments of 0.005 lbs, up to 25 lbs. The dial indicator is a model 25-231J, and is manufactured by the L.S. Starrett Co. This dial indicator has a range of .125" with an accuracy of .0005". A typical scenario for employing this fixture consists of turning the fine height adjustment and recording the deformation from the dial indicator, the force applied from the load cell readout, and the sensor response from the sensor interface program.

This fixture measures the tactile array and the negative z-axis force. For measurement of other moments and forces, the fixture would require additional enhancements.

Prior to the experiment, both the tactile sensor and load cell/readout must be allowed to warmup for one hour. Before data is taken, the load cell readout is zeroed, the tactile sensor is reset, and the dial indicator is adjusted to read 0.0" when the end effector touches the surface of the sensor. The end effector should be in contact with the surface of the sensor, but lightly enough as to not register on the readout.

The Software

It became evident that graphic display software was necessary for understanding and proper characterization of the sensors. We developed a program [ref 3] that performs the following functions:

1. Visualize the tactile output of the sensor array as a grey scale, with choice of color mapping. We feel that a grey scale is more useful than a three dimensional contour map, since the dynamic range of the sensor is quite limited. Forces and moments are displayed numerically, and a subset of them are displayed as a pitch-yaw graph.
2. Record the tactile data for further computer processing.
3. Display pre-recorded sensor data.

This program, TCR, runs on an IBM PS/2 with a color VGA display and mouse. The data is stored in a binary format that can be transferred for further processing on Unix machines via ftp or kermit. (see Figs. 2 and 5)

The Experiments

The sensor and interface were allowed a 45 minute warm-up period to avoid thermal drift in the interface electronics. The sensor was zeroed between data-taking runs.

These experiments measure the tactile array response and the negative z-axis force.

Experiment 1: Displacement Response of Tactile Array

The object of this experiment is to measure the response of the tactile sites to a given deformation. This test is specifically tailored for the LTS-200, as its tactile section measures displacement rather than pressure.

The sensor touch surface is divided into nine areas to account for boundary and interior effects. (see Fig. 4) We used the round flat effector to simultaneously depress tactile sites in one of the nine areas. We do this, since it is not possible to see from the outside of the sensor where an individual tactile site is centered. It also speeds up the data gathering process.

For each of the nine areas, we performed the following: for displacements of 0 to 30

mils, in steps of 2 mils, read the tactile array.

For each area, we have graphed the mean, mean+sigma, and mean-sigma of the excited tactile array sites. Only interior sites were used, to avoid boundary effects. Refer to **Figs. 5-13**. **Fig. 14** shows a composite of all 9 areas. **Figs. 15-24** show the means versus displacement with minimum and maximum values.

Comments:

The sensor under test has seen a fair, though not excessive amount of use. When it left the factory it was calibrated to be quite linear. Experiment 1 clearly shows the degradation of this calibration with wear.

Frequent checks of calibration are necessary to assure accurate tactile data. The exact interval remains to be determined.

An alternative is to take the 'raw' data from the sensor, and use look-up tables to linearize and calibrate the response of the sensor. The necessary data can be obtained using our fixture. There would, however, be an additional computation overhead.

A better approach would be for the manufacturer should add circuitry that permits recalibration of the tactile array in the field. Currently, the LTS-200 can be calibrated only at the factory.

Experiment 2: Repeatability of the Tactile Array

This was performed for areas 1, 4, and 5, as they represent interior, edge, and corner areas, to account for different boundary effects. The tactile array was excited with an even, fixed displacement, and its response recorded. This was done ten times at each of the three sites. Between measurements, the end effector was disengaged from the sensor surface. The results can be seen in **Figs. 25-27**. The values measured were repeatable within 97%.

Experiment 3: Noise of the Tactile Array

This was performed for areas 1, 4, and 5, as they represent interior, edge, and corner areas, to account for different boundary effects. The tactile array has been excited with a displacement of 15 mils, and its response recorded. This is done ten times at each of the three sites. Between measurements, the end effector remains fixed on the sensor surface. Each measurement is made 10 seconds apart. The data is shown in **Figs. 28-30**.

Experiment 4: Z-Force Response

Force was applied in increments of 1 lb, from 0 to 20 lbs. Moments around the X and Y axes were kept at a minimum, and the tactile array was facing down. The elastomeric covering of the array was allowed to settle for 60 seconds. The applied force was recorded from the load cell readout, and the sensor z-force was also recorded. **Fig. 31** shows the response to be quite linear, which is to be expected from a strain gauge instrument.

Experiment 5: Z-Force Noise

A force of approximately 10 lbs was applied to the sensor was in the previous experiment, and the sensor z-force output was measured. The effector remained fixed on the sensor between measurements. We allowed 10 minutes for the elastomeric cover to settle, so that the force applied remains constant. This was verified by monitoring the output of the load cell. The Z-axis force measured by the sensor was recorded. The measurements were made in intervals of ten seconds. (see Fig. 32)

Experiment 6: Contact Threshold Pressure

We determined the minimum force in the z-axis necessary to produce a reading of at least '2' on 90% of all the interior sites at area 1, and then repeated the experiment at area 4 and area 5. (see Fig. 33)

Experiment 7: Tactile Sensor Max Load Pressure

We determined the minimum force necessary to produce a reading of '30' (which is the maximum readable value) on at least 90% of all the interior sites at area 4, and repeated the experiment on area 1 and area 5. During measurement, forces were measured at time of contact. (see Fig. 34)

Comments:

The data suggests that the touch surface is 'stiffer' at the edges than in the interior, which suggests a non-uniform elastic modulus.

Informally, the elastomer touch surface is analogous to a mesh of coupled springs, like a mattress. Similarly, a mattress is harder at the edges, due to wear and side bracing.

Nevertheless, a network of springs may be adequate to model the crosstalk effects.

Experiment 8: Tactile Array Spatial Resolution Measurement with Grating Gauge

Using calibrated gratings provided by Dr. Susan Lederman (Queen's College, Canada), the minimum grating spacing for a "clearly discernable image" on the TCR display was found to be 1/8th inch. This was based on a 'judgement call' by a human observer, which makes the determination somewhat subjective. (see "Improving the Experiment") Fig. 35 shows a profile of the texture used.

Experiment 9: Crosstalk Between Tactile Array Sites

Using the point effector, we applied several amounts of displacement on a single tactile site. As the position of the site cannot be seen from the outside of the sensor, the end effector was positioned so that the crosstalk pattern was symmetric around the site. We recorded the readings from the neighboring sites. Crosstalk shows up mainly in 4-connected neighbors. Crosstalk along the diagonal is negligible. The results can be seen in Fig. 36.

Comments:

Elastomers are commonly used as the material for the touch surface of tactile sensors. This is desirable as it provides some compliance between the transduction

medium, which is generally rigid, and the objects being explored. It also provides good necessary friction for a positive grip when tactile sensors are on the finger tips of robotic hands. [ref 7]

However, this elastomeric covering will impact the tactile measurement. The elastomeric touch surface acts as a spatial low-pass filter, reducing spatial resolution. There may be a positive side to this, as this effect may be thought of as providing needed anti-alias filtering. (The tactile array is a spatial sampler.)

The elastomeric covering introduces a certain amount of site-to-site coupling (or cross-talk). A small amount of crosstalk is desirable to account for details that fall between sites.

The amount of low-pass filtering (i.e. loss of spatial high frequencies) and crosstalk increase with the thickness of the elastomeric touch surface.

The transduction medium is generally rigid, and the elastomeric touch surface provides needed compliance. The elastomer deforms to conform to the details of the surface explored. For a given elastomer the grey scale dynamic range (i.e. the dynamic range of an individual tactile site) increases with the ability of the touch surface to deform. The thicker the elastomer, the larger the grey-scale dynamic range (for given material).

Thus a trade-off emerges between the spatial bandwidth and grey scale dynamic range, due to the thickness of the elastomeric touch surface.

Experiment 10: Viscoelastic Behavior of the Elastomeric Cover

A force of 10 lbs was applied to the sensor cover using the flat effector. The force from the readout of the load cell was recorded at several intervals. The spring constant of the rubber changes under compression with time. However, force measurements change no more than ~10% due to this property. (see Fig. 37)

Comments:

Elastomers are viscoelastic materials. Their elastic modulus increase with strain. More importantly, elastomers exhibit a phenomenon called 'stress relaxation':

<p>Given that:</p> $E = \frac{\sigma}{\epsilon} \quad \text{and} \quad \sigma(t) = \sigma_0 e^{-t/\lambda}$	<p>where E is elastic modulus σ is stress ϵ is strain</p>
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Note that:

$$\frac{\sigma(t)}{\sigma_0} = 1/e \quad \text{and} \quad \lambda = -t / \ln \frac{\sigma(t)}{\sigma_0}$$

- $\sigma(t)$ - stress as a function of time
- σ_0 - stress at initial time t_0
- λ - relaxation time
- $\frac{\sigma(t)}{\sigma_0}$ - the stress ratio

[ref 4]

It means that the material 'gives' with time. Under given strain (deformation) the stress (and hence elastic modulus) changes (decreases) with time according to an exponential law. The process is reversible if the deformation is not excessive, and the material will recover its original stiffness. **Fig. 37** clearly shows this exponential behavior with time.

This phenomenon is referred to as hysteresis, as if the elastomer has 'memory' and it 'remembers' what was done to it recently.

A similar phenomenon can be seen in biological systems. Compare **Fig. 37** with [ref 5, fig 4A].

For the LTS-200, this change does not exceed 10%. In this case it would be possible to determine, subject to this inaccuracy, the pressure at each site from the deformation there (after some suitable calibration step).

Since the LTS-200 measures the total normal force via strain gauges, the tactile array information may suggest how normal forces are distributed along the touch surface ('load-deflection characteristic').

Experiment 11: Thermal Drift of Sensor

The output of the sensor's force/torque section has been monitored over a period of 1 3/4 hours. There was no excitation upon the sensor throughout this period. **Fig. 38** shows the results. Forces are expressed in increments of 0.01 lbs and moments are expressed in increments of 0.01 inch-lbs.

Improving the Testing Procedures

The following improvements of the sensor characterization experiment have been suggested.

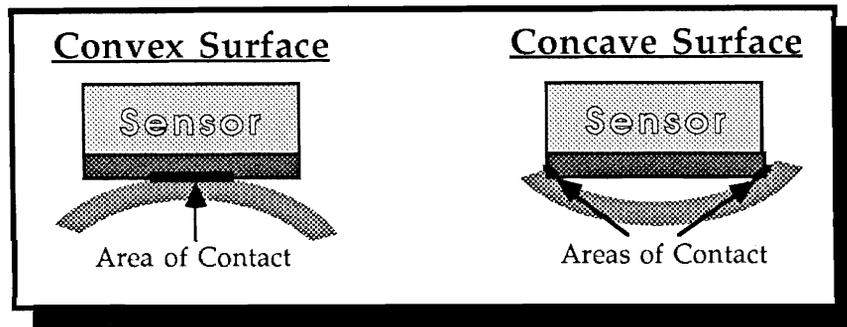
1. Currently the fixture provides the capability to apply a calibrated amount of deflection. But this is not sufficient for certain measurements e.g. 'Z-force repeatability'. The fixture should be modified to allow the application of known amounts of force to the sensor.
2. Experiment 8 includes a human in the measurement, making it somewhat subjective. A more rigorous approach would involve examining the sensor's response to the grating in the (spatial) frequency domain, via FFTs. A minimum threshold would then be set for the frequency component corresponding to the (spatial) period of the grating.

