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STRAW TUBE POSITION MEASUREMENT

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Abstract

This report describes the feasibility of an optical technique developed at Duke University by Quantum Research Services for evaluating the positions and straightness of long straw tube drift cells to a resolution on the order of 10μm.

Traditional, non-contacting sensors such as eddy current probes and capacitance gauges have difficulties associated with relatively large working areas, short standoff distances and specific electrical properties required of the target. To avoid these difficulties, we developed and tested a non-interfering, non-contacting fiber-optic transducer (Optical Sensor) for measuring straw tube drift cell locations relative to a fixed reference. Experiments were performed to determine the static displacement characteristics, target reflectance dependence and optimal standoff distance, fiber size and step size for measuring 4mm straw tube locations. In order to complete the investigation a double axis machine, described in the Appendix, was built to lay straw tubes and evaluate their positions. Straw position measurement resolution with a standard deviation of ~13μm (0.5 mil) was achieved.

1 - Introduction

The project undertaken at Duke University investigated the possibility of laying individual straw tube drift cells onto a cylindrical base as an integral part of the barrel tracker of the Solenoidal Detector Collaboration (SDC) detector. For the initial prototype, however, a flat rather than cylindrical base was used. As described in the Appendix, the machine was designed and built to lay straws onto a flat three meter long plate and to subsequently evaluate their positions relative to a fixed reference wire. The feasibility of subsequently laying straws onto a *cylindrical* base could then be evaluated.

In order to measure the position of a straw tube, a non-contacting method had to be employed since the straws are too soft for traditional contacting methods. After considering eddy current probes and capacitance gauges, an optical method which required smaller working areas, longer standoff distances and no special electrical properties of the target was developed. In measuring the center location of a straw tube, the Optical Sensor depends only on the change in intensity of reflected light as a light source is moved over the straw. The sensor used for these experiments was originally intended for measuring *vertical* displacements along the axis of the fiber bundle, but in our application the bundle was moved *horizontally* across the straws and transverse to the straw axis.

Applications for the Optical Sensor are not limited to the measurement of straw tube drift cell positions since the device will provide distance proportional output for any reflecting target. The determination of the centers of non-rigid spherical or cylindrical objects is particularly useful, as illustrated in this report, but the use of this device can be extended to the position measurement of flat or rigid objects as well.

2 - Optical Sensor Theory of Operation

2.1 Basic Operation

The basic operation of the Optical Sensor is illustrated in **Figure 1**. Near Infrared photons from a light emitting diode (LED) are coupled into the central fiber of a symmetric fiber bundle, consisting of a single emitter surrounded by six or eight receiving fibers. The source and detector functions occur after the bundle bifurcation *at* the instrument. The fiber bundles consist of 100μm, 200μm and 300μm diameter fibers fixed in an epoxy matrix and mounted in an aluminum tube with a 6.35mm outside diameter. Since light enters and exits a single-mode fiber in a cone, the emitter fiber produces a diverging source beam which, upon reflection from a nearby target, will illuminate a specific area surrounding the emitter fiber. The area covered by this reflection and the intensity distribution within that area is related to the distance of the target from the fiber termination and practically vanishes when the sensor to target distance is zero. The reflected light detected by the receiving fibers is directed to an infrared filter and then a photo-diode detector. The measured intensity is output as a

voltage which is directly proportional to target vertical distance and is not influenced by ambient light conditions (room light rejection) because of the infrared filter in the unit.

