An Optical Tactile-Array Sensor

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ABSTRACT

This paper describes a new type of tactile sensor intended for robotic applications. It is based upon the frustration of total internal reflection at an optical surface caused by an opaque elastic membrane. An optical image is created in which the intensity is monotonically related to the strains or pressures created by an impressed object. This image is subsequently converted to digital form by a CID camera. The performance characteristics of two planar tactile array sensors are presented.

The first sensor is a tactile "table" with an active area measuring 7 x 12 cm. A 128 x 128 pixel CID camera is used to image a 3.3 x 3.3 cm section of the active area, thereby resulting in an effective tactile element density of 1500 taxels/sq-cm. The second sensor is a small, compact unit designed for use on robot gripper fingers. A coherent cable of optical fibers convey the strain image to a remotely-located CID camera, resulting in a tactile element density of 54 taxels/sq-cm over an active area measuring 2.2 x 2.5 cm. Such optical tactile sensor arrays are seen to offer significant promise in the area of robotics where they can provide the advantages of high spatial resolution and non-planar sensor geometries (e.g. cylindrical and hemispherical).

This paper was presented at the SPIE conference on Intelligent Robots and Computer Vision held in Cambridge, Massachusetts, November 1984.

INTRODUCTION

It is generally accepted that robots must be equipped with vision, touch, and force sensors if they are to adequately perform tasks such as parts manipulation, assembly, and object manipulation. An additional benefit of sensor-equipped robots is that costs can be reduced significantly by avoiding the need for precision mechanical components. Massive rigid structures may be replaced by ones using light weight materials such as aluminum, plastics and high strength composites.

This paper is concerned with tactile sensors for robotic applications. The characteristics that a good tactile sensor should possess are summarized in Table 1.

TABLE 1

Desirable tactile sensor characteristics for robotic applications.

- Low cost
- High ruggedness
- Low sensing head volume (compactness)
- Easily tailored sensor shape (planar, hemispherical)
- Compact communication/interface cable
- On-board preprocessing capability
- Monotonic response (preferably linear)
- Low hysteresis
- Frequency response from 0 to several hundred Hertz
- Freedom from cross-talk (ghosting, cross-coupling)
- Good lateral spatial resolution
- Large depth resolution and range
- Large force resolution and range
- Good reproducibility
- High accuracy
- Low drift

Examples of technologies employed in the fabrication of tactile sensors include; electrical conduction [1-3], optical [4,5], capacitative [6], piezoelectric [7], magnetic [8], and mechanical [9]. Two general reviews have been provided by Harmon [10,11].

The sensor described in this paper is based on an optical force-transduction method. Contact forces are converted into an visually perceivable image (henceforth called an imprint) in which the light intensity is monotonically related to the applied pressure distribution. The following sections describe the transduction process in more detail, and present the performance of two different implementations of this technology.

DESCRIPTION OF THE OPTICAL TACTILE SENSOR

The use of optical phenomena to transduce contact pressure and shape information into a computer-readable form is not new. Bejczy [4], for example, describes a 4 x 4 tactile sensor array (TSA) that relies upon optical reflection. Each sensing element was an optical fiber pair consisting of an emitter and receiver, each pair being placed at a fixed distance from a reflective elastomer membrane. The latter was deflected inwardly by forces associated with contacting objects and thus changed the quantity of reflected light detected by the receiving fiber.

Rebman and Trull [5] describe a sensor manufactured by the Lord Corporation of Cary, North Carolina (model LTS 200). It transduced mechanical strains associated with object contact into an electrical signal by eclipsing a light beam with a mechanical edge connected to an elastic membrane. Thus, force and displacement response characteristics could be altered independently of the strain transduction mechanism, leading to freedom from crosstalk, greater flexibility in design, and inherently high ruggedness. This sensor had 16 tactile elements (taxels) per sq-cm over an active area measuring 2 x 3 cm. Each taxel had a force range of 0 - 1.2 N and a resolution of 0.2 N.

The basic physical principle upon which our optical tactile sensor (OTS) is based involves the frustration of total internal reflection at an optical surface caused by contact between an object and an opaque elastomeric film resting upon the optical surface. (A similar effect may be observed by looking down into a glass of water and noting the disappearance of the silver lining wherever the outer surface of the glass is touched.) The general arrangement of components in the OTS is shown in Figure 1. A transparent plate is illuminated from one or more edges. Most of this light is confined to the interior of the plate by total internal reflection at the two non-edge surfaces. Additionally, all edges through which light does not enter are made reflective so as to further minimize light losses.

A thin elastic transducer membrane is placed in contact with the transducing (top) surface of the transparent plate. This membrane is opaque and suitably textured on one side, e.g. possessing a distribution of pyramidal, conical, or hemispherical asperities. Finally, a cover membrane is placed over the transducer membrane. The latter is black so as to screen-out ambient light. It also provides mechanical protection for the transducer membrane and serves as a mechanism for altering the response characteristics of the sensor.

An object pressed against the front of the OTS causes the asperities in the transducer membrane to come into contact with the transducing surface of the transparent plate, thereby frustrating total internal reflection at those sites where contact has occurred. Light normally confined within the transparent plate is absorbed by the opaque transducer membrane at the contact sites, and then diffusely re-emitted back into the transparent plate. However, this light is emitted at all angles, and some light rays will no longer satisfy the conditions for total internal reflection within the transparent plate, and may exit from the opposite side to be detected.

It is possible to infer the strains imparted by an object to the transducer and cover membranes from the average intensity of light in a local area of the imprint. In the idealized situation shown in Figure 1, each asperity is considered to be the center of a square cell. The average intensity of light emanating from the cell is directly related to the fraction of the cell filled by the deformed asperity (assuming total internal reflection is fully destroyed wherever contact occurs between the asperity and the transducer surface). By this mechanism, an imprint may be acquired in which local light intensities represent the magnitude of the normal (but not shear) strains or forces associated with an object in contact with the sensor.

IMPLEMENTATIONS

This section will describe two tactile sensors that embody the priciples described above. The first sensor is a large-area tactile sensor (LATS), and the second is a small, compact optical tactile array (COTA) designed primarily for attachment to robot gripper fingertips. The primary difference between the two sensors is their physical size and the means by which the force imprint is transported from the transduction area to the camera.

Large-area tactile array:

A schematic of the LATS is show in Figure 2. The camera may be any device capable of imaging the imprint (e.g. photographic, solid state, etc.), and may be mounted from below or from the side (in the latter case, a front-surface mirror was used to deflect the image). The taxel density clearly depends on the camera and lens system employed to capture an imprint. The transparent plate is ordinary window glass, and provides an active tactile sensing area measuring 7 x 12 cm. Light is injected only through one edge of the plate, and the other edges are covered with aluminum foil to minimize light losses. The light scource is a 40 W bulb that possesses a linear filament 10 cm long. Aluminum foil is used as a reflective shroud to direct as much radiation as possible into the edge of the plate. Various transducer and cover membranes were employed in this study, and are listed in Table 2.