What is Optimal Sensor Size

Assume a sensor with a flat transduction surface, (and hence a flat touch surface).

The size and relative position of flat objects can be determined when these objects are small as compared with contact area of the sensor. The coordinates of the sensor are known from the positioning mechanism employed (i.e. robot, gripper, etc.).

With a flat touch surface, problems arise when the curvature of surface under exploration is significant in relation to the size of the sensor. A convex surface will contact only a few sites. A concave surface will only contact the edges of the sensor. The size of the sensor constrains the curvature of the surface being explored.



The sensor can be made smaller, but this is undesirable as it decreases the throughput of the measurement: fewer sites are read in parallel for a given density of tactile sites and additional sensor movement is required.

When the sensor is curved these problems vanish, but the contact area is smaller, requiring more manipulation of the sensor to explore the same area as a flat sensor. Curved sensors use a rolling exploratory motion, while flat sensors use a 'press-down then lift' motion.

Suggestions

What is desirable is a non-rigid transduction surface, but this does not seem feasible at this time. A possible compromise could be a sensor consisting of several small flat touch surfaces which are hinged together. A mechanism to detect the angles of the 'hinges' would allow the measurement of gross features like overall curvature. We may think (informally) of such a sensor as having two level of compliance: a 'gross compliance' due to its hinged nature and a 'fine compliance' due to the elastomeric covering. The 'gross compliance' increases the dynamic range of the measurement.

It should be noted that the transduction media of the human finger is non-rigid. In fact we may think of finger tips as parts of a larger composite sensor, like the hinged sensor. Positioning of the finger tips also allows change of the overall area of contact.

Sensor AC Response

The version of the LTS-200 we have can scan, process and transmit the entire tactile array data 5 times per second. This suggests that tactile phenomena with temporal rates of change up to 2.5 Hz (Nyquist frequency) can be detected. The sensor will thus exhibit a 'temporal or AC frequency response'. This should not be confused with its spatial frequency response.

We have not measured the AC frequency response of the sensor.

Surface Texture

One way people determine the roughness of a surface is by dragging a finger along its surface. This is dynamic measurement, it produces a definite AC response. In

contrast, most of the measurements we performed on the LTS-200 were on a static or DC nature.

The LTS-200 cannot be employed in a similar fashion because its tactile array is not sensitive enough to read at pressures which are low enough to permit dragging of the sensor along a surface. Its elastomeric covering has a non-negligible friction coefficient and enough pressure for a reading will very likely cause binding and even shear damage.

The elastomer can have its coefficient of friction reduced by applying a slippery coating, such as PTFE (teflon) tape. However, it will no longer be possible to positively grip objects with the sensor.

At this time the most convenient approach is to construct a separate sensor, specifically tailored for AC measurements. It does not need to be an array. If it is small enough it may be possible to embed it into the touch surface of the tactile array sensor. An AC tactile sensor requires a higher sampling rate and different signal processing.

Therefore the LTS-200 acts essentially as a DC sensor.

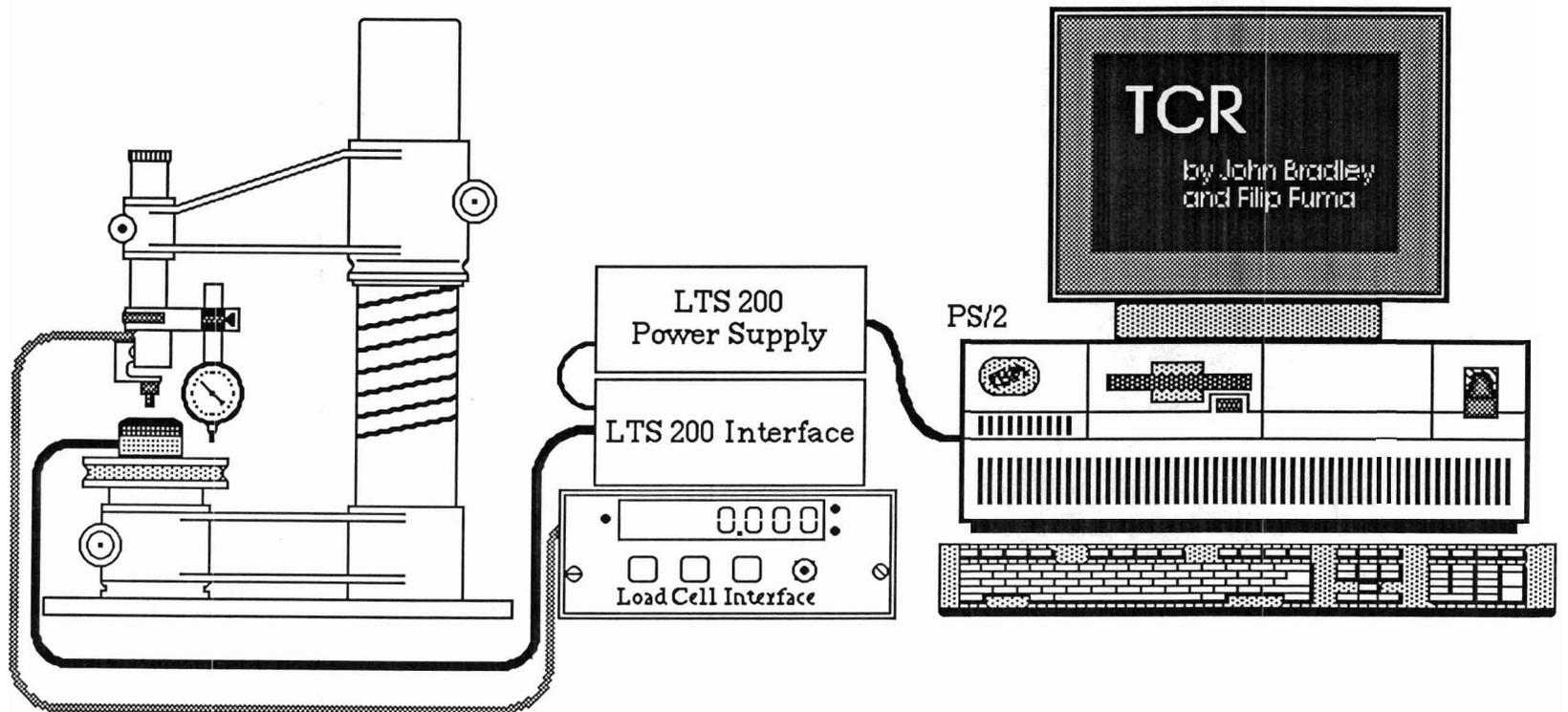
Open Problems

The LTS-200 tactile array measures deflection (displacement) directly via optical means. It does this over a range of 0.030". We can think of its output as 3D range data. Surface textures can be (within limits) imaged by the tactile array. While it would be possible to convert the range data from the tactile array into contact pressure data, this information can be readily obtained for the force/torque module. In the LTS-200 the elastomer cover is only the touch surface, as the transduction medium is underneath.

Another popular technology is the pressure sensitive tactile array using piezo-electric, piezo-resistive materials and conductive elastomers. In the case of the conductive elastomer sensor, the touch surface and the transduction medium are the same. One question about this type of sensor is: given the result of experiment 7 (Sensor Max Load Pressure) and more generally the viscoelastic nature of elastomers, can the pressure data of the array be reliably converted into range data?

References:

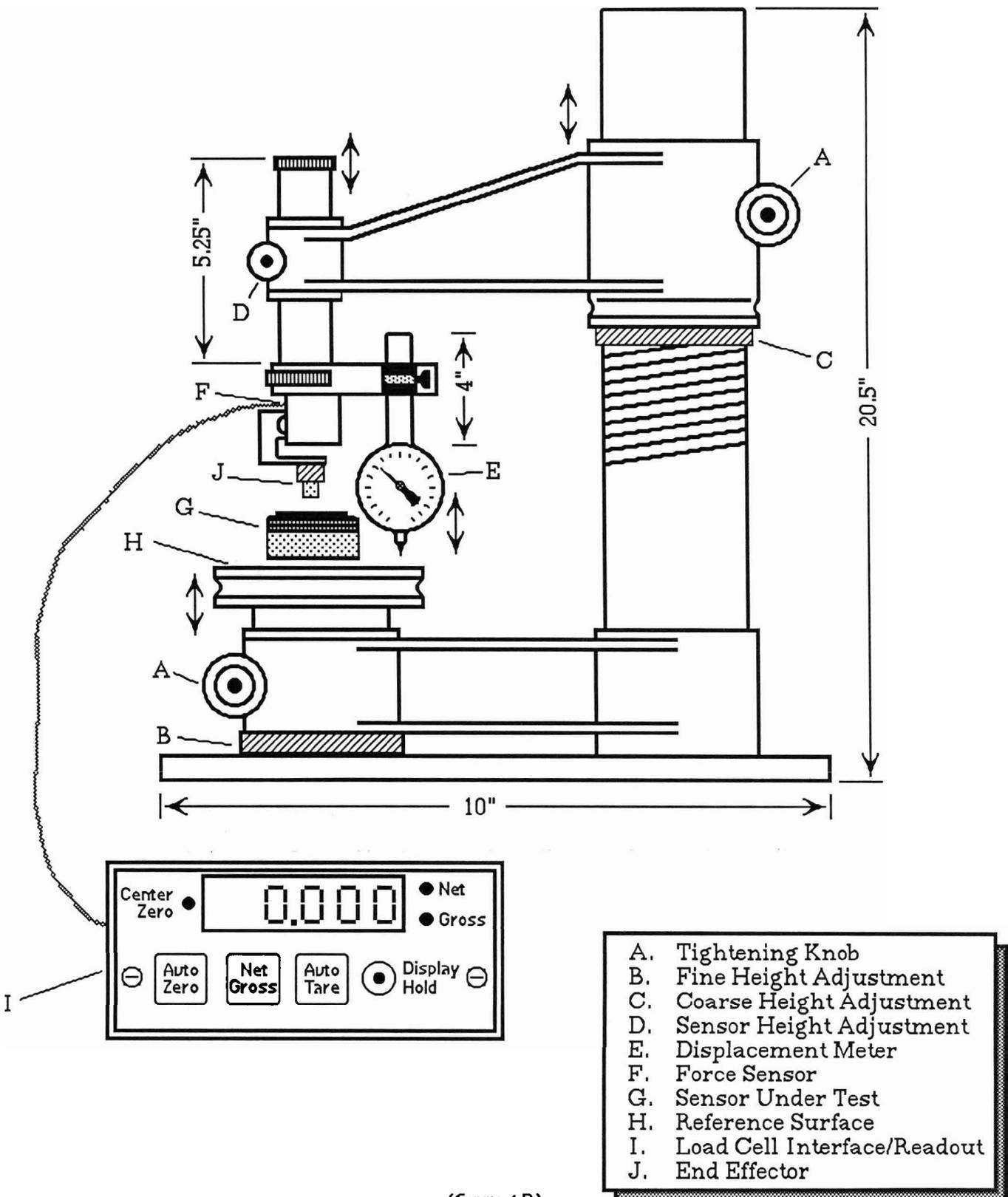
- [1] "Installation and Operations Manual for the LTS-200 Sensor," LORD Corporation; Cary, North Carolina; (1985)
- [2] "Model 8320 Digital Weight Indicator - Installation, Calibration, and Operations Manual," Interface Inc.; Scottsdale, Arizona; (1986)
- [3] Bradley, John and Fuma, Filip, "TCR Documentation," University of Pennsylvania; Philadelphia, Pennsylvania; (1988) (see Appendix A)
- [4] Van Vlack, Lawrence H., "Elements of Material Science and Engineering," 3rd ed., Addison-Wesley, (1977) pp. 235-240
- [5] Petit, Julien and Galifret, Yves, "Sensory Coupling Function and the Mechanical Properties of the Skin"
- [6] Rebman, J. and Trull, M. W., "A Robust Tactile Sensor for Robot Applications," LORD Corporation; Cary, North Carolina; (1983)
- [7] Rebman, J, "Compliance: The Forgiving Factor," LORD Corporation; Cary, North Carolina; (1979)