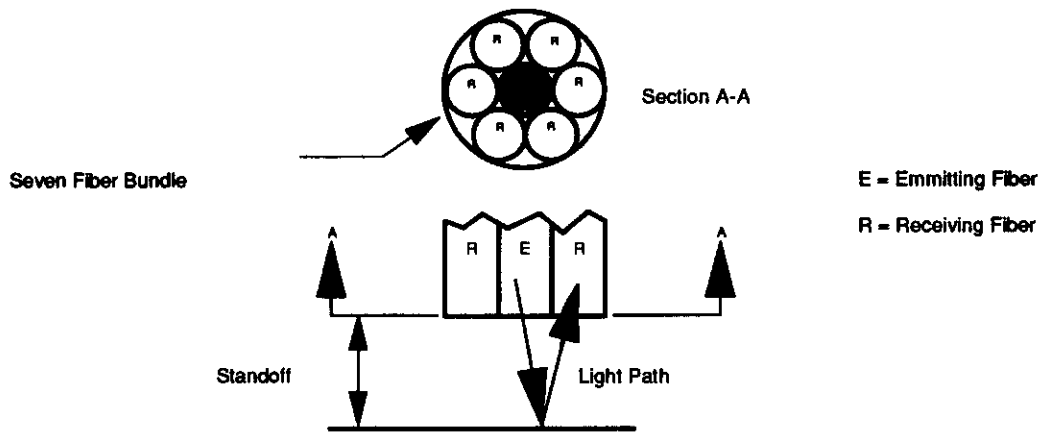

Figure 1 - Optical fiber bundles and illustration of standoff distance.

Evaluating the DC voltage output of the Optical Sensor while displacing the sensor tip vertically produces the characteristic curve shown in **Figure 2**. The voltage rises rapidly on the **near-side** slope peaking at a displacement of 0.05mm to 6mm depending upon the tip used. On the **far-side** slope the voltage decreases more gradually, settling to a base voltage of 0.02V to 0.20V at a vertical distance greater than 10mm. The **near-side** slope is extremely sensitive to standoff distance and is therefore ill-suited to transverse scanning to measure straw locations, as shown in **Figure 3**.

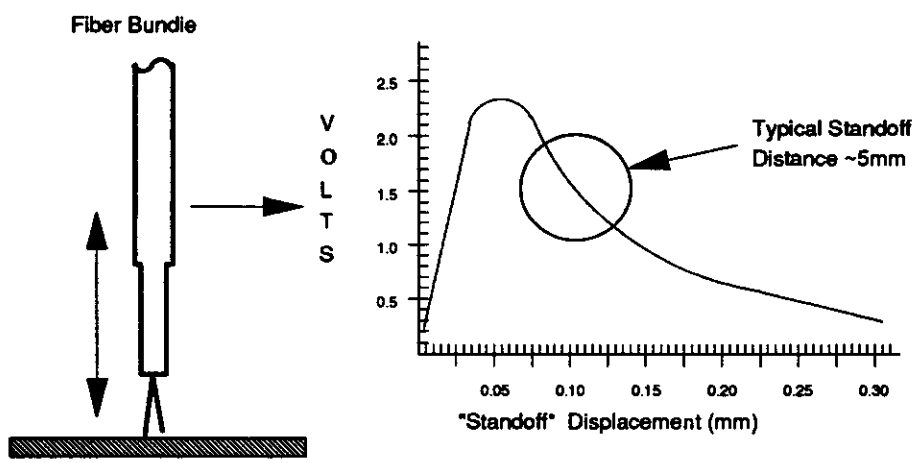

Figure 2 - Vertical fiber displacement and resulting characteristic curve.

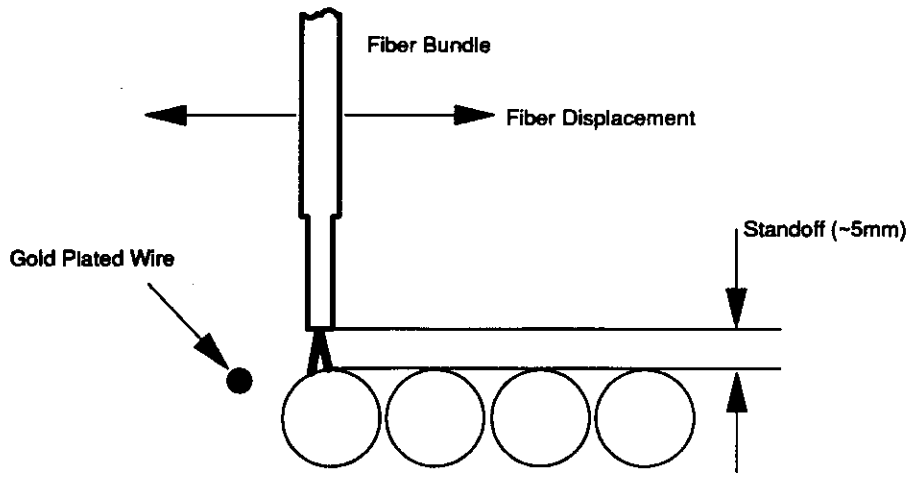

Figure 3 - Straw scanning setup and illustration of horizontal displacement.