Figure 3 contains a sequence of tactile imprints taken with a 128 x 128 pixel CID camera that imaged a 3.3 x 3.3 cm section of the LATS, and shows imprints of objects that might be encountered in a robot environment. This configuration resulted in a tactile sensor with an effective taxel density of approximately 1500 taxels/sq-cm. Figure 3e was taken using the transducer membrane WP25 only, and illustrates the fine force and spatial resolution that the LATS is capable of achieving. These imprints may be interpreted as detailed normal-force maps associated with object contact, or as depth maps (of narrow range) that reveal the topology of the object surface. Ellis [12] discusses processing such imprints to extract tactile features such as edges, holes, and texture.

TABLE 2

Transducer and cover membranes used in this study.

Code	Description
Tranducer membranes:	
WP25	- White plastic (bread-wrapper), 25 micrometers thick.
WP125	- White plastic (frozen-food bag), 125 micrometers thick. Abraded on one side with coarse sandpaper to a matte finish.
L725	- Parallel rows of white Lycra fibers (sock) 600 micrometers diameter bonded to a tape backing 125 micrometers thick. 725 micrometers total thickness.
Cover membranes:	
BP125	- Black plastic sheet, 125 micrometers thick.
RB200	- Rubber sheet (balloon wall), 200 micrometers thick.
RB380	- Rubber sheet (balloon wall), 380 micrometers thick.
BN890	- Black neoprene sheet (rubber glove), 890 micrometers thick.

Compact optical tactile array:

The LATS is physically large and would only be used in robotic applications in which the part to be examined or operation to be performed could be brought to the sensor. In contrast, the COTA unit was designed to enable convenient installation on the fingertips of robot grippers. Figure 4 shows a prototype version of the COTA. It uses a coherent array of optical fibers to convey the tactile imprint to a remote location where it may be viewed with a camera. The sensor head measures 3.5 x 3.5 x 1.0 cm. 295 fibers are arranged in a trianglar array and are separated by a distance of 1.6 mm. The array measures 2.2 x 2.4 cm, yielding an effective taxel density of 54 taxels/sq-cm. Several tactile imprints are shown in Figure 5. The limiting factor in the resolution of a sensor based upon this approach is primarily determined by the optical fiber spacing and not upon the resolution of the imprint.

SENSOR CHARACTERIZATION

In this section, some performance characteristics (see Table 1) of the optical tactile sensors are examined.

The response characteristics depend on a number of interrelated parameters concerning the physical properties of the transducer and cover membranes, e.g. the total thickness of the membranes, the size and shape of the microtexture on the transducer membrane, and the mechanical properties of the membranes. These parameters directly influence the depth and lateral spatial resolution, force or strain response, degree of hysteresis, and time response characteristics of the sensor.

If the membranes are thick or if the microtexture on the transducer membrane is coarse, then the mechanical spread function will be large and fine spatial detail will be lost. However, the ruggedness will be high and the sensor will have a large depth sensing range. Furthermore, the mechanical properties of the transducer membrane and the shape of the microtexture would be expected to have a strong influence on the pressure range and the shape of the response curve, e.g. conical or pyramidal asperities might produce a significantly different response curve than hemispherical ones. This may make it possible to tailor the response to be linear, logarithmic, or whatever shape the particular application demanded.

The primary parameters that are considered here will be the total membrane thickness and the microtexture of the transducer membrane. The influence of the mechanical properties of the transducer or cover membrane upon the response characteristics are not considered here.

The response of the tactile sensor to uniform pressure was measured with the aid of the pneumatic pressure applicator shown in Figure 6. This device was capable of exerting uniform pressures of up to 0.414 MPa (60 psi) over an area measuring 13 x 13 cm. A single silicon photodetector with a response time of approximately 2 ms and a viewing window of 7 mm diameter was used to characterize the pressure response of the LATS with several transducer and cover membranes. The results are shown in Figure 7, where the light intensity output has been normalized in each situation to the maximum output occurring at the maximum applied pressure of 0.414 MPa (60 psi). The following points may be inferred from Figure 7:

1. All membranes result in a non-linear, monotonically increasing response with increasing pressure.
2. A noticable amount of hysteresis is present. Also, it is significantly larger for the L725 transducer membrane than for the WP125 membrane, and is possibly a reflection of the differing microtexture or surface adhesion properties of these two materials.
3. The pressure response characteristics are not dramatically influenced by the thickness of the cover material.
4. Despite the large differences in microtexture shape and size, the response of the L725 transducer membrane is very similar to that of the WP125 + RB200 + RB380 membrane. (Note that the total thicknesses are nearly the same.)

Sensor drift was assessed by applying a constant pressure of 0.345 MPa (50 psi) and monitoring the output over time. The results for the WP125 and L725 transducer membranes are shown in Figure 8. The drift is similar for both membranes and is seen to continually increase over a period of 300 seconds. This behaviour is satisfactory for most robotic applications in which the task execution time ranges from 0.1 to 10 seconds.

An assessment of the sensor response time was made by observing the output signal in response to an input pulse supplied by a rubber ball bouncing on the sensor surface. Typical output pulse widths were approximately 10 ms, indicating that the rise or fall response time of the sensor is no greater than 5 ms.

The relationship between the membrane thickness, microtexture, lateral spatial resolution, and depth resolution was qualitatively explored through the analysis of tactile imprints. One would intuitively expect that fine lateral or depth features would require the use of membranes that are "thin" or have a "fine" microtexture relative to the dimensions of the features of interest, i.e. it is neccessary to minimize the spread inherent in the transmission of stresses and strains through a homogeneous elastic medium. (However, more sophisticated transducer materials could employ decoupled elements to avoid this problem. Such materials have not been considered here.)

This interrelationship was demonstrated with the LATS using the CID camera. Figure 9a shows that WP125 + RB380 is a good combination for detecting details such as the columns in the building or the text on a penny. However, this combination does not have sufficient depth range to render an identifiable imprint of the head on a nickel: see Figure 9b. Conversely, Figure 9d shows that increasing the total membrane thickness to 705 micrometers does provide the needed depth resolution to acquire a good imprint, but, as Figure 9c shows, the sensor now lacks sufficient lateral or depth resolution to register the finer details on a penny.

A similar effect can be demonstrated regarding the size of the microtexture. The total membrane thickness was kept constant in Figures 10a and 10b, but WP125 and L725 were used as the transducer membranes, respectively. As expected, the larger microtexture of the L725 membrane resulted in a larger depth range, and thus could register deeper features compared to the performance of the other membrane.

CONCLUSIONS

A new optical tactile transduction technique has been presented. Two implementations have been discussed, one a large area tactile sensor and the other a compact tactile array suitable for mounting on robot gripper fingers. The response charcteristics of the sensor have been assessed, and the results show that the approach holds significant promise for applications in robotics. The primary advantages are high taxel densities, relatively steady static response, a high speed response of approximately 5 ms, and a force range of 0 to 0.414 MPa (60 psi).