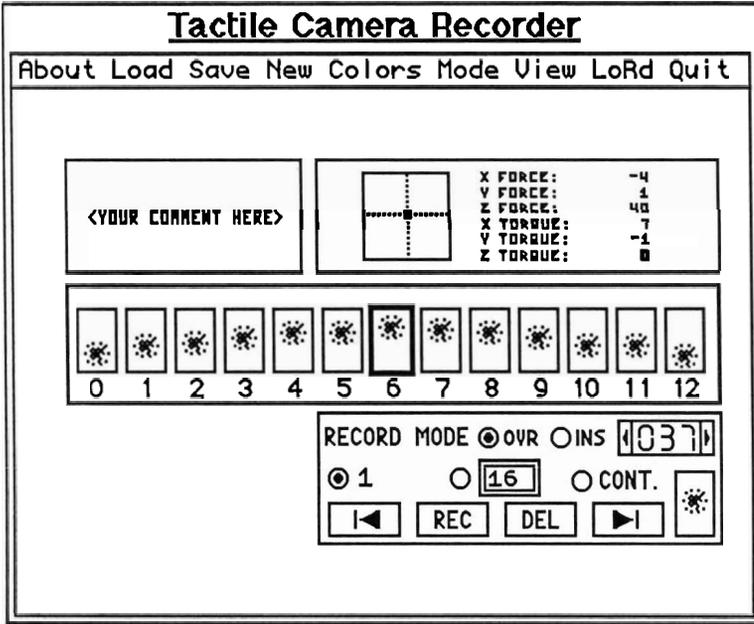
The Experiment

(figure 1A)

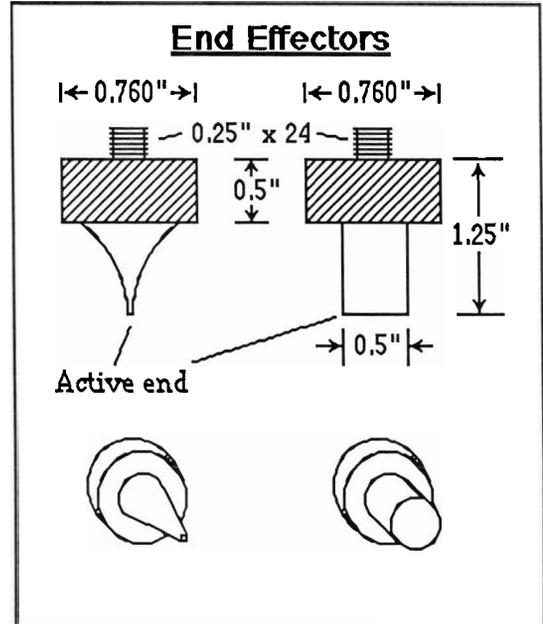
Sensor Testing Fixture



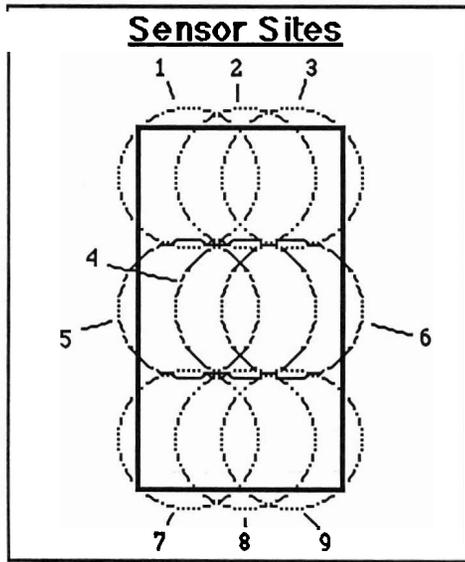
(figure 1 B)



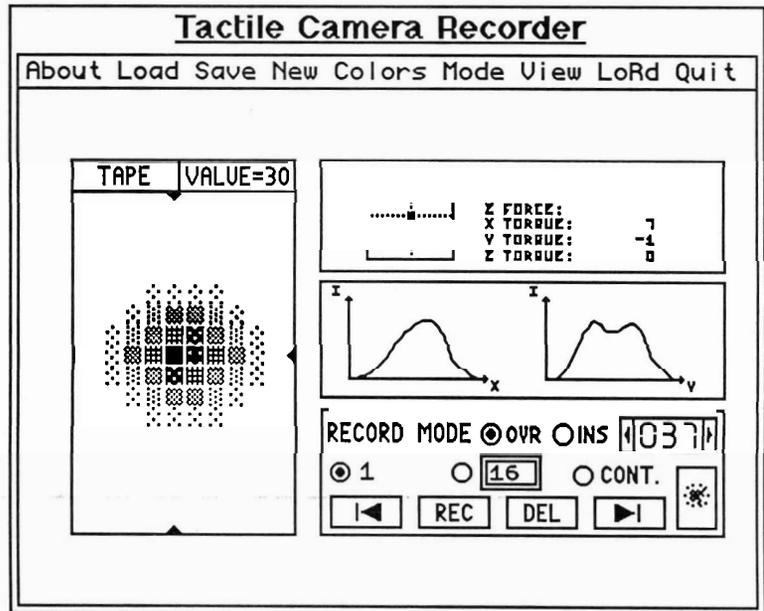
(figure 2)



(figure 3)

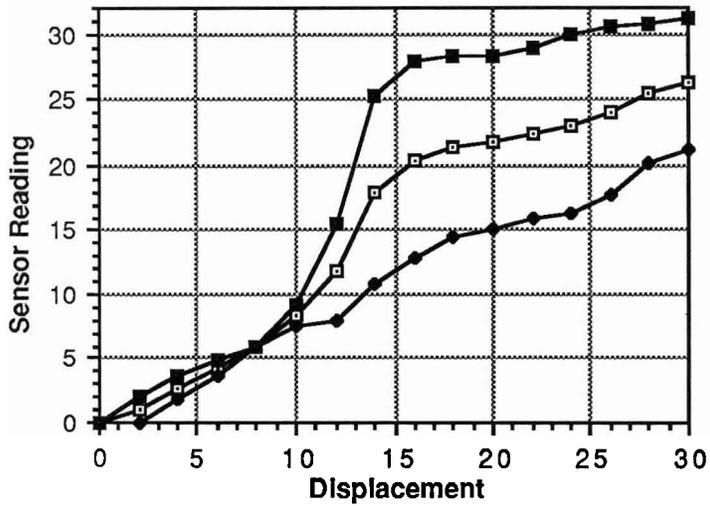


(figure 4)



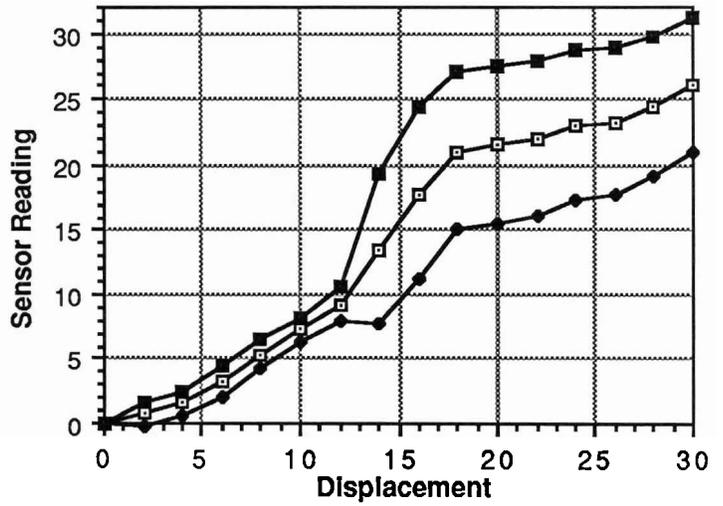
(figure 5)

Experiment 1: Site 1



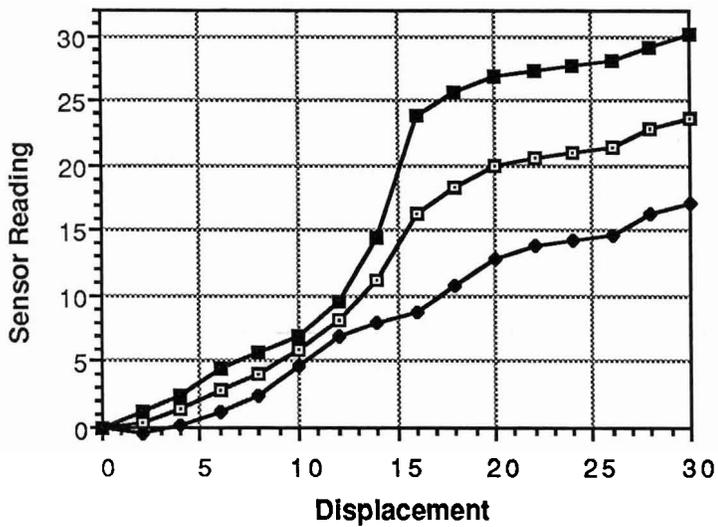
(figure 5)

Experiment 1: Site 2



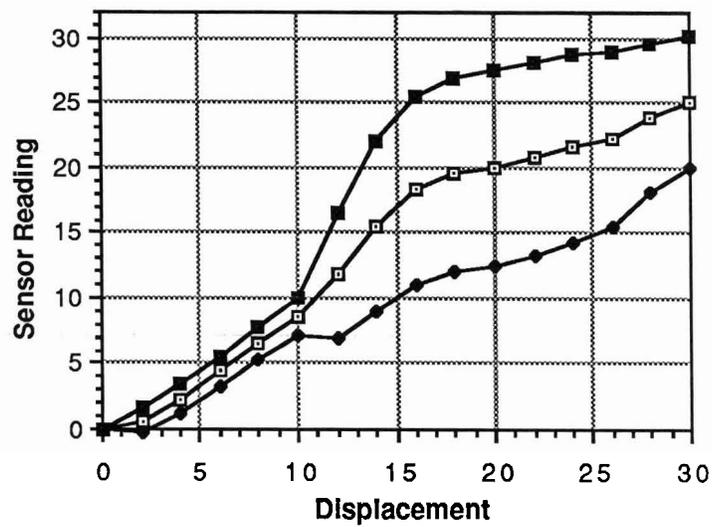
(figure 6)

