FINGERTIP-SHAPED OPTICAL TACTILE SENSOR FOR ROBOTIC APPLICATIONS

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ABSTRACT

Progress is described regarding the development of a high-density, fiberoptic, fingertip-shaped tactile sensor specifically designed for application to dexterous robotics. The sensor operates on optical principles involving the frustration of total internal reflection (TIR) at a waveguide/elastomer interface, and generates a grey-scale tactile image that represents the normal forces of contact. The sensor contains 256 taxels (sensing sites) distributed in a dual-density pattern that includes a tactile fovea near the tip which measures 13 x 13mm and contains 169 taxels. The details regarding the design and construction of this tactile sensor are presented, in addition to photographs of tactile imprints.

INTRODUCTION

Tactile sensation is an important element of any manipulation system in which high dexterity plays a prominent role, e.g., robotics, teleoperation, and prosthetics. Numerous tactile technologies have been explored over the last decade, e.g., piezoresistive, piezoelectric, magnetic, optical, capacitive, and sonic, and many planar tactile arrays have been developed for low dexterity applications involving simple parallel-jaw grippers (for general reviews, see Harmon [1] and Hollerbach [2]). However, there are few sensors available for highly dexterous end-effectors such as the JPL/Stanford (Salisbury [3]) or the Utah/MIT (Jacobsen et al. [4]) hands. Some important sensor characteristics required to effectively control such devices are:

1) Ability of the sensor to assume the geometry of the dexterous robotic fingertip.

2) High taxel density corresponding to that of a human fingertip (e.g., 100 taxels/cm^2).

3) Capability of sensing both normal (vertical) and shear components of force at each taxel site.

4) High reliability and ruggedness in a variety of mechanical, electrical, and chemical environments.

The conductive elastomer approach by Allen and Bajcsy [5], the piezoelectric approach by Dario et al. [6, 7], the capacitive approach by Fearing [8, 9], the strain gage approach of Brock and Chiv [10], and the optical approach currently under development by the author are the leading examples of efforts to develop tactile and force sensors that exhibit some of the above-mentioned characteristics. This paper summarizes the author's efforts in developing an optical, fingertip-shaped tactile sensor specifically designed for dexterous robotic applications.

PRINCIPLES OF OPERATION

Figure 1 illustrates the principles of operation underlying the optical tactile sensor. Light is injected into the edge of a planar waveguide where it is initially confined by total internal reflection (TIR) between the parallel faces. A white, textured, plastic membrane is placed in contact with one face of the waveguide. Forces exerted against this membrane cause TIR to be frustrated at the contact locations due to light absorbtion by the membrane material. That fraction of diffuse light emanating from these contact locations that no longer satisfies the angular conditions for TIR within the waveguide is then observed when it emerges through the opposite face.

The primary advantages of this technology are: 1) non-planar, compact sensor designs are feasible, 2) high taxel densities are possible, 3) the capability exists of sensing both shear and normal contact forces (though the device described

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herein only detects the normal force component), and 4) high immunity from electromagnetic interference in the robot's work environment.

TIR sensor technology has been employed in many pressure, position, and touch sensing applications. Betts et al. [11, 12] described a TIR device that was used to determine the pressure distribution associated with the human foot, and a similar approach was employed by Kissinger et al. [13] in a study concerning skin microvascularization. Kasday [14] described a binary (on/off) TIR touch device designed for determining the touch position on a cathode ray tube (CRT) screen, and a similar optical switch (using an array of light-emitting diodes rather than a CRT) is offered by OptiSensor (Askim, Sweden).

Several researchers have independently applied the TIR approach to the development of tactile sensors specifically intended for robotic applications, e.g., Mott et al. [15], Tanie et al. [16], Begej [17, 18], and White and King [19]. These sensors were all planar in geometry, with the central differences between these efforts being the methods used to visually detect the tactile imprint.

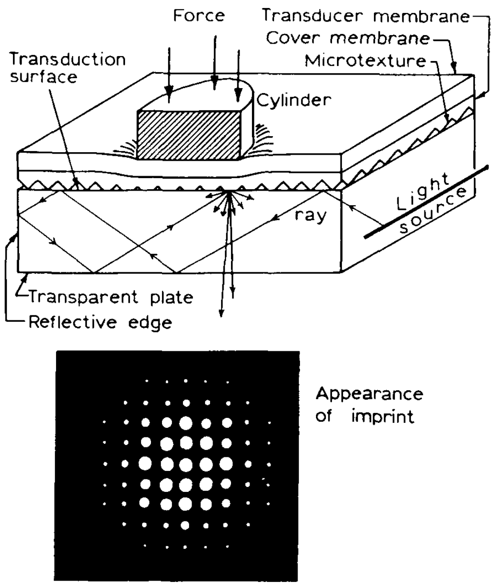


FIGURE 1: General arrangement of components for sensing force or pressure distributions by frustration of total internal reflection. Bottom diagram illustrates how areas subject to higher pressures appear as regions of higher average light intensity.