FUTURE RESEARCH

The Laboratory for Perceptual Robotics is currently developing a tactile sensing system that acquires and processes tactile data under the control of a 16-bit microprocessor. Data will be supplied by a 32 x 32 optical tactile sensor array with an active area measuring 3.2 x 3.2 cm and packaged into a sensor head measuring 6.5 x 4.5 x 1.0 cm, thus resulting in a sensor with a taxel density of 100 taxels/sq-cm. Furthermore, future work will include the development of a fingertip sensor that is hemispherical in shape for use on the Salisbury Hand [13]. A current prototype measures 2.2 cm in diameter and has 625 taxels distributed over a cylindrical finger with and hemispherical fingertip, yielding an average taxel density of 70 taxels/sq-cm. The results of this research will be reported at a later date.

ACKNOWLEDGEMENTS

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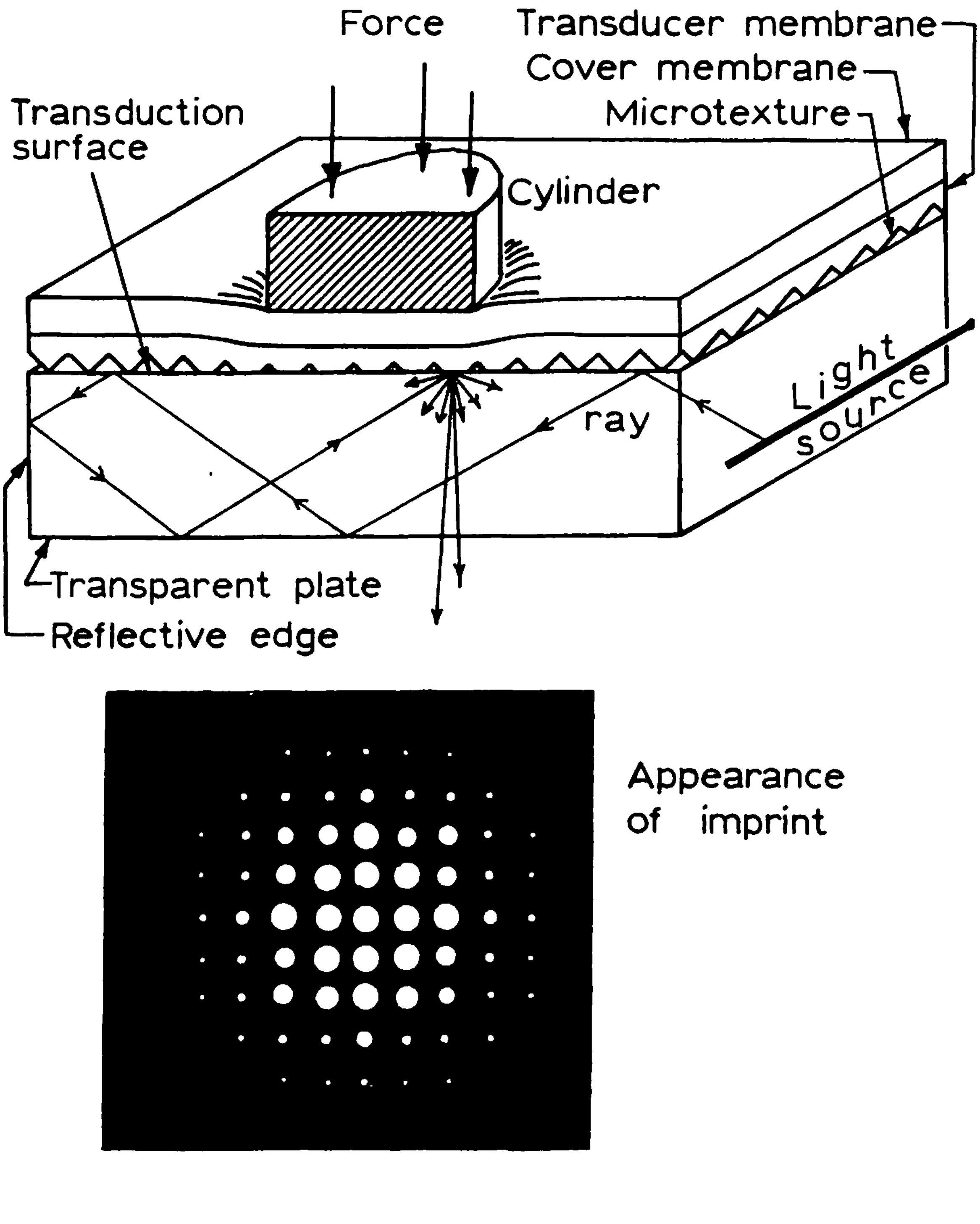

Figure 1: General construction of the OTS. Top diagram is a cross-sectional view. Bottom diagram illustrates how areas of greater contact appear as regions of higher intensity.