Experiment 1: Site 3

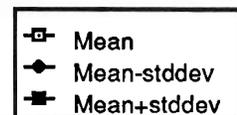


(figure 7)

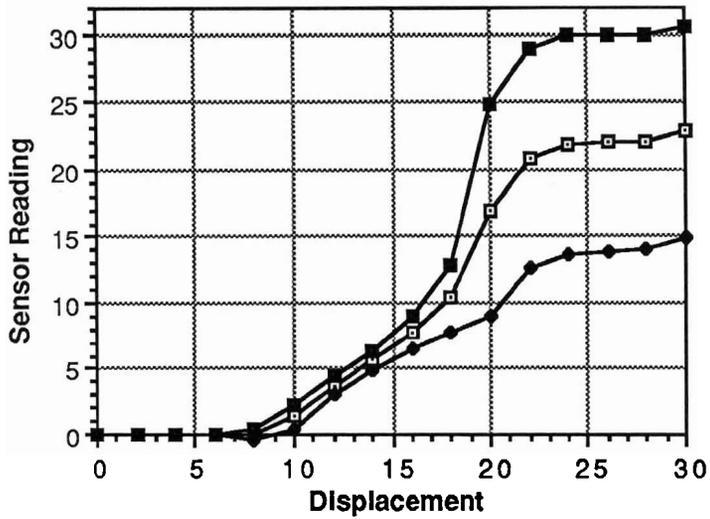
Experiment 1: Site 4



(figure 8)

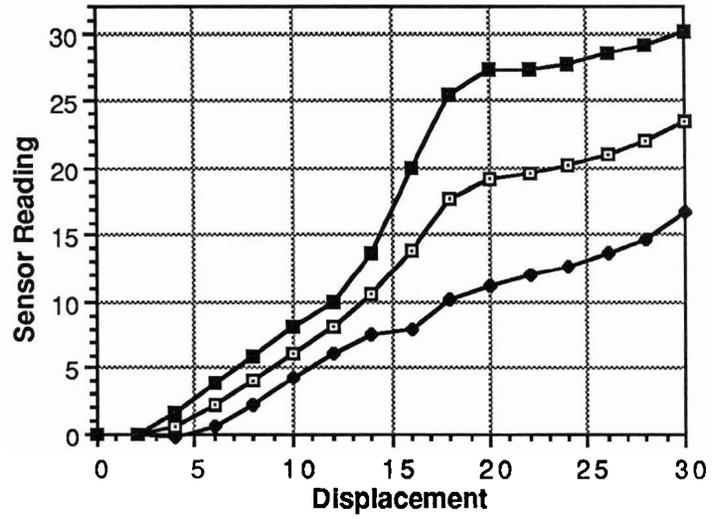


Experiment 1: Site 5



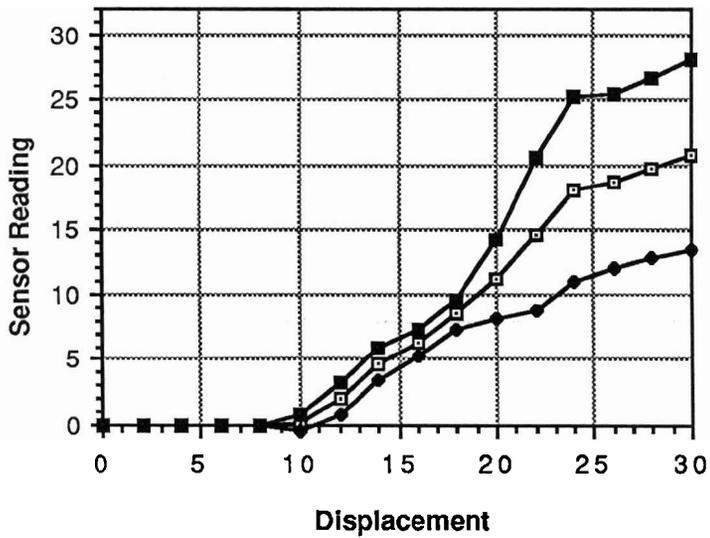
(figure 9)

Experiment 1: Site 6



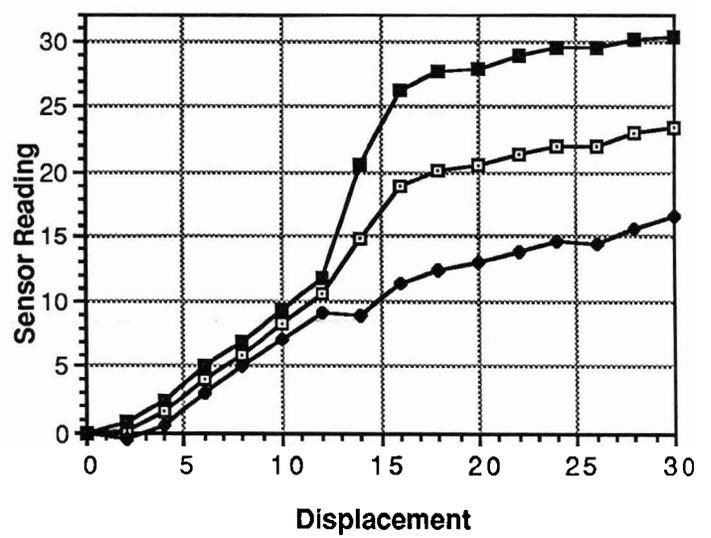
(figure 10)

Experiment 1: Site 7

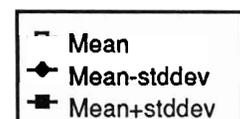


(figure 11)

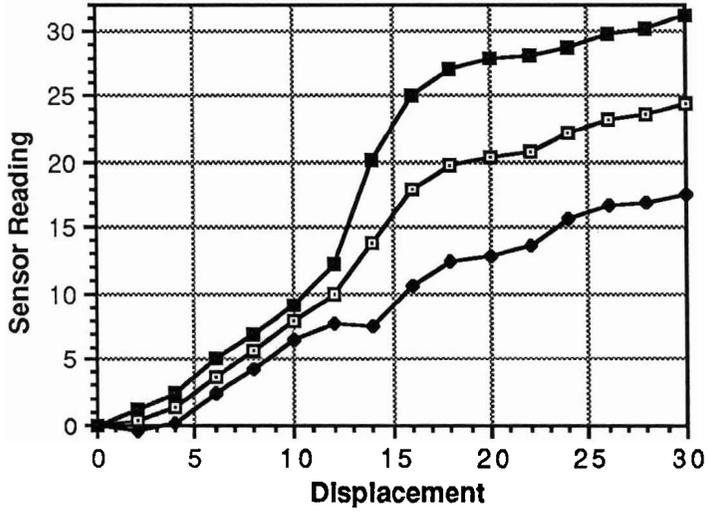
Experiment 1: Site 8



(figure 12)

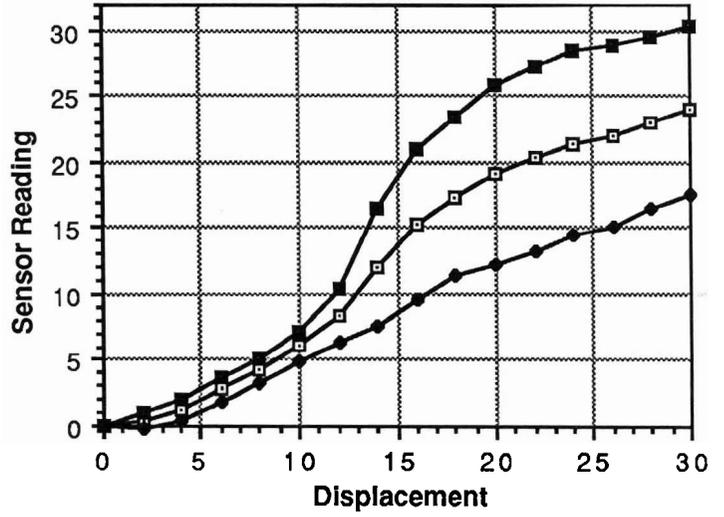


Experiment 1: Site 9

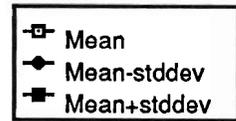


(figure 13)

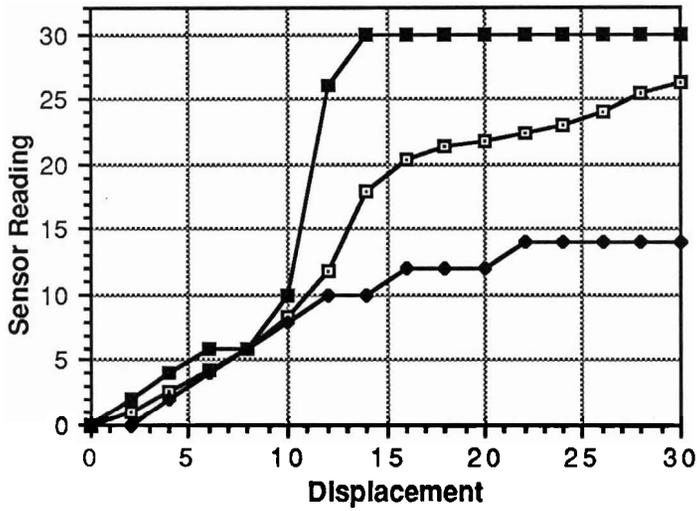
Experiment 1: Average of All Sites



(figure 14)

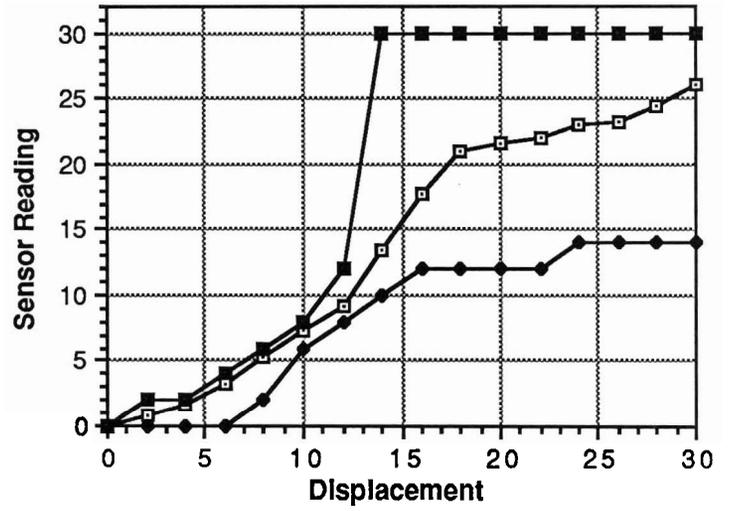


Experiment 1: Site 1



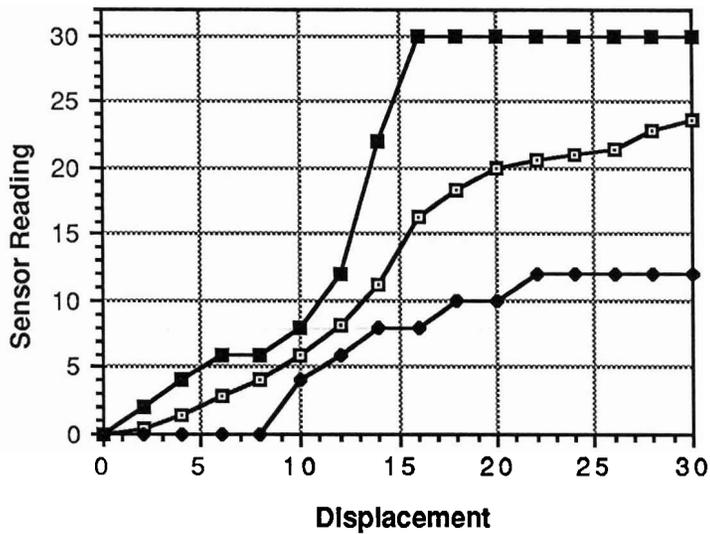
(figure 15)