2.2 Straw Tube Scanning

To measure straw tube locations, the fiber bundle is first mounted to the straw guide axis on the straw laying machine. Mounting the fiber bundle is not critical since measurements are made relative to an arbitrary reference such as a taut wire (in our case a 100μm diameter gold wire) which is measured at runtime with the rest of the straw layer. The bundle should be within 3 degrees normal to the plane of the measured straws. During straw scanning setup, the approximate center of the first item to be measured is found by maximizing the Optical Sensor output and the vertical distance is adjusted until the peak of the standoff distance curve is found. The vertical distance is then increased until the output voltage falls to 85% of the peak level, thereby assuring that during a transverse scan the peak is not "crossed", producing ambiguous or unexpected results, (i.e. only the **far-side** of the curve is used). **Figure 3** illustrates this transverse scanning setup.

2.3 Optical Sensor Electronics

The light intensity from the receiving fibers is directed to a photo-diode detector. The output from the detector is amplified at gains (sensor gains) ranging from -10dB to 40dB in 10dB increments when adjusting the standoff distance and performing the initial setup for a scan. Then the signal is routed to both a liquid crystal diode (LCD) and a high-pass filter/op-amp combination. The LCD on the front panel displays a static (DC) signal, while the dynamic (AC) signal is high-pass filtered and amplified with gains of 10, 100 and 1000 (signal gains) for use in vibration analysis. The signal terminates at a coaxial connector for output to the analog to digital (A/D) converter which can then be read by the computer. For the measurement of straw positions (scanning), the AC filtering is not used since only the DC proportional signal is of interest in performing transverse scans.

2.4 Surface Finish Dependence

Surface finish is an important consideration when using the Optical Sensor for vertical distance measurement as well as transverse scanning in measuring straw locations. An experiment was performed to determine the effects of different surfaces on the static displacement (DC) curves. Various surface finishes from an S-22 Micro finish Comparator "Surface Roughness Scale" manufactured by GAR Electroforming Division were tested (**Table 1**). The finishes were produced by either lapping, grinding, milling or turning and represented average roughnesses ranging from 0.2μm to 13μm. The output voltage from the sensor as well as the sensitivity decreased as surface roughness increased due to the scattering of light caused by surface roughness.

Machining Method	Roughness μm	Peak Volts	Sensitivity V/mm
Lapped	0.20	0.326	0.384
Ground	0.40	0.256	0.326
Ground	0.80	0.246	0.297
Ground	1.58	0.252	0.316
Turned	3.13	0.270	0.326
Turned	6.25	0.301	0.365
Milled	3.13	0.308	0.365
Milled	6.25	0.301	0.374
Milled	12.50	0.283	0.355

Table 1 - Optical Sensor response to various surface finishes.

3 - Fitting Routine

The data produced by the Optical Sensor are fed into a series of programs. First the voltage is recorded by the CONTROLS program, then the CONVERT program produces files which are input to the FITGAUS2 fitting program. The fitting routine used in FITGAUS2 employs a modified gradient search procedure to fit the data to a Gaussian function.

$$G(b,\mu,\sigma,A) = A \times \exp\left[\frac{-(b-\mu)^2}{2\sigma^2}\right]$$

Where,

b = *Plate Axis Position (Abscissa)*
μ = *Gaussian mean value*
σ^2 = *Variance Parameter*
A = *Magnitude Parameter*