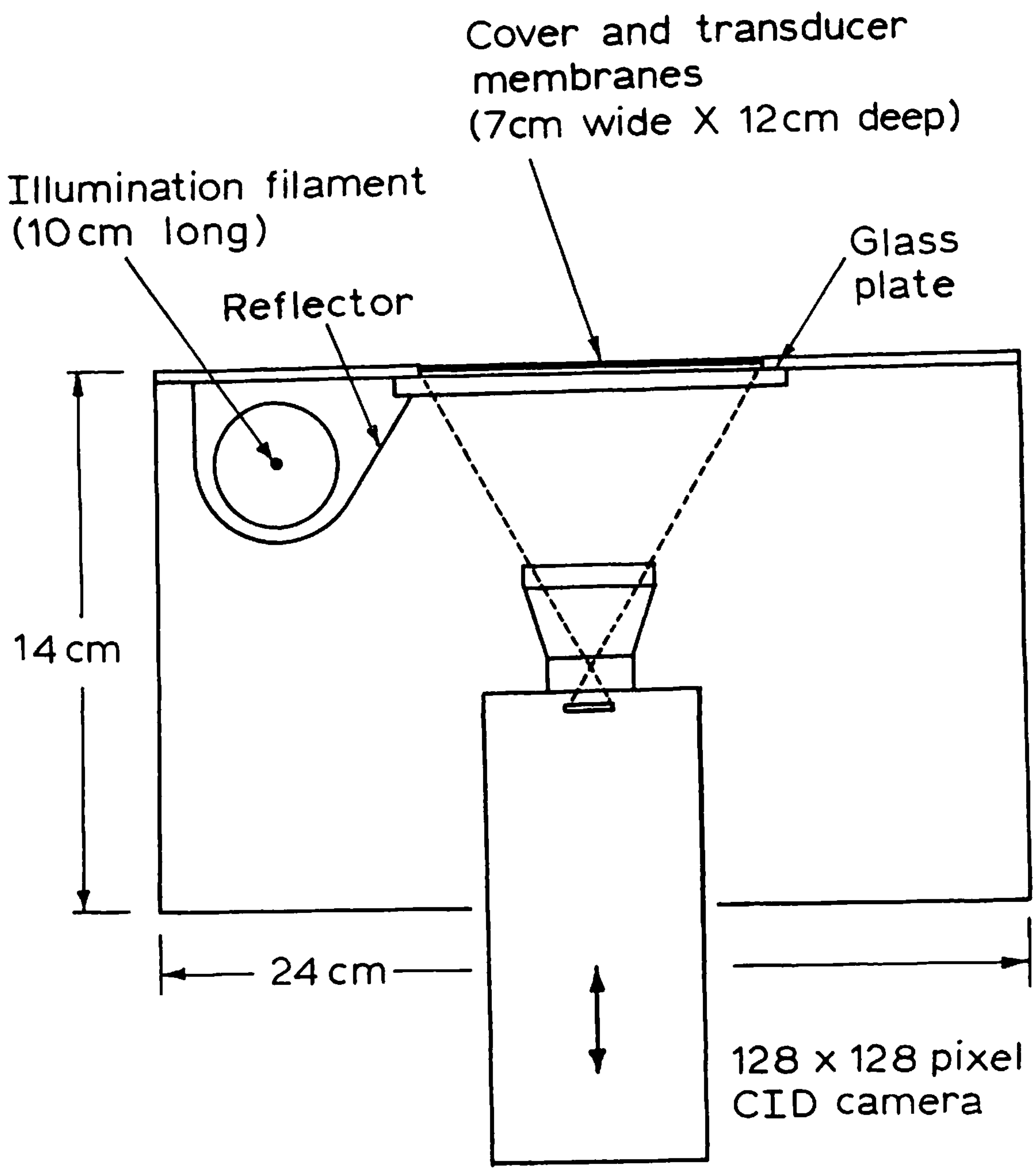

Figure 2: Cross-sectional view of the LATS. The resolution of the sensor may be varied by moving the camera along the vertical axis.

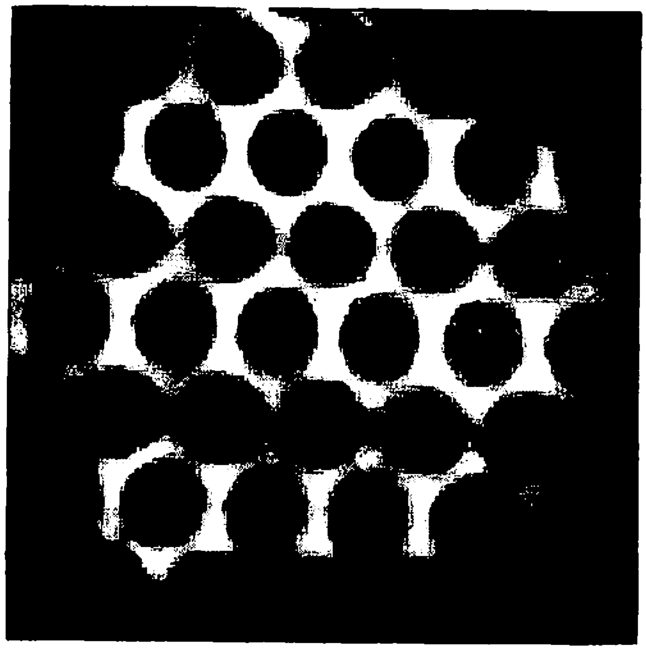

Figure 3a: LATS imprint of a perforated metal panel (WP125 transducer membrane with RB380 cover membrane).

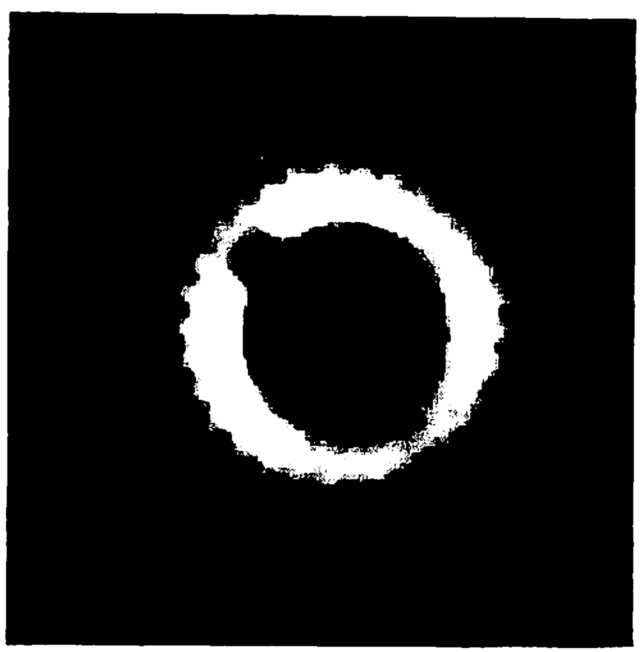

Figure 3b: Gear (WP125 + RB380).

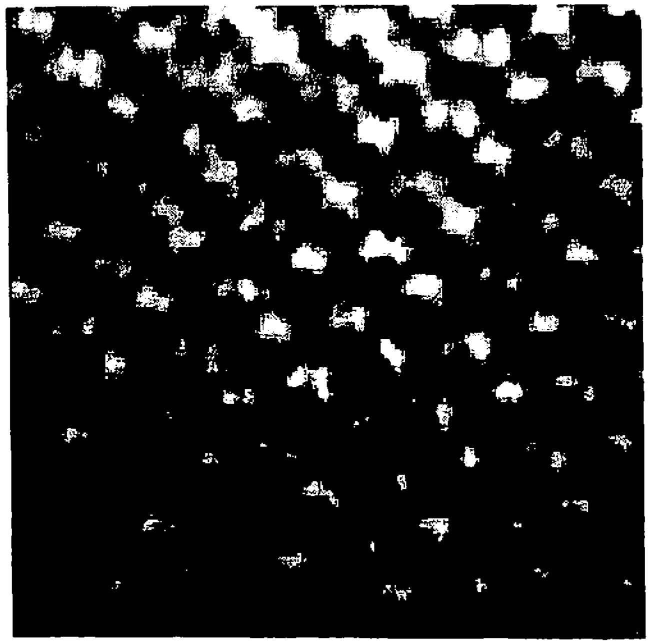

Figure 3c: Sweater (WP125 only).

Figure 3d: Penny (WP125 + RB380).

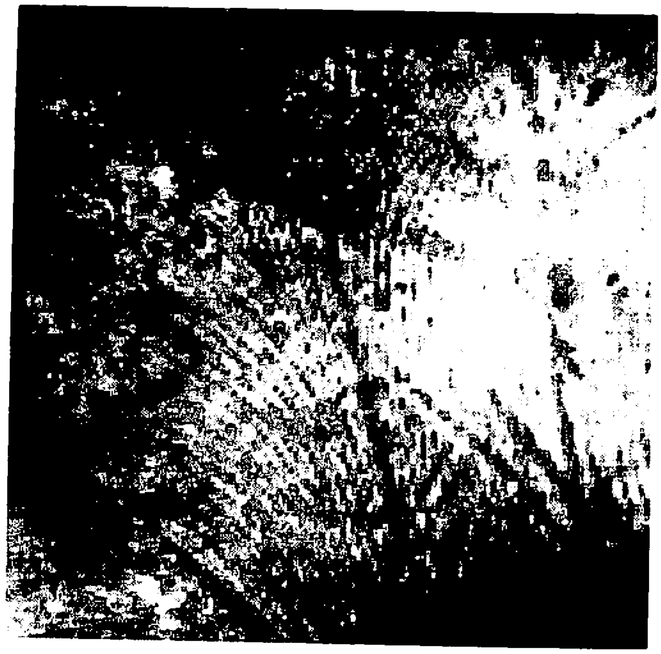

Figure 3e: Palm print (WP25 only).