Experiment 1: Site 2



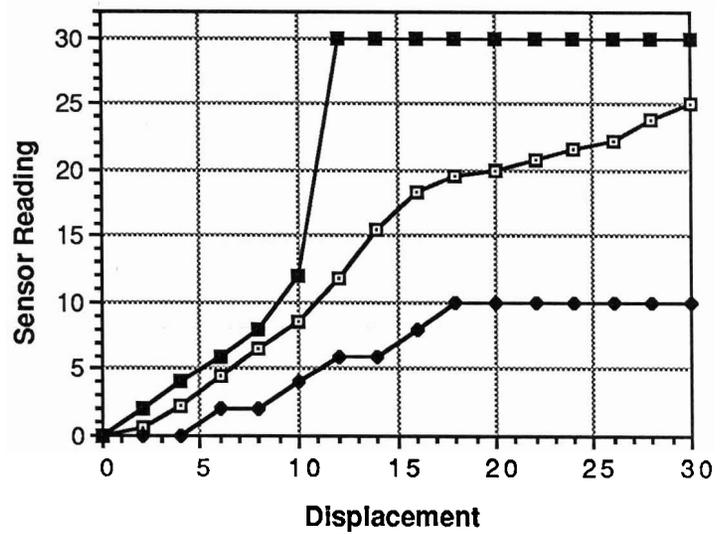
(figure 16)

Experiment 1: Site 3

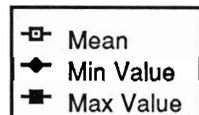


(figure 17)

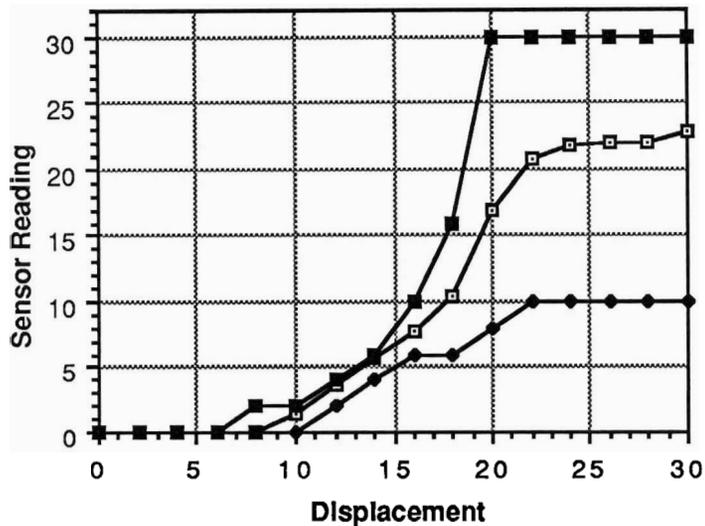
Experiment 1: Site 4



(figure 18)

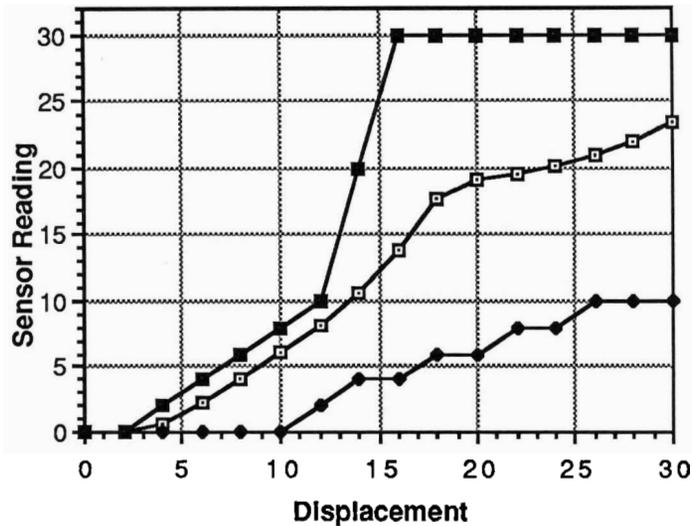


Experiment 1: Site 5



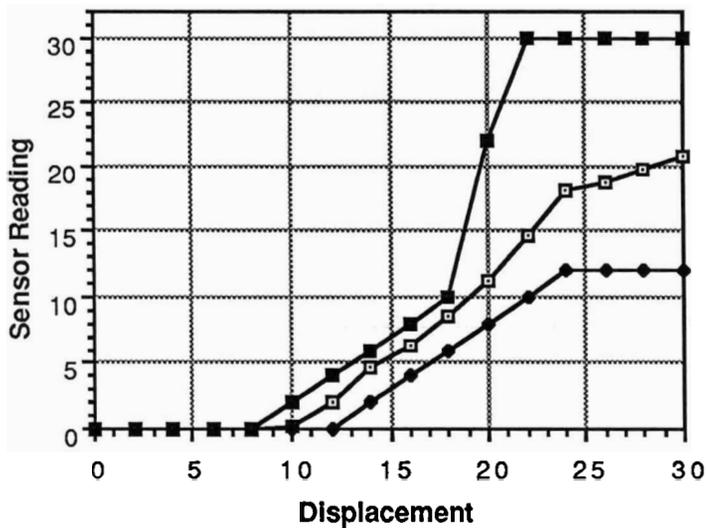
(figure 19)

Experiment 1: Site 6



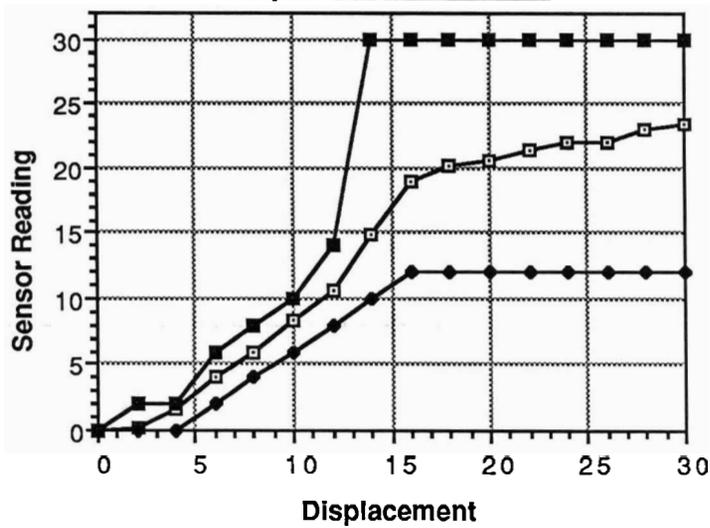
(figure 20)

Experiment 1: Site 7

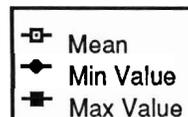


(figure 21)

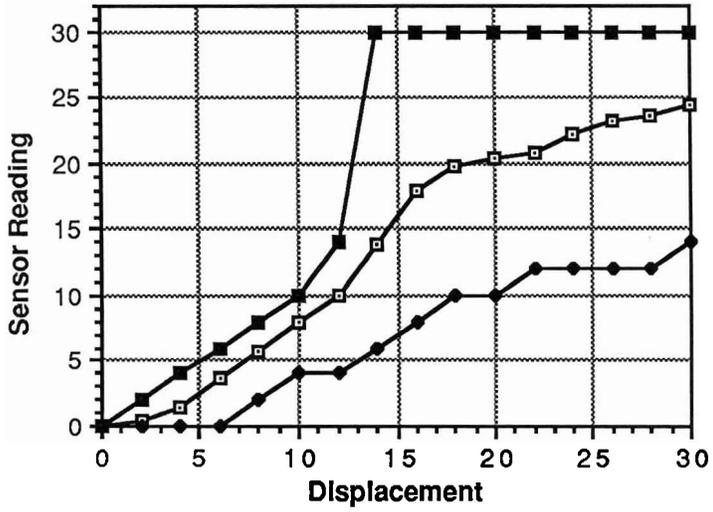
Experiment 1: Site 8



(figure 22)

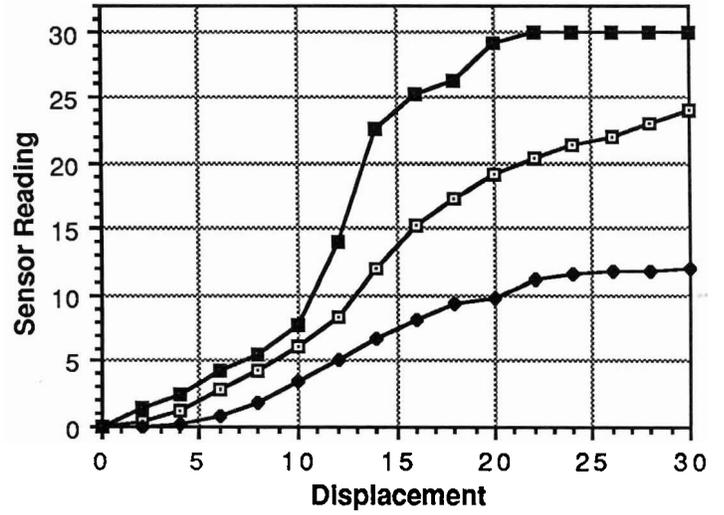


Experiment 1: Site 9

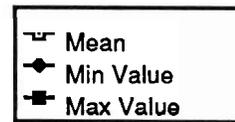


(figure 23)