FINGERTIP-SHAPED TACTILE SENSOR

Early Development Efforts:

An important feature of the TIR approach is that numerous sensor geometries are feasible (e.g., curved waveguides such as cylinders and hemispheres), provided the thickness of the waveguide is small compared to its curvature so to minimize light losses. The first TIR fingertip-shaped sensor developed by the author utilized the end of a 25 mm diameter pyrex test tube as the waveguide element, and employed a small "fisheye" lens located inside the finger to image the tactile imprint onto the end of a coherent, 25 x 25-element optical fiber cable.

A photograph of this first sensor is shown in Figure 2. The lens element had a field-of-view of approximately 170 degrees and was positioned 25 mm from the tip of the finger. This enabled capture of the tactile imprint over the entire hemisphere of the fingertip in addition to a 10 mm portion of the adjacent cylindrical section. The transduction membrane consisted of a white polyethylene sheet 25 um thick that was folded over the fingertip and held in place with a black neoprene cover 890 um thick. The waveguide was illuminated through the edge using an array of optical fibers coupled to an external high-intensity light source.

Figure 3a shows the tactile imprint generated by this sensor when pressed into a corner consisting of three perpendicular walls, whereas Figure 3b shows the imprint of a 12 mm diameter hole in a washer. If

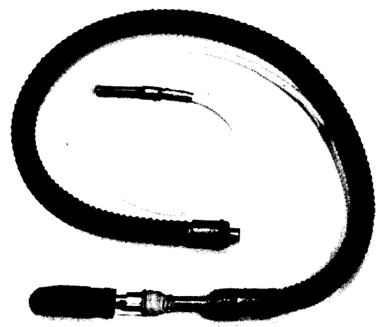
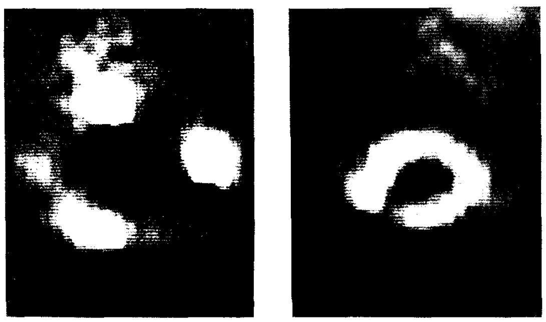


FIGURE 2: Photograph of the lens-based, fingertip-shaped tactile sensor (shown at bottom), display array and camera coupler (center), and illuminator coupler (top).

this sensor were appropriately calibrated, the information present in the single imprint shown in Figure 3a would be sufficient to permit extraction of the local geometry of the surface patches in contact with the sensor (e.g., planar), and also permit computation of the surface normals from which the relative orientation of the patches could be determined (e.g., mutually perpendicular). This same task performed with a planar sensor would be much more laborious, as multiple sensor placements would be required to fully explore the corner.

The primary problem associated with this first fingertip-shaped sensor was its long length. Some shortening could have been affected by reducing the dimensions of the illumination array and the coupling member between the sensor and image cable, but little could be done to shorten the optical path in lens system. This situation inspired a search for other designs for a compact fingertip sensor suitable for dexterous robotic hands.



(a) (b)

FIGURE 3: Tactile imprints generated by pressing the lens-based fingertip-shaped tactile sensor into (a) a corner, and (b) a washer with a 12 mm diameter hole.

Fiber Optic Tactile Sensor:

To achieve the desired degree of compactness, the lens arrangement used to image the tactile imprint was replaced with a direct imaging technique utilizing an aboral distribution of optical fibers ("input array") located inside the fingertip and placed directly adjacent to the waveguide element. The general characteristics of this fingertip sensor are summarized in Table I, and a photograph is shown in Figure 4.

TABLE I

General characteristics of the fiberoptic, fingertip-shaped tactile sensor.