Figure 3f: Printed circuit board showing the surface relief after etching (WP125 + RB380).

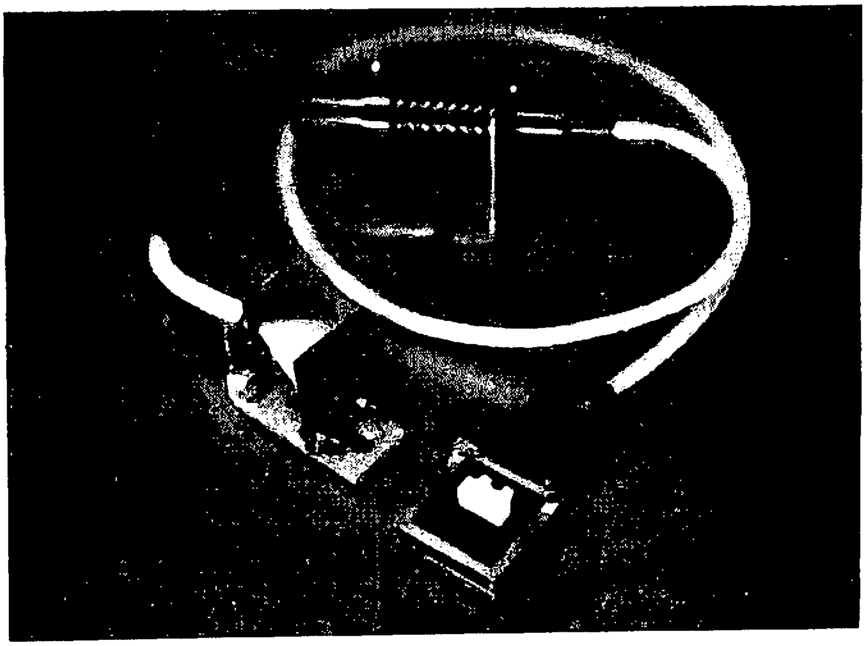

Figure 4a: COTA sensor head (bottom), optical fiber display array (center), and illuminator unit (top).

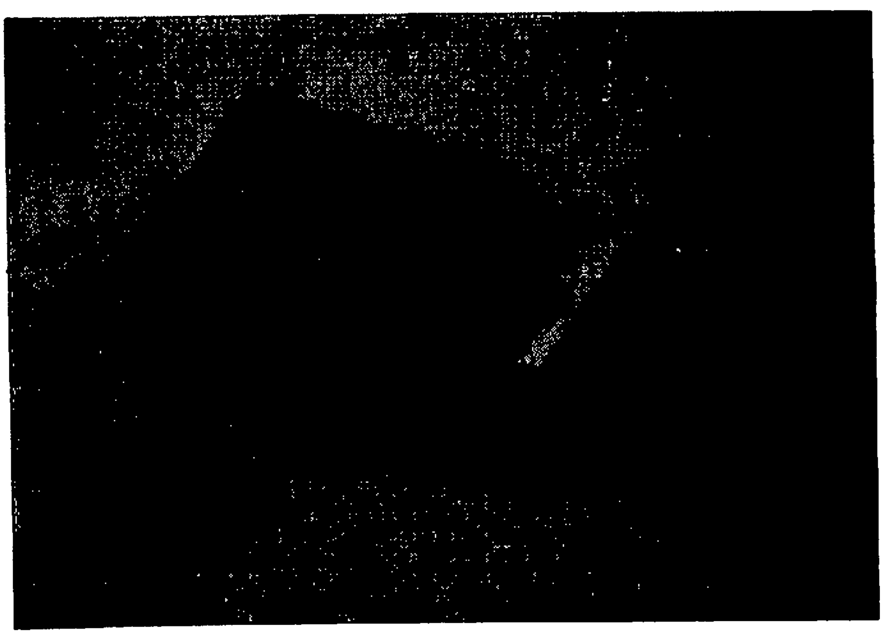

Figure 4b: Details of COTA sensor head. The cover membrane has been removed to reveal the L725 transducer membrane.

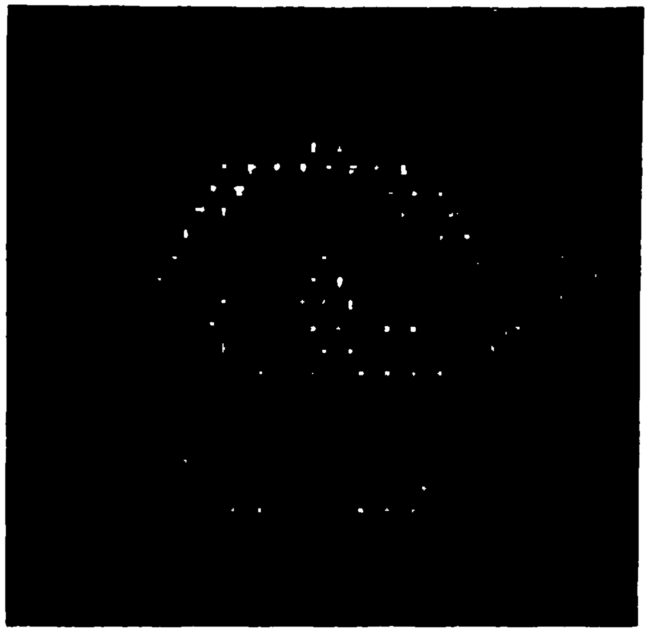

Figure 5a: COTA sensor imprint of the back of a nickel (L725 transducer membrane with BP125 cover membrane).

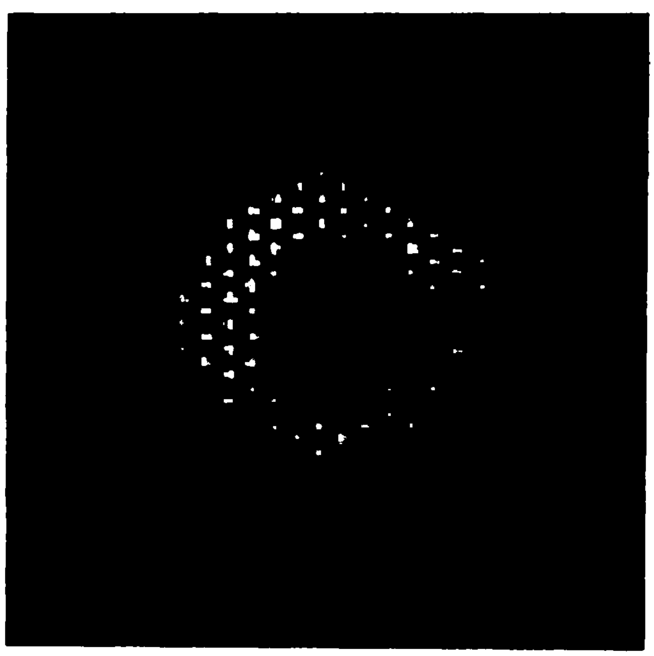

Figure 5b: Gear imprint (L725 + BP125).