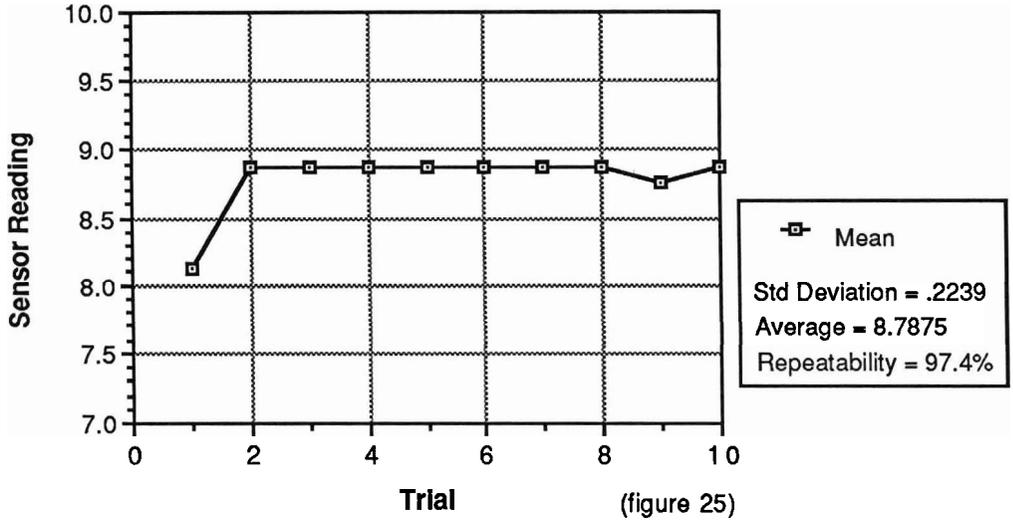
Experiment 1: Average of All Sites



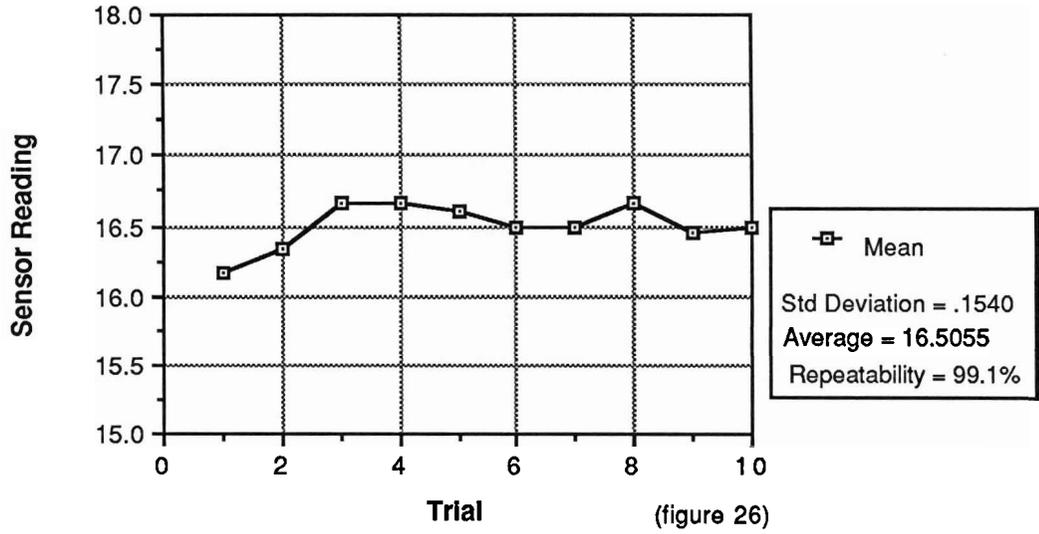
(figure 24)



