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Tactile Sensor Array Using Prismatic-Tip Optical Fibers for Dexterous Robotic Hands

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***Abstract*—This paper presents a novel approach of performing artificial tactile sensing based on the deployment of prismatic-tip optical fibers. The primary principle of the sensing schemes relies on light intensity modulation for detecting the deformation of an elastic element experiencing a force load. By measuring the change of light signal intensity, the magnitude of the applied force can be determined. The force distribution over an area can be evaluated using an array of optical fibers. The tactile sensor array prototype described in this paper demonstrates its capability and feasibility in performing tactile sensing and force measurement over a range of approximately 0 to 4.8 N. Due to its simple sensing structure, it is easy to manufacture and the sensor can be miniaturized for applications in dexterous robotic handling.**

I. INTRODUCTION

For several decades, robots have been deployed to use in many application areas including those in industry, military, and space. The deployment of robotic equipment has brought about a significant impact in manufacturing automation especially in automated product handling and manipulation process. Although a great number of robots were initially employed in industry, the growth of their population in other sectors such as education, entertainment, and medicine has been rapidly increasing [1]–[3]. Intelligent path planning and navigation methods have been created, allowing robots to enter new application areas and markets [3], [4]. To date, it becomes more common for robotic manipulators to conduct, for instance, surgical tasks in hospitals [5], [6] and scientific tasks in space [7].

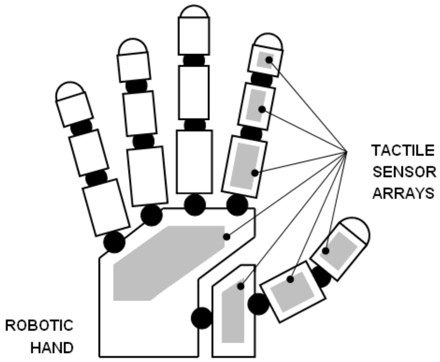

Fig. 1. Conceptual diagram of the tactile sensor array that performs sensing on a dexterous robotic hand.

Object handling and manipulation is a primary task of robotic systems installed for uses in almost all fields of applications. To permit an object to be effectively handled and manipulated, mechanisms of a robotic hand have to be able to ensure appropriate grasping support and contact forces. Several complex mechanical designs such as anthropomorphic and metamorphic multi-fingered hands having ability to handle complex-shaped objects have been proposed recently [8], [9]. However, the effectiveness on object grasping and manipulation not only relies on the dexterity and capability in actuation, but also depends on feedback information indicating the presence of the object being manipulated and its properties identified. Thus, tactile sensory information has become one of the keys to cutting-edge research on dexterous robotic hand.

Recently, a great number of force and tactile sensors have been developed for dexterous robotic handing application. Several fundamental sensing approaches have been investigated and applied including resistive-based, conductive-based, capacitive-based, piezoelectric-based, and optical-based sensing [10]–[16]. Among all these currently available sensing technologies, optical-based sensing technique provides a distinctive advantage of being simple and compact sensing structure [17]–[21]. By employing optical fibers as the primary optical sensing principle, a tactile sensor can be created in a miniature matrix form, known as a tactile sensor array, and used to perform accurate handling force measurement on a robotic hand (see Fig. 1). Rather than relying upon electrical signals to conduct measurements, as many other conventional sensing techniques, an optical signal is exploited instead for force measurement. Since none of the electrical components is required at the sensing site, the optical fiber tactile sensor could operate with extremely high electromagnetic

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interference (EMI) immunity [17]–[21].

In this paper, the proposed optical-based tactile sensor array is presented and described. In Section II, the overview of a new concept of tactile sensing based on the deployment of prismatic-tip optical fibers is presented. The development of the tactile sensor array prototype as well as the fabrication method is described in Section III. Testing methods and experimental results as well as possible future works are discussed in Sections IV and V. Finally, conclusions are drawn.

II. SENSING CONCEPTS

A. Light Intensity Modulation Based on Prismatic-Tip Optical Fibers

Optical fibers with a prismatic-type tip at its end (angle: 45°) with a polished surface can be used to achieve a total internal reflection of 90°. This occurs due to the optical effect that reflects rays of light which travel through a medium boundary (the cut at the end) at an angle larger than the critical angle. Fig. 2 shows the paths of the light rays transmitted out of a fiber whose tip is cut in an angle of 45°—the "prismatic fiber". It can be seen that the light is allowed to pass through the optical fiber until it hits the prismatic end—the place where the light changes its path by 90° before being emitted out of the fiber. Inversely, the incident rays laterally entering the fiber will also change the direction by 90° and then continue to travel along the optical fiber. By employing such a prismatic-tip fiber, several approaches for light intensity modulation can be derived. In Fig. 3, different possible designs of the light intensity modulation mechanisms are illustrated. Fig. 3(a) shows possibly the simplest intensity modulation configuration that can be achieved without additional components. Two straight parallel optical fibers placed close to each other are used to modulate the light intensity. The incident light laterally emitting out of the transmitting optical fiber tip can be collected by another fiber located nearby. By changing the distance between the two fibers, the light intensity received by the receiving fiber can be modified. Fig. 3(b) shows another possible configuration; here, a light interrupter (or shutter) is added. While the two fibers are kept stationary, a change in the position of the interrupter will cause the intensity of the light collected at the receiving fiber to vary. If a single fiber is used for both transmitting and receiving light, the light intensity modulation can be achieved by having a movable mirror located on the side of the fiber (Figs. 3(c) and 3(d)). By moving the mirror vertically or horizontally, the intensity of the reflected light traveling back to the same fiber can vary according to the movement of the mirror.