Number of taxels:	256
Taxel spacing:	1 mm over tactile fovea area (169 mm^2), 3.2 mm over remaining area (811 mm^2)
Size (sensor head):	21 mm dia 31 mm long
Mounting post:	4.65 mm dia 10 mm long (i.e., Salisbury hand [3])
Force detection:	Normal forces only. (Shear forces are not detectable.)
Force range:	0 - 0.4 N/taxel
Frequency response:	0 to 200 Hz
Immunity to electrical interference:	Very high due to optical nature of sensor.
Image array dimensions:	19 mm wide 21 mm high
Image cable length:	0.76 m
Illuminator cable length:	0.87 m

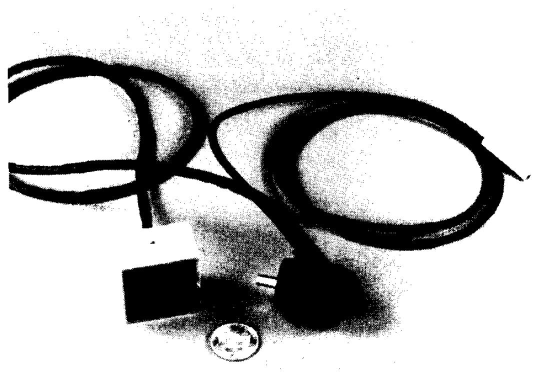


FIGURE 4: Fiberoptic, fingertip-shaped tactile sensor. Shown from left to right are the output array, sensor, and illuminator cable.

In general, the fiberoptic tactile sensor was similar in size, shape, and taxel distribution to it's human counterpart. The size corresponded approximately to the tip of a human thumb, though somewhat more cylindrical in cross-section. Additionally, the taxels were distributed in two densities to approximate the variation in density observed in human fingers. The principal functional distinction between this sensor and a human fingertip was that the former was only capable of detecting normal forces, while the latter can detect both normal and shear forces.

A cross-sectional view of the sensor is shown in Figure 5. The sensor had two optical fiber cables emanating from it, the first being an image cable (256 plastic fibers, 125 um diameter) used to transport the tactile imprint to a remote display (output) array, and the second being a smaller optical fiber cable (38 fibers, 254 um diameter) used to illuminate the waveguide ("transduction substrate"). The total number of taxels (256) was selected as a compromise between the desire for a large quantity of tactile information and the need to minimize the diameter (i.e., maximize the flexibility) of the image cable.

The distribution of taxels on the fingertip was motivated by the observation that the taxel distribution on human fingertips is non-uniform, being high on the tip (opposite the fingernail) and lower elsewhere. This distribution was approximated in the TIR fingertip sensor by placing a high density (1 taxel/mm^2) tactile fovea containing 169 taxels on the underside of the fingertip, and a lower taxel density (0.1 taxel/mm^2) elsewhere. No taxels were placed on the back of the fingertip or on the fingernail area. This distribution pattern is shown in Figure 6.

The distribution pattern in the output array is shown in Figure 7. It reflects a compromise between a display that presented the tactile imprint to a human observer much as it would appear if it were possible to place the eye within the fingertip, and a display that formed a regular lattice to maximize the efficiency with which a solid state imaging array could be utilized to capture a tactile image.

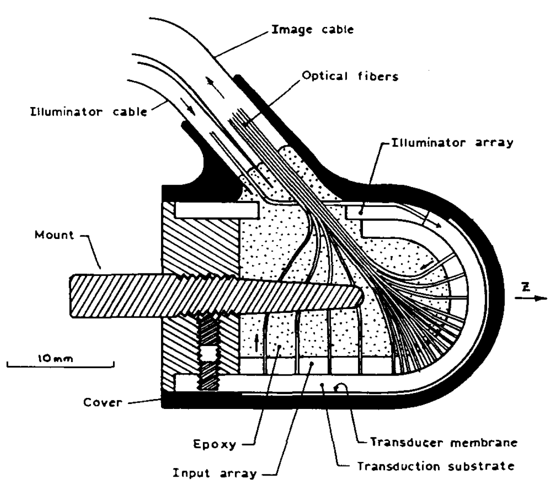


FIGURE 5: Cross-sectional view of the fiberoptic, fingertip-shaped, TIR tactile sensor.