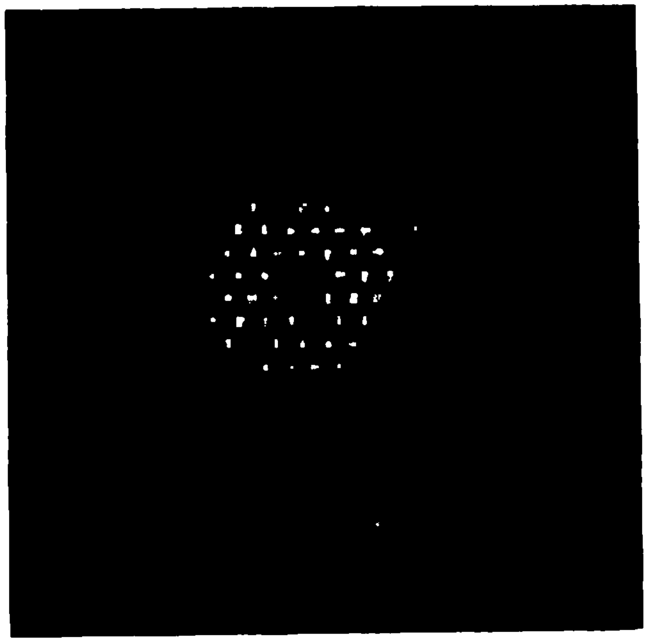

Figure 5c: Phillips head screw imprint (L725 + BP125).

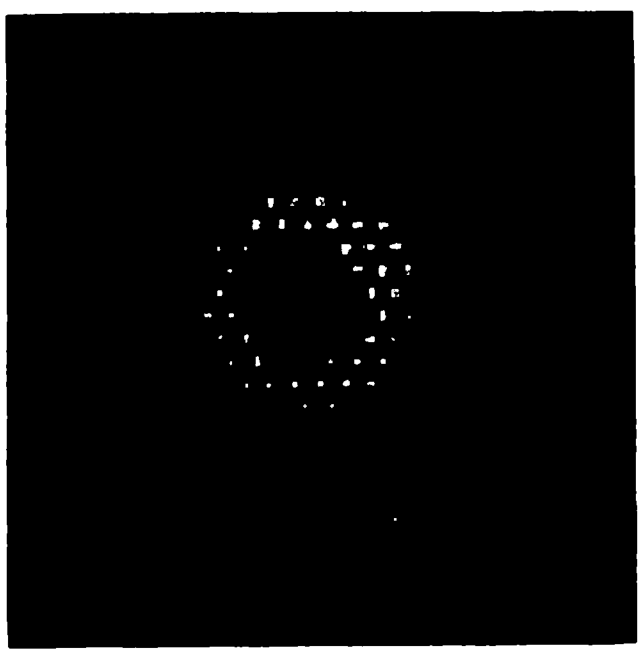

Figure 5d: Allen head screw imprint (L725 + BP125).

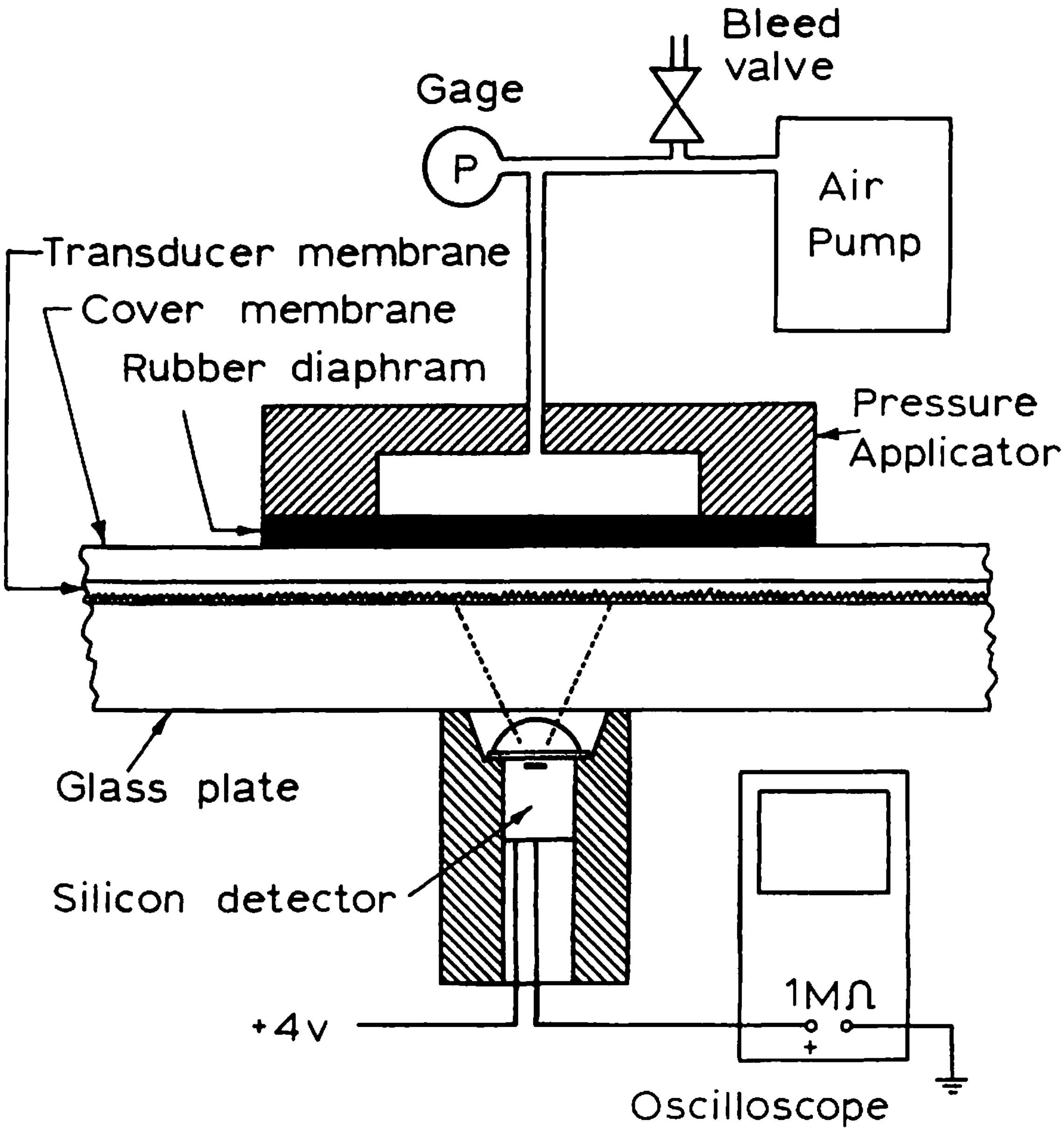

Figure 6: Pressure applicator and light sensor used to evaluate the response characteristics of the OTS.