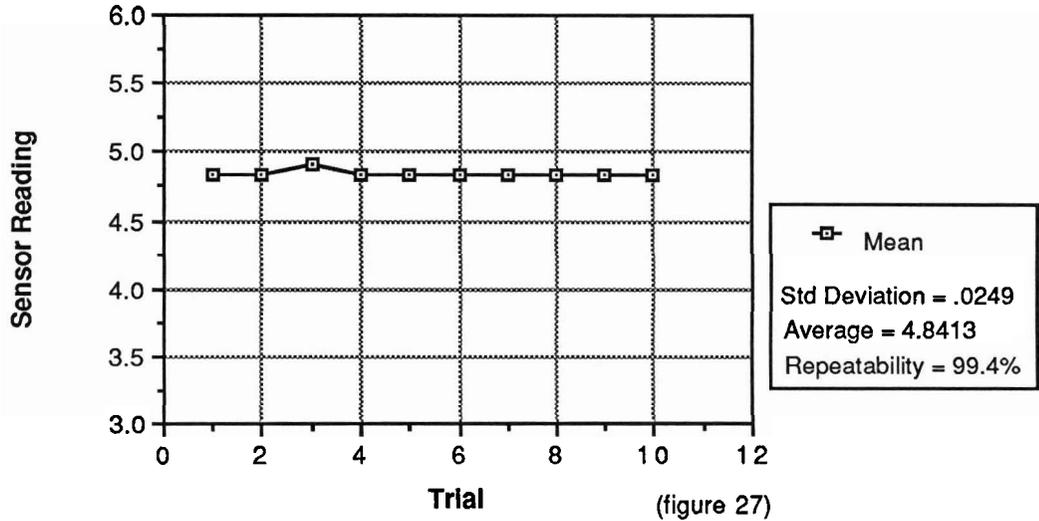
Experiment 2: Site 1



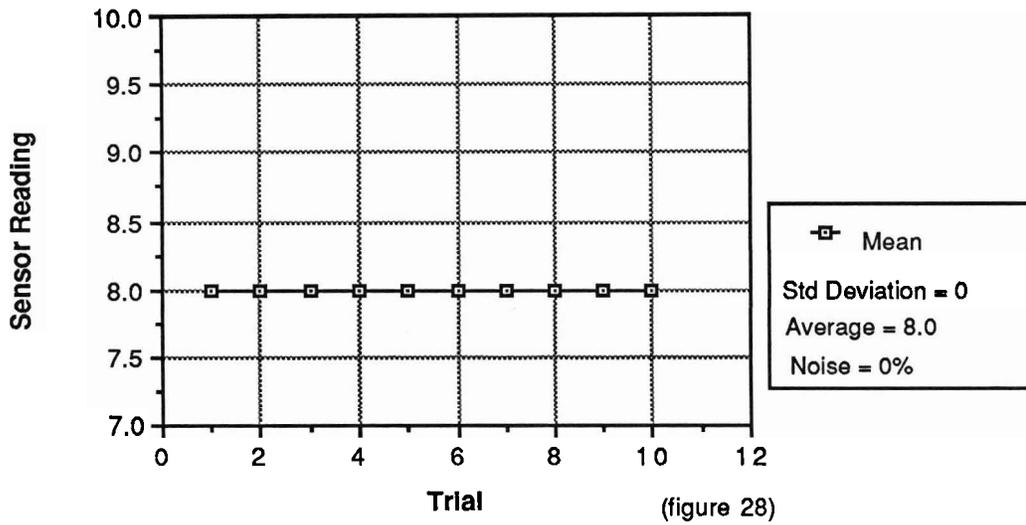
Experiment 2: Site 4



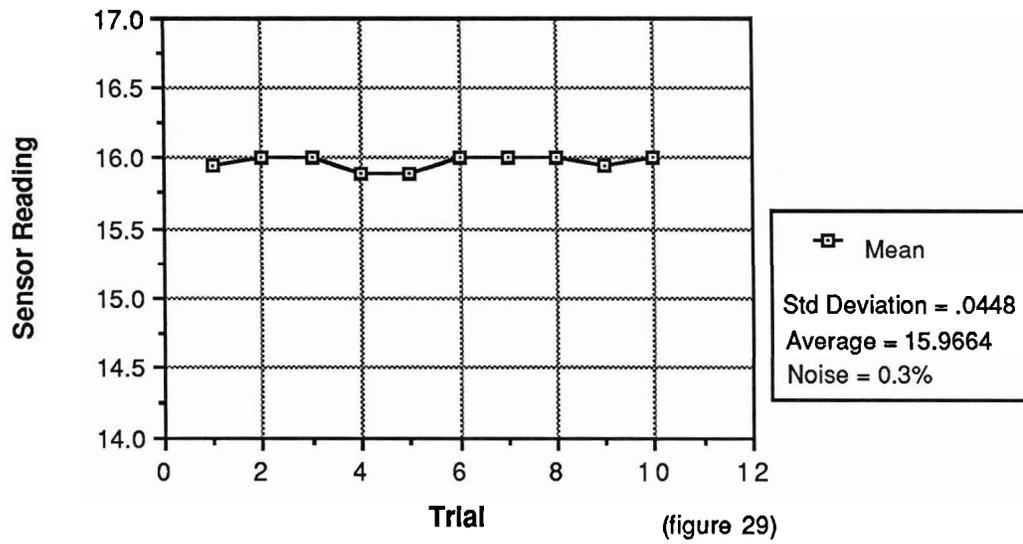
Experiment 2: Site 5



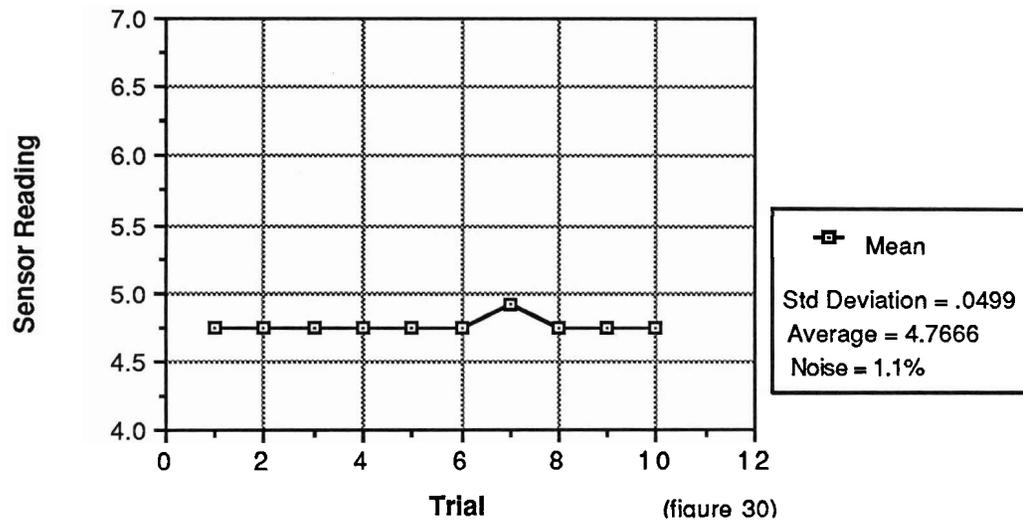
Experiment 3: Site 1



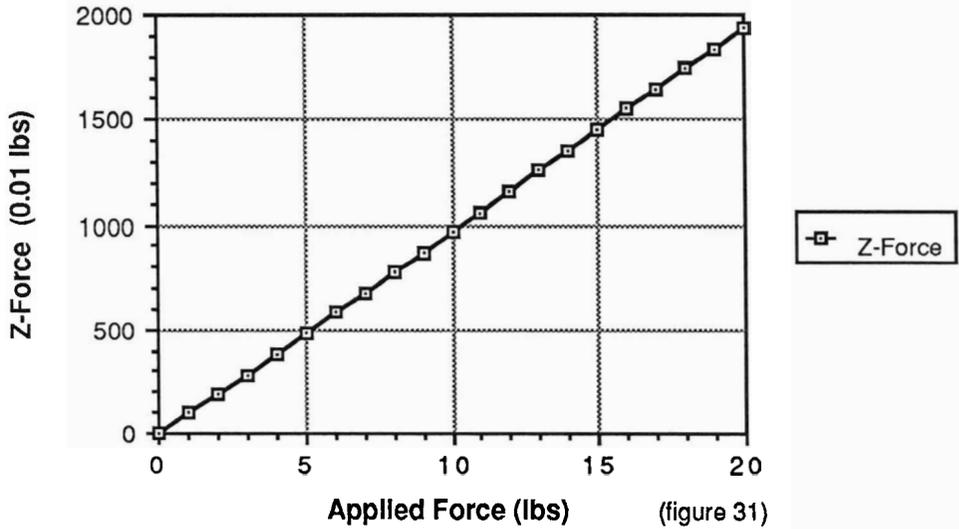
Experiment 3: Site 4



Experiment 3: Site 5

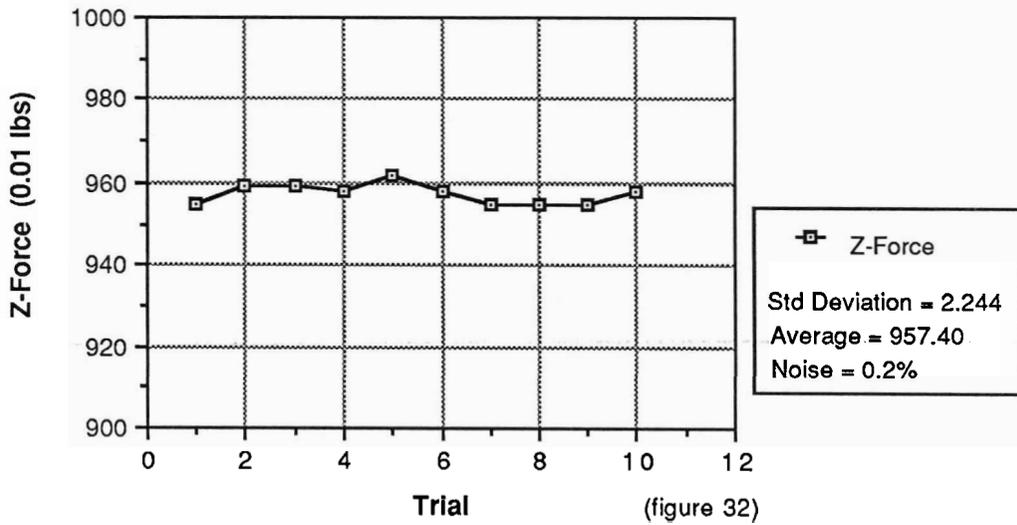


Experiment 4: Site 4



(figure 31)

Experiment 5: Site 4



(figure 32)

Experiment 6

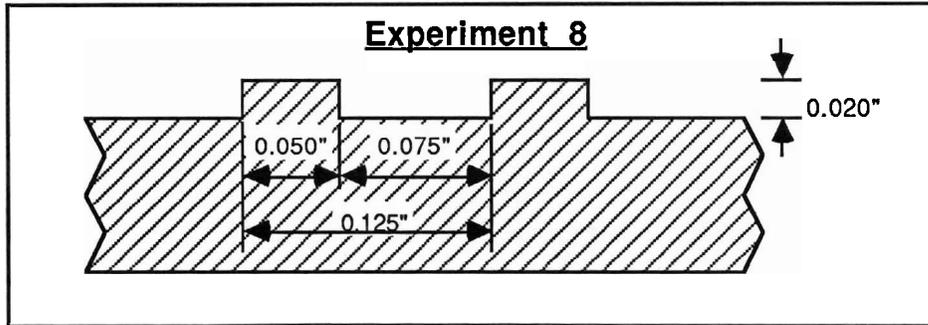
Site	Minimum Contact Pressure
1	1.858 lb / in ²
4	1.858 lb / in ²
5	2.622 lb / in ²

(figure 33)

Experiment 7

Site	Maximum Load Pressure
1	89.07 lb / in ²
4	60.09 lb / in ²
5	91.46 lb / in ²

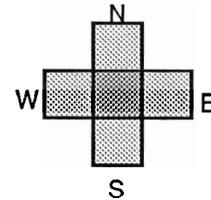
(figure 34)



(figure 35)

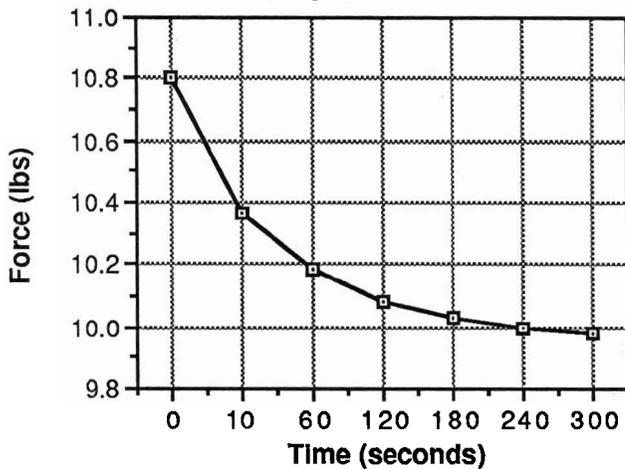
Experiment 9

Central Site Reading	Crosstalk				Average Crosstalk	Percent Crosstalk
	N	S	E	W		
12	4	2	2	2	2.5	20.8 %
24	8	4	4	4	5	20.8 %
30	10	6	6	4	6.5	21.6 %



(figure 36)

Experiment 10



(figure 37)

Experiment 11

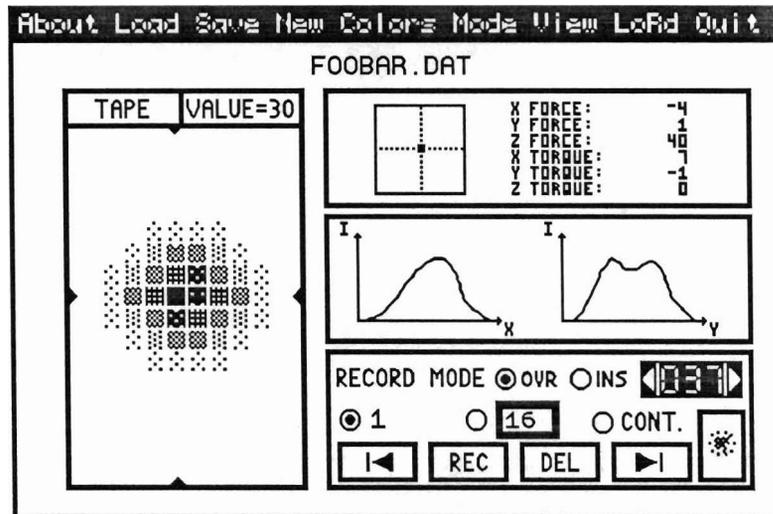
Time	Fx	Fy	Fz	Tx	Ty	Tz
0	-2	6	-5	-1	1	-2
15	-2	4	-6	-1	1	-3
30	-4	7	-6	-1	1	-4
45	-4	9	-5	-1	1	-5
1:00	-4	1	-4	0	0	-5
1:15	-4	1	-4	0	0	-7
1:30	-6	13	-4	0	0	-7
1:45	-6	13	-3	0	0	-7

(figure 38)

Appendix A:
TCR Manual

TCR Docs

What is TCR?: TCR is an abbreviation for Tactile Camera Recorder. It allows you to view, record, and playback data taken from the Lord LTS-200 Tactile Array Sensor. This sensor consists of a 10x16 array of displacement sensors, and a 6-axis force gauge. The LTS-200 is capable of transmitting this information approximately 4-5 times per second.



Operation: TCR provides you with two main modes of operation. The first, **Playback Mode** allows you to look at recorded sequences and make measurements of individual sites. **Playback Mode** doesn't require you to have a Lord sensor hooked up to the machine.

The second mode, **Record Mode**, does require a Lord sensor. It allows you to view 'live' data coming right off the sensor, record sequences, edit them, and save them to disk.

TCR also supplies you with two different ways of looking at the data. **Detail View**, the default view, features a single, large 10x16 grid. You can get the actual displacement values for each site, and see cross-sections along the two axes. **Strip View** loses these abilities, but allows you to view a large number of frames simultaneously.

Hardware Requirements: TCR requires you to have an IBM PC-compatible with a VGA display, a serial port, and a mouse.

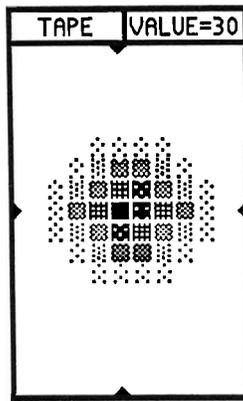
Terminology: TCR operations are, in many respects, analogous to those of a video tape recorder, or a movie camera (with built-in playback unit and editing lab). The Lord sensor does not generate a continuous stream of data. Instead, the controlling

program asks it "What's your state?," and a short time afterward the sensor returns a snapshot of its state when the request was made. These snapshots are called **frames**, in keeping with the film analogy. These frames are organized into a **sequence**, the analog of a strip of film. TCR operates on a single sequence, which can be up to 200 frames long.

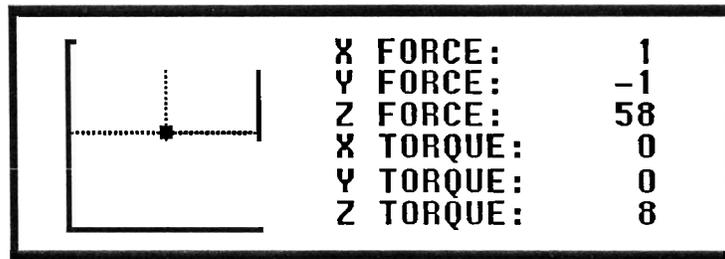
About Load Save New Colors Mode View LoRd Quit

The Menu Bar: The menu bar lists several commands that may be executed at any time. Some of them may be 'dimmed', and cannot be selected at this time. (For example, you cannot 'Save' while in **Playback Mode**, because you couldn't have recorded anything.) You can select these commands by clicking the mouse in the menu bar, and dragging it to the desired command. Alternately, you can type the first letter of the requested command (except in the case of "LoRd", where the command-key is "R" (the "L" already having been used for "Load")).

- About:** Clicking the mouse on this command brings up an 'About' box, which lists the authors, gives the version number of the program, and provides some gratuitous animation.
- Load:** Allows you to load recorded sequences from disk. Loading a sequence overwrites any sequence that was already in memory.
- Save:** Only available while in **Record Mode**. Saves the current sequence to disk, for later analysis.
- New:** Clears the current sequence.
- Colors:** Cycles between the three color schemes used to represent the amount of sensor displacement. The default is a grey-scale where no displacement corresponds to black, and maximum displacement corresponds to white.
- A second color scheme is the opposite grey-scale, where white equals no displacement, and black equals maximum displacement.
- The third color scheme utilizes pseudo-color to represent displacement. The colors follow the standard spectrum, with the 'colder' colors (blue, violet) corresponding to small displacement, and the 'warmer' colors (yellow, red) corresponding to large displacement.
- View:** Toggles between the two display modes, **Detail View**, and **Strip View**.
- Mode:** Allows you to toggle between **Playback Mode** and **Record Mode**. You may only select this command when there is a Lord sensor connected to the machine.
- Lord:** Lets you tell the program that there is a Lord sensor hooked up to the machine, and which port it's connected to. Also lets you reset or zero-out the Lord sensor, if one is connected. (See "**Lord Dialog**" below.)
- Quit:** Used to exit the program.