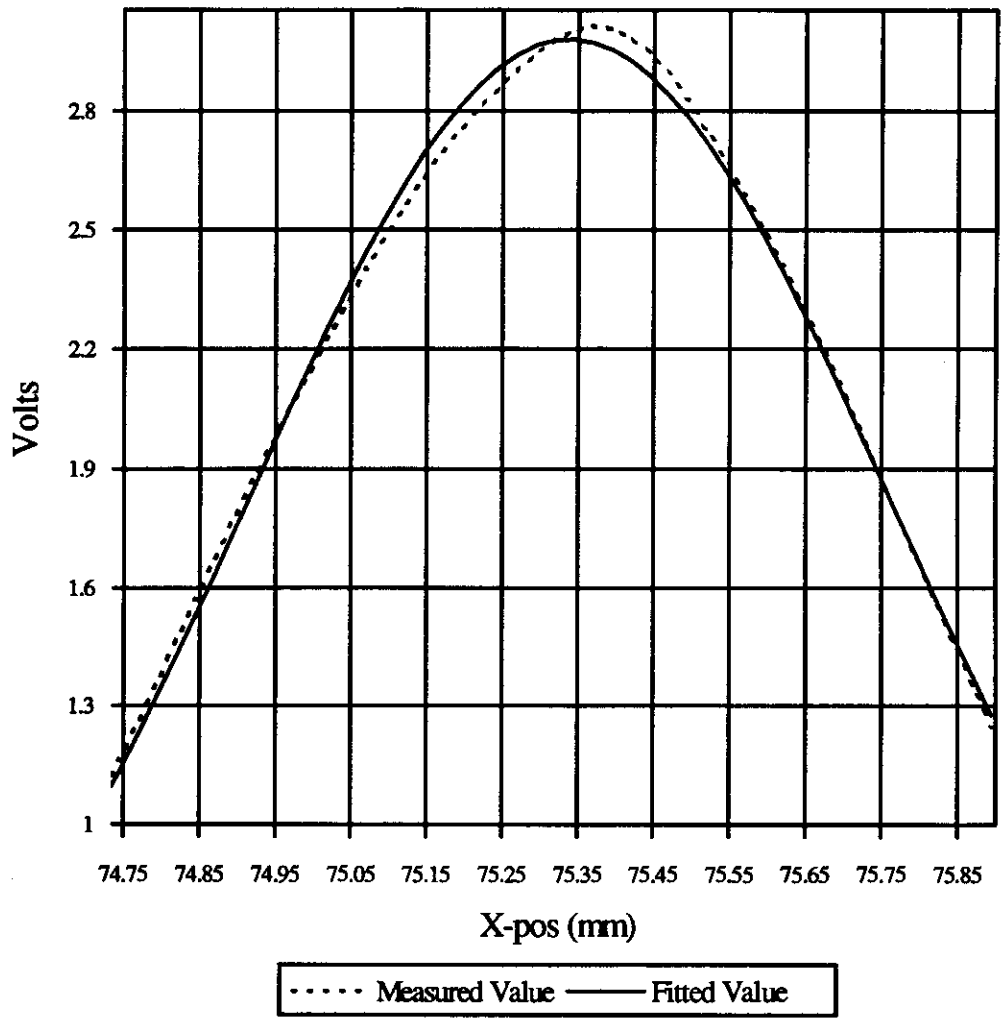

Figure 4 - Scanning results from a 5 mm rod using a 200μm fiber diameter tip.

FITGAUS2 produces long and short output files. The *quality of fit* can be evaluated from the reduced Chi-Square in the *long* output file and the data can be plotted as illustrated in **Figure 4**. As shown, the Gaussian function produces a close fit to the measurement data. The short output file lists only straw center positions.

4 - Results

To evaluate the potential of the Optical Sensor for evaluating straw tube locations, *repeatability* and *accuracy* tests for straws and for two sets of precision steel rods were performed. In each case a set of nine straws or rods comprised one *measurement set* and the measurement of each set was repeated three times. The nine average positions were normalized so that the values listed represent 27 measurements or deviations. This method was chosen so the results would be based on a representative sample of

measured items, not on a single straw or rod, and it produced consistent results for a given set of conditions. To measure the positions of the precision ground steel rods, nine were pressed together so that the nominal distance between their centers would be equal to the diameter (4mm or 5mm).

In estimating *repeatability*, data from the optical sensor were fit and the resulting positions of the test elements (rods or straws) were found for each trial. The offset of each element from the average position was used to calculate the repeatability values using the standard deviation estimator.

$$\sigma = \sqrt{\frac{\sum (\Delta)_i^2}{n-1}} \qquad \text{where,} \qquad \begin{array}{l} \Delta = (l - l_0) = \textit{Normalized Offset Distance} \\ n = \textit{Sample Size } (= 27) \end{array}$$

(Note: These standard deviation estimates are not true *repeatability* values with prescribed uncertainty levels or population sizes.) The results of several tests are summarized in **Table 2**.