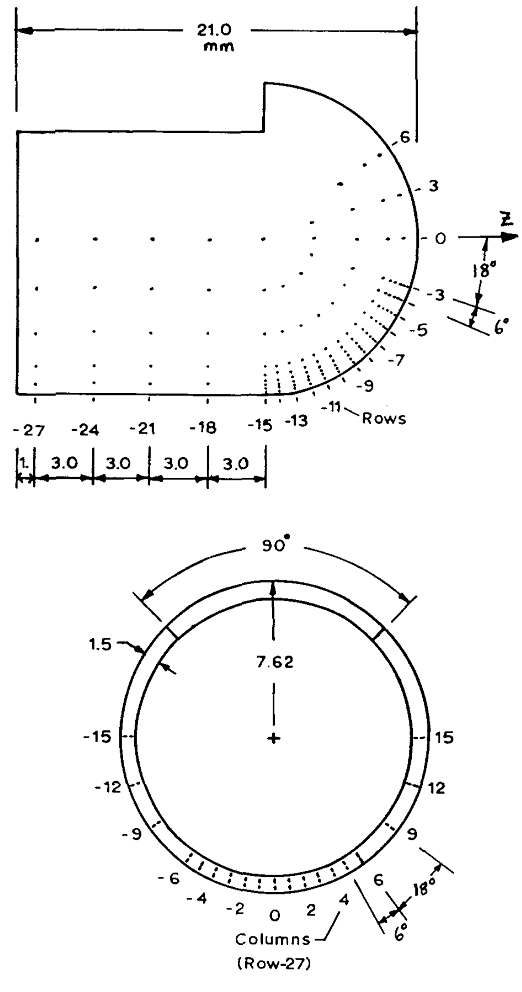


FIGURE 6: Distribution of taxels on the input array within the fingertip-shaped tactile sensor. The bottom diagram is the end view (+Z axis into paper).

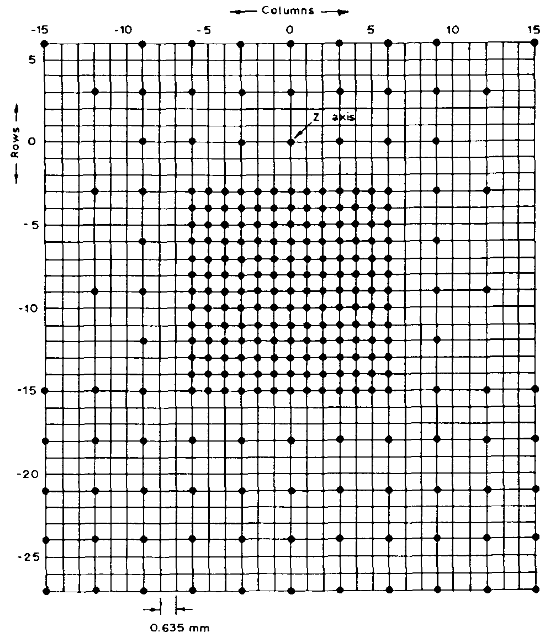
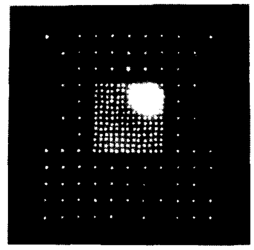


FIGURE 7: Output array dimensions and taxel indexing convention. The displayed imprint appears as though the viewer's eye were inside the sensor and looking forward in the +Z direction (into the paper).

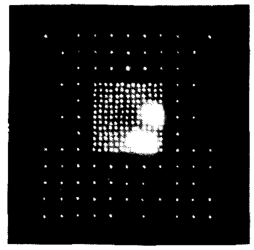
Figure 8 shows the tactile imprints generated by a planar surface, a gap between two plates, and a hole in the middle of a washer. The primary tactile features were deliberately located within the tactile fovea of the sensor to permit easier visual interpretation, though in actual practice all active portions of the sensor would be used. These imprints provide sufficient information such that (with proper calibration) the orientation of the plane relative to the sensor, the dimension and orientation of the gap, and the diameter and orientation of the hole could readily be determined without the need for multiple placements of the sensor.

CONCLUSION

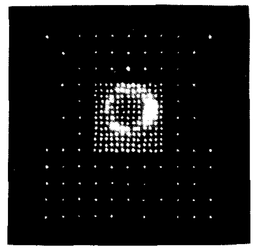
This paper described several stages in the ongoing effort to create a tactile sensor with characteristics functionally equivalent to that of a human fingertip, thereby achieving a sensor well suited for application to the control of dexterous robotic hands. A high-density, fiberoptic, fingertip-shaped sensor based on a TIR approach has been described, and the results have demonstrated the favorable potential of this technology with regard to robotic applications.



(a)



(b)



(c)

(c)

FIGURE 8: Tactile imprints generated by various objects (the central array represents the tactile fovea of the fingertip):
(a) planar surface (applied force ◘ 50N),
(b) 3 mm gap between two plates (40N),
(c) 6 mm diameter hole in a washer (50N).