The Detail Window: This window shows a greatly magnified view of a frame of sensor data. Along the four edges are **Indicators**, which allow you to specify two lines through the data. These lines are used in the **Cross Section** window (see below). The indicators can be moved with the arrow keys on the keyboard, or by clicking the mouse in the data area. The value of the site at the intersection of these two lines is shown at the top right of the window, where it says "VALUE=nn". The button at the top left of the window, (where it says "TAPE"), allows you to choose whether the detail window will show you the current frame from the recorded sequence, or live action ("LIVE"). To select live action, you must first be in **Record Mode**.



The Force Sensor: This display presents the force data that the Lord sensor is capable of measuring. The first three values are the forces along the X, Y, and Z axes, respectively, in hundredths of a pound. The last three values are torques around the X, Y, and Z axes. The small window shows three of these values graphically.

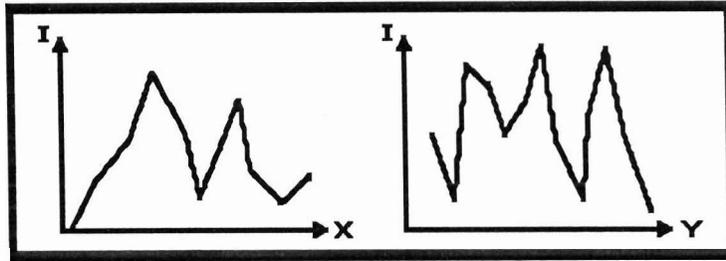
Z force is represented by the color of the small square. The coloration is as follows:

FORCE	COLOR
0.0 -- 0.5 lbs	Grey
0.5 -- 8.0 lbs	Green
8.0 lbs and above	Red

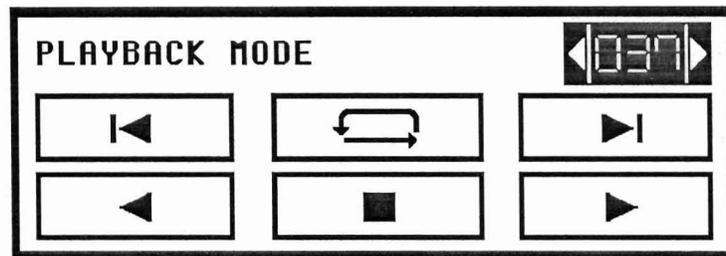
The idea here is that when taking measurements, you should try to keep the force in the 'green zone'. When the square is grey, you're not pressing hard enough, and when it's red, you're pressing too hard.

X torque and Y torque are illustrated by displacing the small square from the center point. One thing that isn't inherently obvious is that X torque results in vertical displacement, and that Y torque results in horizontal displacement. The reasoning behind this is that when you're generating X torque, you're pressing above (or below)

the X axis, rather than right on it. Likewise for Y. The square reflects this behavior.

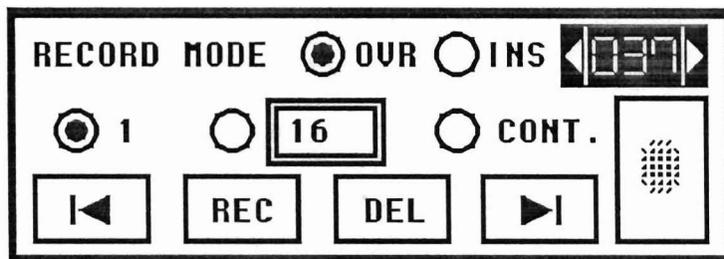


The Cross Section: (Only available in **Detail View**.) The cross section window allows you to get some idea of what the displacements measured actually look like. It takes the data values along the two lines indicated in the **Detail Window**, and plots them on these two graphs.



Playback Controls: This window contains all the controls that handle sequence playback. The large left and right arrows allow you to run the sequence forward or backward. The center square stops the playback. The arrows with the vertical lines allow you to advance the sequence (in either direction) by a single frame. Holding either of these buttons down continues to advance the sequence until you let go. The top center button allows you to specify whether sequence playback 'wraps-around' at the ends, or simply stops.

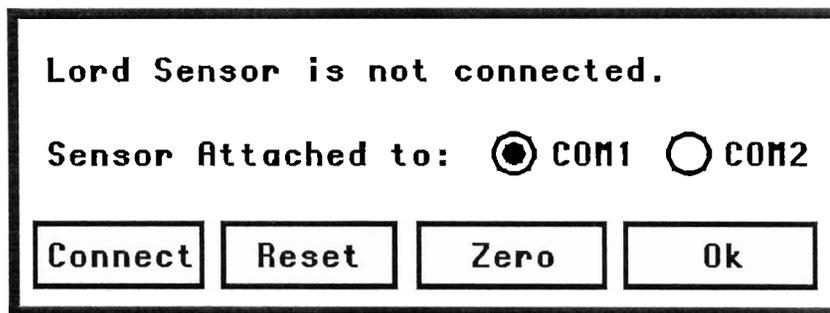
The frame counter control (at the top-right of the window), performs three separate functions. The two arrows in the counter allow you to instantly move to the beginning or end of the sequence. Clicking in the numeric part of the frame counter lets you enter a frame number, and jump directly to it.



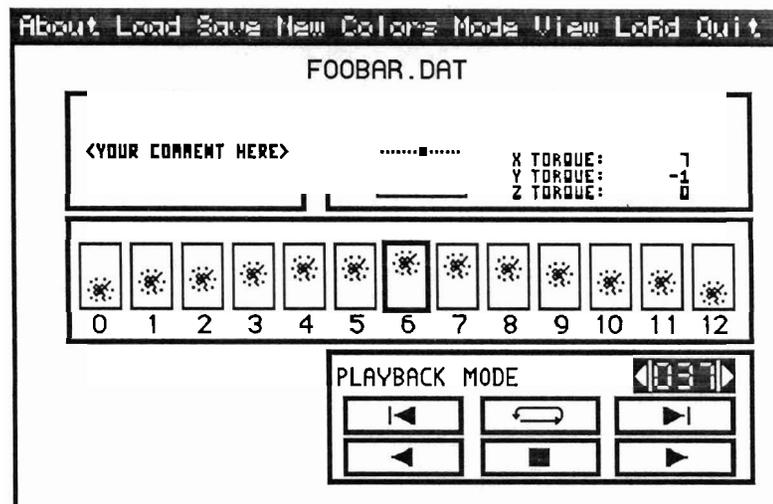
Recording Controls: This window contains all the controls that handle sequence recording and editing. The two buttons with the arrows let you move forward and backward within the sequence. The 'OVR' and 'INS' buttons select whether recording new frames OVerwrites existing frames, or INSerts new frames at the current frame number.

The '1', '16', and 'CONT' buttons select how many frames you want to record. The '1' button records 1 frame, the 'CONT' button records CONTinuously, until stopped, and the '16' button is editable to record any fixed number of frames, between 1 and 199. Note that these buttons only affect the number of frames that will be recorded. They do NOT actually do the recording. Once you've set up number of frames to be recorded, press 'REC' to actually DO the recording. Press 'REC' (or, in fact, any of the controls in this box) to stop recording. (Recording will turn off automatically when the selected number of frames has been recorded, unless, of course, you've selected CONTinuous recording.)

The 'DEL' button allows you to delete the current frame. The frame counter allows you to go to the beginning of the sequence (by pressing the left arrow), the end of the sequence (by pressing the right arrow), or any random frame within the sequence (by clicking on the numeric part and typing in a new frame number).



The Lord Dialog: When you click on the **Lord** command in the menu bar, you'll be presented with this dialog box. One or more of the buttons may be non-selectable, depending on the state of things. For example, the first time you see this box, the Lord Sensor will not be connected (as far as the program is concerned), and the only valid choices will be 'Connect', and 'Ok'. If the sensor is connected, the valid choices will be 'Reset', 'Zero', and 'Ok'. 'Reset' sends a reset command to the sensor. 'Zero' sends a zero command, which tells the sensor that whatever deflection it's tactile array is at now is the 'zero' position. See the Lord manual for more information on these commands.



Strip View: This view allows you to see many frames at once. Useful for editing sequences with the **Recording Controls**. It also lets you see the comment describing the sequence, which was entered when the sequence was saved.

Usage

Command Line Arguments: There are none. Just type 'TCR', and you're ready to run.

Looking at Other People's Data: Once you've got the program up and running, choose **Load**, on the menu bar. A window (the **Load Dialog**) will come up listing the current directory. The name of the current directory will be printed at the top. You may enter a subdirectory by double-clicking on a subdirectory name in the list. You may go UP the directory tree by clicking on the directory name (at the top). A menu will pop up, listing the components in the current path. Go up the directory tree as far as you want.

Once you're in the subdirectory that's got the data in it, double-click on the file you want to open. One warning: Opening non-TCR data files will almost certainly be 'interesting', and may even cause TCR to go 'out to lunch'. Opening non-TCR files is therefore not recommended.

You may also want to click on the **View** command, in the menu bar, to go into **Strip View**. Or not.

Repeat this process as necessary. Click on the **Quit** command when finished.

Recording Some Data of Your Own: First, get the program up and running. Now, click on the **Lord** command in the menu bar. The **Lord Dialog** will come up. Tell this dialog box what serial port the sensor is plugged into, and click on the 'Connect' button in the dialog box. The cursor should turn into a spinning circle for a bit, and within 5 seconds the cursor should turn back into an arrow. If the program was able to talk to the sensor, the box should now say "The Lord Sensor is connected.", and the 'Connect' button should now be dimmed. Click on the 'Ok' button (or press return).

If the program was unable to talk to the sensor, verify the sensor connections, the on-ness of the power supply, and press reset on the sensor interface. If the problem still persists, try talking to the sensor directly (at 9600 baud) with Kermit, or some other terminal program. See the Lord manual for a list of things to 'say' to the sensor.

Assuming you've gotten the sensor to connect, you can now select **Record Mode** by pressing on the **Mode** command in the menu bar. You'll probably also want to select **Strip View**, just so you'll have a better idea of what's going on.

The small rectangle in the lower-right corner of the **Recording Controls** box monitors the sensor at all times. If you press your finger on the sensor, you should see a blob appear in this rectangle. This verifies that the sensor is working, and also allows you to wait until you've got the sensor in the 'right' position before you start recording.

You can record and edit your sequence using the controls in the Recording box, as

described above.

Once you've got the sequence correctly recorded, you can save it to disk by clicking on the **Save** command in the menu bar. This will bring up a dialog box similar to the **Load Dialog** mentioned above. Once you've bounced around to the subdirectory you wish to store the data in, you merely enter a file name, and press return. A second dialog box will pop up, prompting you for a comment describing this data. Enter one, and press return again. The file should now be saved.

Credits

TCR was written by John Bradley (bradley@cis.upenn.edu), a Graphics Weenie at the University of Pennsylvania.

This program was based on a series of excellent ideas from Filip Fuma (fuma@cis.upenn.edu), an Electrical Engineer (and Bradley's boss) at the University of Pennsylvania.