Measurement Description	σ (μm)
4mm rods - 200μm tip - 20μm step size	0.7
Same except layer measured in forward & reverse	4.8
5mm rods - 100μm tip - mixed step size	12.8
5mm rods - 200μm tip - mixed step size	6.4
5mm rods - 300μm tip - 15μm step size	4.7
5mm rods - 300μm tip - 25μm step size	2.9
Straws - 200μm tip - 20μm step size	7.1

Table 2 - Optical Sensor measurement repeatability.

In the first case, the 4mm rods were measured with the 200μm fiber diameter optical bundle and a step size between measured points of 20μm was used. This combination of fiber size and step size produced the best repeatability results. The 4mm rods were then measured at one location transversely along their axis, first in one and then in the opposite direction to evaluate possible tip angle influence on the repeatability and accuracy results. The tip angle was not found to be a critical factor in the experiments and an angle of ±3° is allowable. Similar cases were run with the 5mm rods using various tip and step sizes and also using mixed step sizes. Finally, a layer of straws was installed on the Plate and the relative position of each straw was measured and compared, producing similar results. As **Table 2** shows, repeatability of the measurement of a straw tube layer is about 7μm (0.3 mil).

To evaluate the *accuracy* of the Optical Sensor device, only the precision steel rods were used as reference since their cylindricity is <1μm and their diameters are known within 2μm. The relative positions of the rods, when pressed together, are therefore known to approximately ±3μm serving as an adequate measurement reference. In each case the rods were scanned *once* and the fitted positions were compared with the

nominal value of 4mm *or* 5mm. Various combinations of step sizes and tips were used as with the repeatability evaluation and the accuracy was calculated using the following equation.

$$A = \frac{1}{n}\sum_{i=1}^{n}|\Delta_i| \qquad \text{where,} \qquad \begin{array}{l} n = \textit{Sample Size (9 Rods)} = 8 \\ \Delta_i = \textit{Linear Nominal Difference} \end{array}$$

The average differences for several measurement sets are listed in **table 3** and the results illustrate the *worst case* since all inherent machine and measurement errors are hidden in these values. The standard deviation of these offsets are also listed in the table and show a consistent accuracy offset since the standard deviation of the eight values is ~2-5μm. As was true for the repeatability tests, the best case when evaluating the accuracy is the 4mm rods with a 200μm diameter fiber tip and a step size of 20μm. As **Table 3** shows, the accuracy of measurement of the Optical Sensor is about 13μm (0.5 mil) for the 4mm rods.

Item			A (μm)	σ (μm)
4mm Rods	Trial #1	200μm Tip and	12.8	3.5
	Trial #2	20μm Step Size	10.6	2.8
	Trial #3	"	12.8	4.0
5mm Rods	Trial #1	300μm Tip and	19.3	5.1
	Trial #2	Mixed Step Size	14.5	2.4
	Trial #3	"	17.0	3.2
	Trial #4	"	13.6	1.9

Table 3 - Optical Sensor measurement accuracy.

5 - Conclusions

The Optical Sensor described herein has proven to be an excellent device for the measurement of straw tube drift cell positions. Using the optimal tip bundle with *six* 200μm diameter fibers and a step size of 20μm (0.8 mil) produces an average repeatability (standard deviation) of 7μm (0.3 mil) for straw tubes. The accuracy when measuring 4mm rods is 13μm (0.5 mil), which can be improved with an alternate measurement source since the LVDT used was not designed for micron resolution. This device itself proves quite capable for position measurement of straws or any other round and reflective objects.

The overall straightness of straw tube bundles can be evaluated by referencing the Optical Sensor measurements at several axial positions to a fiducial gold plated wire. The transverse locations of the straw tubes relative to the wire should be determined to a resolution (σ) of ~13μm (0.5 mil), although the precise value will depend on the quality of the straw tube surface and the measurement reference used.

Appendix - Equipment Setup

A.1 System Configuration

The system configuration (**Figure A-1**) is based on a PC-AT computer. The processor board has an Intel 80286 cpu and 1Mb of RAM, one parallel port, two serial ports and 8 bus slots. Mass storage is provided by a 40Mb hard drive and 1.4Mb 3.5" floppy disk drives. The operating Environment is MS-DOS v5.0, and the monitor is monochrome.