Future work will concentrate on refining the TIR sensor in two important aspects. First, a shear force sensing ability will be implemented using an independently-developed technique related to that of White and King [19], thereby more closely approaching the tactile sensory capability of the human fingertip. Secondly, means will be explored whereby the optical nature of the tactile sensory data would be advantageously used to reduce the number of optical fibers in the cable from several hundred to only two: one for illumination, and one for transmission of tactile data. This would result in an extremely thin, flexible and rugged connection cable that would significantly reduce the problem of cable-routing through the intricate and crowded passageways within dexterous robotic hands, thereby enhancing the attractiveness of this tactile sensor in such applications.

ACKNOWLEDGEMENTS

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REFERENCES

[1] L.D. Harmon, "Tactile sensing for robots," in Recent Advances in Robotics, v. 1, J. Wiley & Sons, 1983.

[2] J.M. Hollerbach, "Robot hands and tactile sensing," paper presented at the MIT AI Workshop, Cambridge, MA, USA, January 1986.

[3] K.J. Salisbury Jr., Kinematic and Force Analysis of Articulated Hands," Dept. of Computer Science, Stanford University, Report STAN-CS-82-921, July 1982.

[4] S.C. Jacobsen, J.E. Wood, D.F. Knutti, and K.B. Biggers, "The Utah/MIT dexterous hand: Work in progress," Robotics Research, (eds) M. Brady and R. Paul, pp. 601-653, MIT Press, 1984.

[5] P. Allen and R. Bajcsy, "Object recognition using vision and touch," 9th Int. Conf. on AI, Los Angeles, CA, USA, August 1985.

[6] P. Dario, A. Bicchi, F. Vivaldi, and P.C. Pinotti, "Tendon actuated exploratory finger with polymeric, skin-like tactile sensor," Proc. IEEE Int. Conf. on Robotics and Automation, St. Louis, MO, USA, pp. 701-706, 1985.

[7] P. Dario, M. Bergamasco, D. Femi, A. Fiorillo, and A. Vaccarelli, "Tactile perception in unstructured environments: a case study for rehabilitative robotic applications," Proc. IEEE Int. Conf. on Robotics and Automation, Raleigh, NC, USA, pp. 2047-2054, March 1987.

[8] R.S. Fearing, A. Rise and T.O. Binford, "A tactile sensing finger tip for a dexterous robot," Proc. of the Intelligent Robots and Computer Vision Conference, Cambridge, MA, USA, pp. 378-387, October 1986.

[9] R.S. Fearing, "Some experiments with tactile sensing during grasping," Proc. IEEE Int. Conf. on Robotics and Automation, Raleigh, NC, USA, pp. 1637-1643, March 1987.

[10] D. Brock, and S. Chiv, "Environmental perception of an articulated robot hand using contact sensors," ASME Conf. on Robotics and Manufacturing Automation, Miami Beach, FL, USA, pp. 89-96, November 1985.

[11] R.P. Betts, and T. Duckworth, "A device for measuring plantar pressures under the sole of the foot," Engineering in Medicine, vol. 7, no. 4, pp. 224-228, 1978.

[12] R.P. Betts, T. Duckworth, I.G. Austin, S.P. Crocker, and S. Moore, "Critical light reflection at a plastic/glass interface and its application to foot pressure measurements," J. Medical Engineering and Technology, vol. 4, no. 3, pp. 136-142, May 1980.

[13] J.F. Kissinger, P.J. Verhonick, and D.W. Lewis, "Edge light: a new approach to studying the microvascularization of the skin," Bulletin of Prosthetics Research, pp. 65-78, Spring 1978.

[14] L.R. Kasday, Touch Position Sensitive Surface, U.S. patent no. 4,484,179, 20 November 1984.

[15] D.H. Mott, M.H. Lee, and H.R. Nicholls, "An experimental very high resolution tactile sensor array," 4th Int. Conf. on Robot Vision and Sensory Controls, (ed) E. Pugh, London, UK, October 1984.

[16] K. Tanie, K. Komoriya, M. Kaneko, S. Tachi, and A. Fujikawa, "A high resolution tactile sensor," 4th Int. Conf. on Robot Vision and Sensory Controls, (ed) E. Pugh, London, UK, October 1984.

[17] S. Begej, "An optical tactile array sensor," Proc. SPIE Intelligent Robots and Computer Vision Conference, Cambridge, MA, USA, pp. 271-280, November 1984.

[18] S. Begej, A Tactile Sensing System and Optical Tactile Sensor for Robotic Applications, MS thesis, COINS Technical Report no. 85-06, Computer and Information Science Department, University of Massachusetts, Amherst, USA, May 1985.

[19] R.M. White and A.A. King, "Tactile array for robotics employing a rubbery skin and a solid-state optical sensor," Int. Conf. Solid State Sensors and Actuators, Philadelphia, PA, USA, pp. 18-21, June 1985.