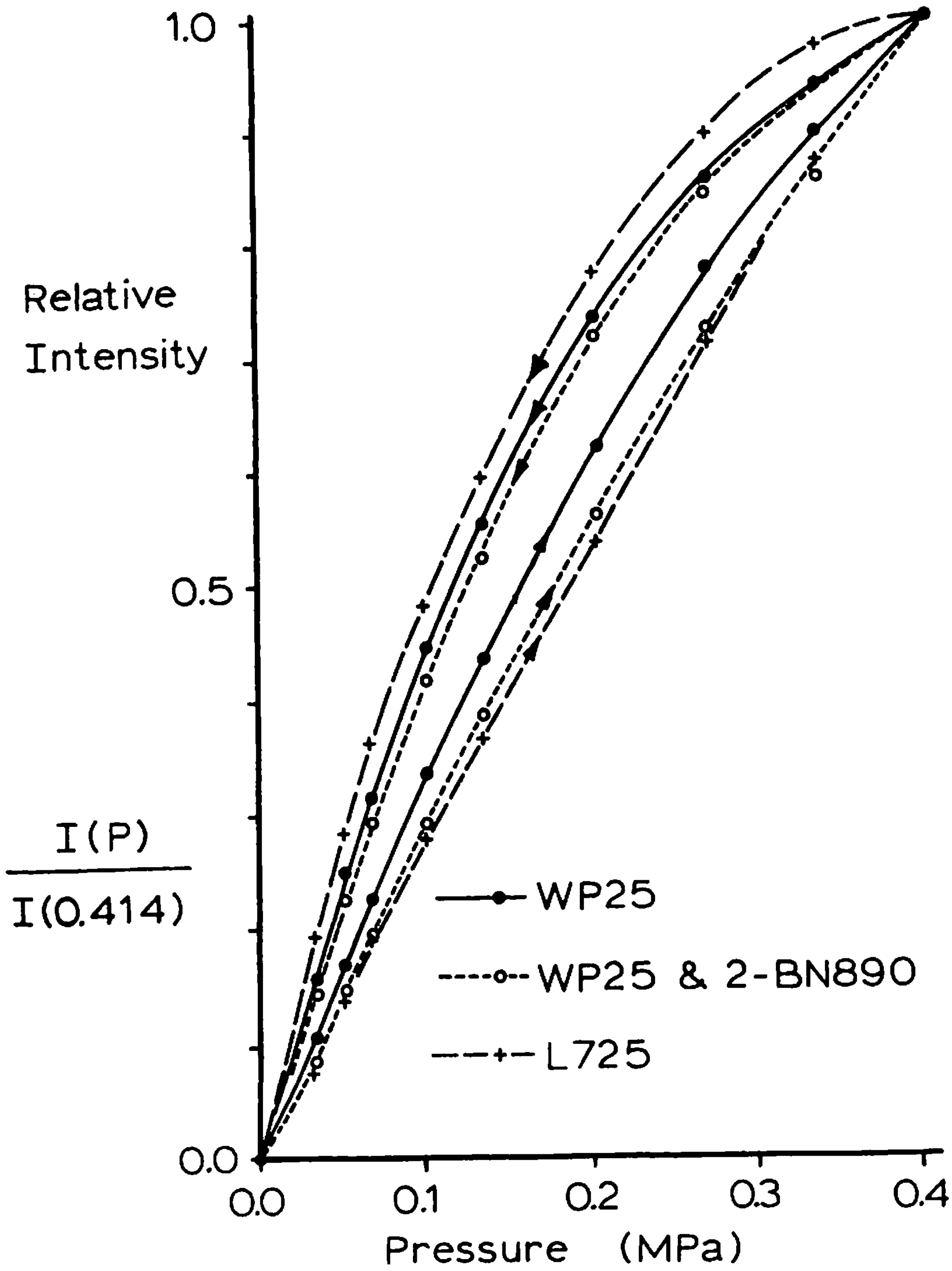

Figure 7: Pressure response characteristics of the OTS for various transducer and cover membranes.

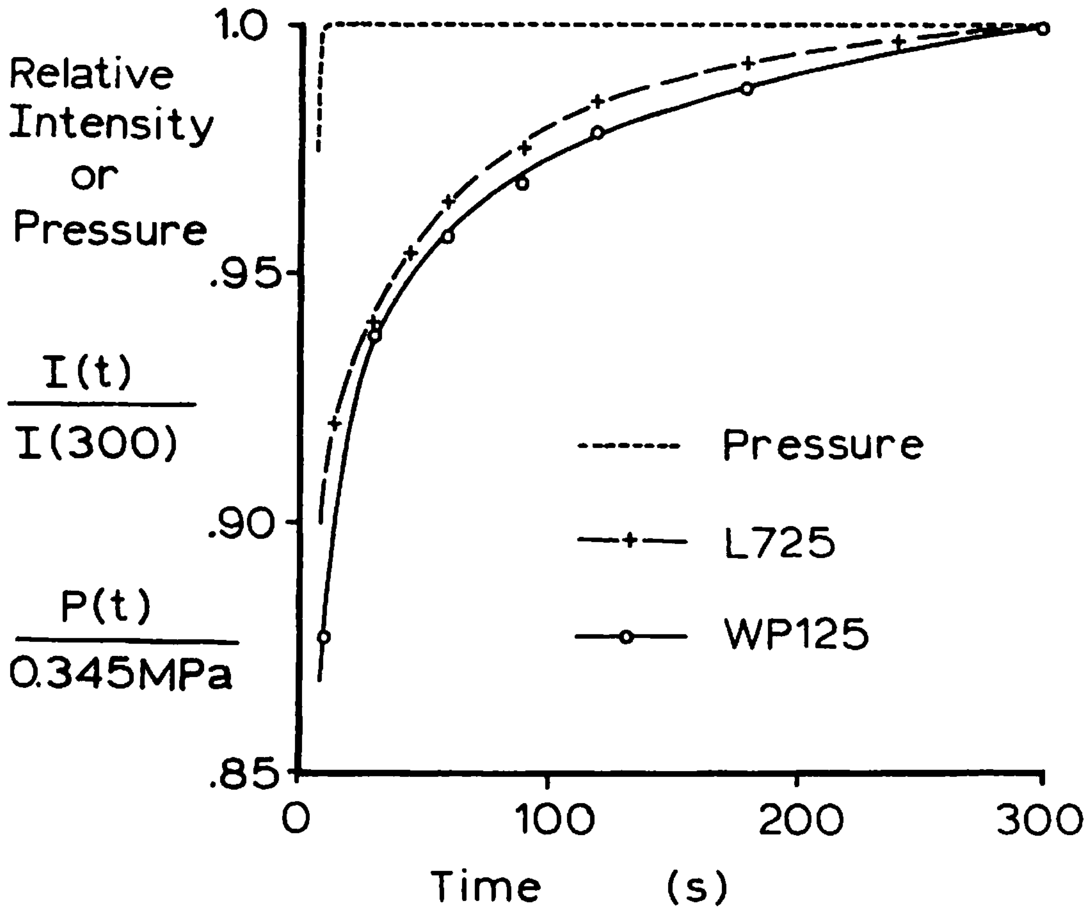

Figure 8: Drift in the pressure response of the OTS for the L725 and WP125 transducer membranes under an applied pressure of 0.345 MPa (50 psi).