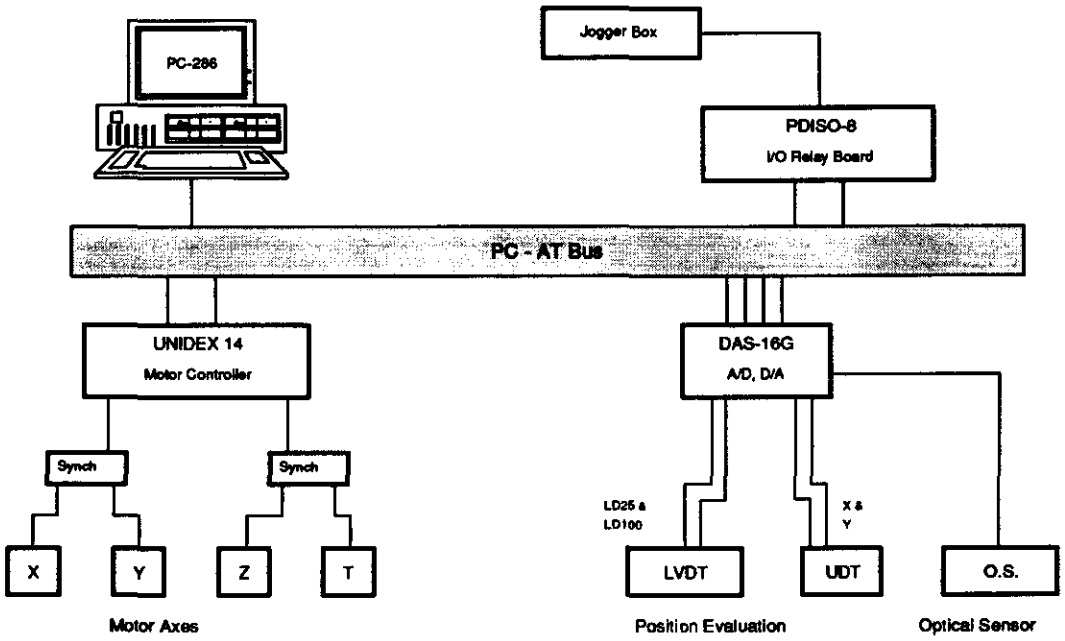

Figure A-1 - System configuration.

The Aerotech UNIDEX 14 drive controller communicates with the computer via an interface card which uses 4 consecutive bits starting at Hex-300. The controller reads simple mnemonic commands written to the bus to control the four motors (two axes). In order to synchronize the motors for each axis, the CONTROLS software first writes acceleration, velocity and distance information to the controller and then synchronizes the initiation of a move command so that the slides remain aligned throughout the operation.

The DAS-16G data acquisition board operates in much the same way as the UNIDEX 14 board and uses 16 consecutive bits starting at Hex-310. This board has eight 12-bit A/D channels and eight D/A channels available. Channels 1 and 2 are used for the UDT Detector's X and Y axes, channels 4 and 5 are used for the LVDT 25 and LVDT 100 respectively and channel 3 is used for the Optical Sensor output voltage. DC voltage offsets for each channel can be adjusted using variable resistors or by setting the offset using the *channel offset* routine in the CONTROLS software. Any channel can be monitored by selecting the transducer and *monitor* mode from the inputs menu.

The PDISO-8 Input / Output relay board is used to control the machine in remote mode using a hand held **Jogger** and also to control air supply for the automatic straw pickup and feeder (this latter feature is not implemented). PDISO-8 requires 4 consecutive bits starting at Hex-308 and the first two bits are used for input and output. The board provides eight input and eight output channels and the channels are bit operated, i.e. writing a byte to the output address with bit 3 *on* would turn the output channel 3 *on*.

A.2 Software Overview

The CONTROLS software package consists of three parts, the CONTROLS interfacing program for actuation and data collection, the CONVERT and CONVERTG conversion programs for data formatting and the FITGAUS2 gaussian fitting program used to fit Optical Sensor output to a gaussian function to find a straw's midpoint.

The programs CONVERT and CONVERTG convert various formats of data produced by the CONTROLS program during straw measurement (scanning), equipment monitoring or other routines. Using the switches L, M or G the program converts an input file to LVDT, Motor or "G" (Spreadsheet) format. LVDT and Motor formatted files can be read directly by the FITGAUS2 program as input files for the fitting routine.

The CONTROLS program is an interactive, menu-driven software package used to control the machine. The user interface consists of selected menus displayed at the top portion of the screen, with a *Work Area* below used for communications and a *Help/Warning Area* used to display help, status and warning messages. In addition, the current (selected) action is explained on the bottom of the screen. A brief overview is given below.

Straw Scanning Routine

Used to monitor, set up and initiate the scanning of straws. Data can be saved in files ending with the .OUT extension, and a file can be archived for backup. Options such as step size and straw spacing can be selected.

LVDT to Motor Correlation Routine

Used to correlate motor step size with the LVDT. The new calibration factor is calculated and stored until the CONTROLS program is terminated.

Straw laying Routine

This routine can be used to facilitate the laying of straw layers. The UDT detector is used to position the Straw Guide (vertical) axis to within 30μm. Motor parameters such as distance, velocity and acceleration for both axes can be preselected before entering this routine.

Controls Axis Setup (Plate *and* Straw Guide)

These menus are used to select axis acceleration, velocity and move distance as well as other parameters. The units can be set to *Inches*, *mm*, *Microns* or *Motor Steps*.

Monitor Mode

For each measurement input (i.e. LVDT, UDT or Optical Sensor) a timer can be set and sample size, calibration factors, channel DC offset and gain can be modified.

A.3 Machine Layout

The machine base consists of a double axis structure as shown in **Figure A-2.** Actuation is performed by four precision servo drive motor slides controlled by a UNIDEX14 motor controller using an internal velocity feedback loop to control position and velocity. The Straw Guide or vertical axis consists of a precision four meter long ground steel beam with a flatness of 25μm (1 mil). For horizontal positioning, the Plate axis consists of two aluminum plates with a flatness of 125μm (5 mils). The least significant bit (LSB) position resolution for both axes is 1μm (0.04 mil) and the controller/motor combination produces a true position repeatability of 5μm (0.2 mil) for the Plate axis and 10μm (0.4 mil) for the Straw Guide axis. The mounting brackets for the motors and slides are all made of precision ground steel and are flat to within 25μm (1 mil). The servo motors and four axis controller are supplied by Aerotech and the data acquisition boards and LVDTs are supplied by Omega Inc..

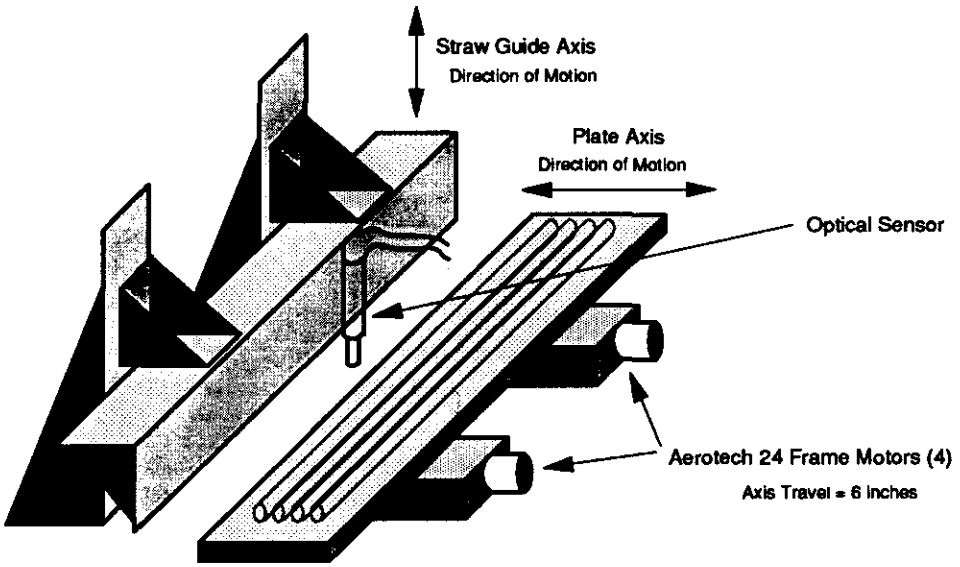

Figure A-2 - Straw laying and measurement machine.