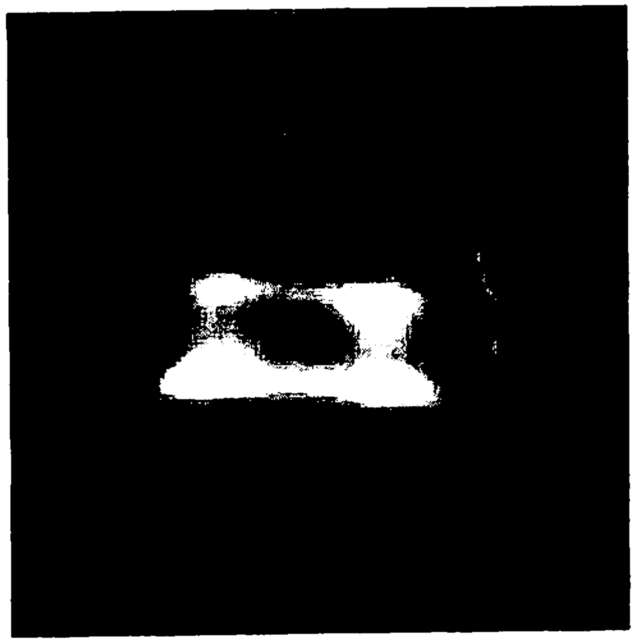

Figure 9a: LATS imprint of a penny under 28.9 N load. The WP125 transducer membrane and RB380 cover membrane was used.

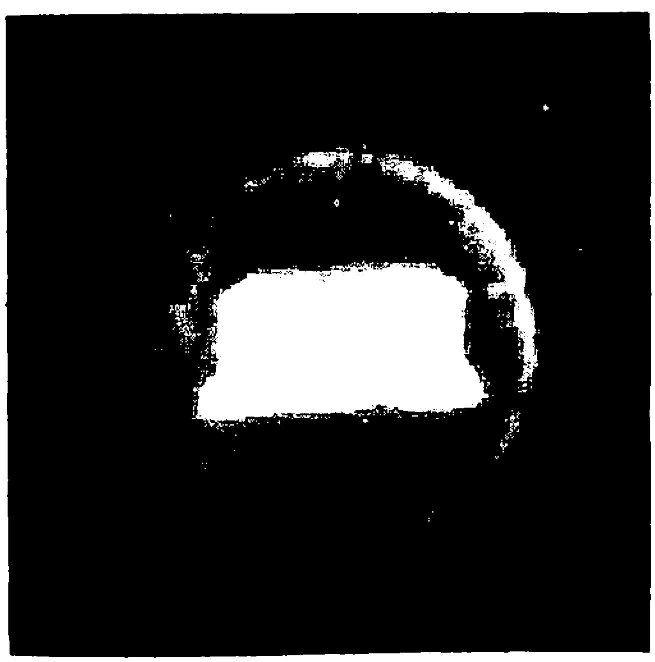

Figure 9c: Same as 9a except using the BN890 cover membrane.

Figure 9b: LATS imprint of the front of a nickel under 28.9 N load. The WP125 transducer membrane and RB380 cover membrane was used.

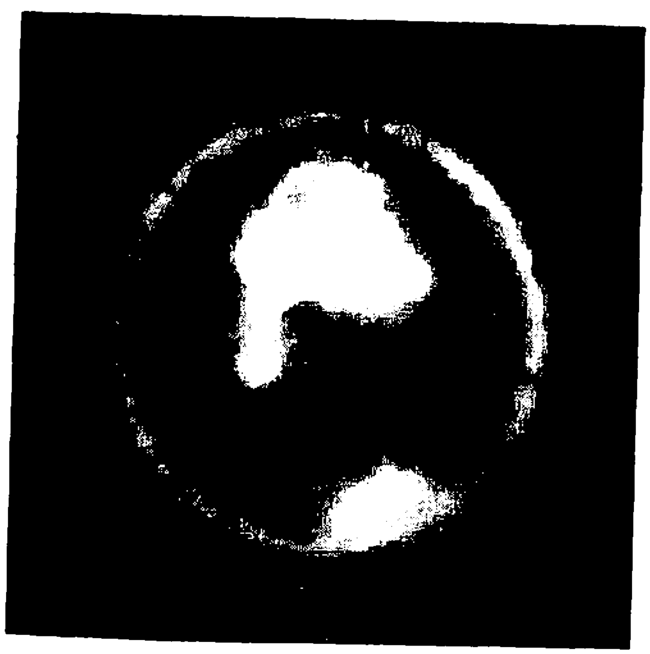

Figure 9d: Same as 9b except using the BN890 cover membrane.

Figure 10a: LATS imprint of the front of a nickel under 28.9 N load. The WP125 transducer membrane and RB200 + RB380 cover membranes were used.

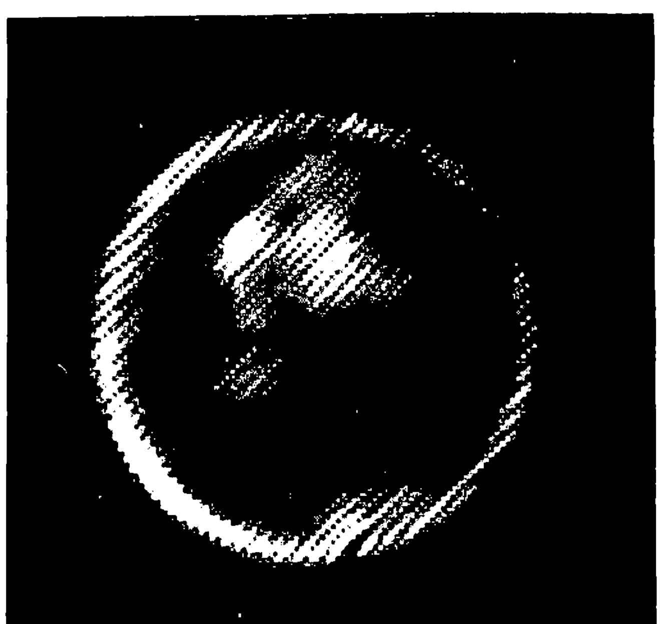

Figure 10b: Same as 10a except using the L725 transducer membrane and no cover membranes.