B. Optical Fiber Tactile Sensing

Due to the benefit of being a compact sensing structure which is easy to be realized for tactile sensing application, the light intensity modulation mechanism shown in Fig. 3(d) is selected here for the development of a tactile sensor prototype. Fig. 4(a) shows a sensing configuration that incorporates a prismatic-tip optical fiber, a mirror, a coupler, a light source, and a photodetector. The light signal traveling to the mirror and reflected back is coupled into the same fiber. The reflected light that continues to travel through the fiber is then divided into two portions at the coupler. A portion returns to the light source while another is guided to the photodetector so that its intensity can be measured. Fig. 5 shows a typical normalized voltage output response of the sensing mechanism which makes use of a 1-mm-diameter prismatic-tip optical fiber. By increasing the distance between the mirror and the fiber tip, the output level is decreased. Fig. 4(b) shows how an elastic element can be

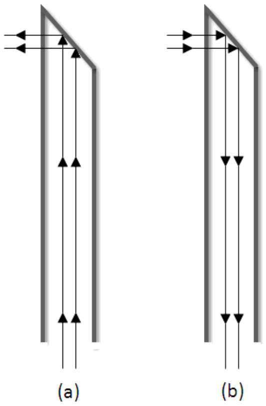

Fig. 2. Reflection of light traveling through the prismatic-tip optical fiber. (a) The light emits out of the fiber. (b) The light enters the fiber.

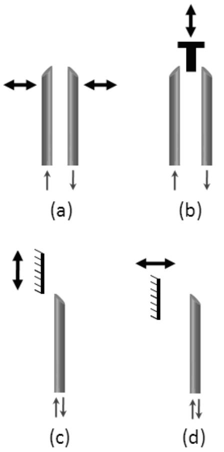

Fig. 3. Possible different sensing configurations of the light intensity modulation. (a) Dual fiber configuration. (b) Dual fibers with an interrupter. (c) Single fiber with a vertical sliding mirror. (d) Single fiber with a laterally moving mirror.

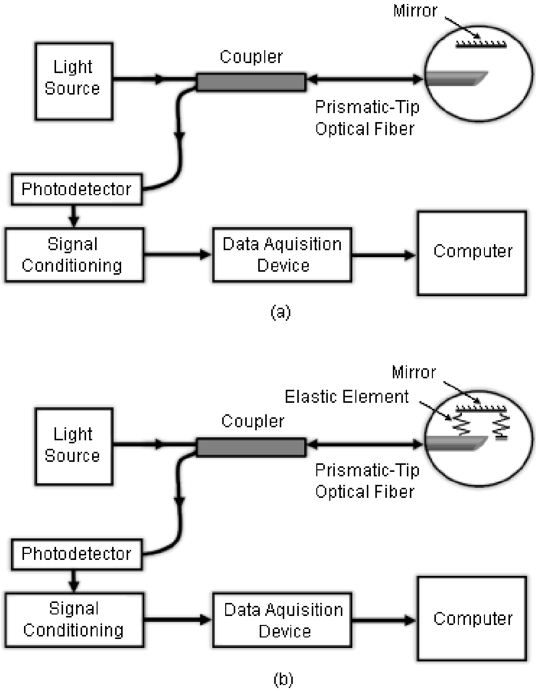

Fig. 4. (a) Schematic of the light intensity modulation technique for displacement measurement. (b) Schematic of the light intensity modulation technique for force measurement.

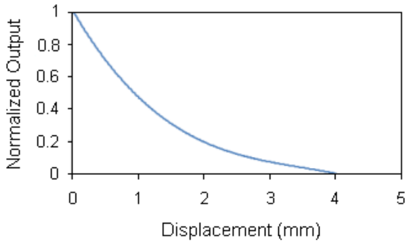

Fig. 5. Normalized response of the light intensity modulation mechanism which makes use of 1-mm-diameter prismatic-tip optical fiber.

added to the sensing configuration such that the force exerted on the mirror can be measured using the light intensity modulation scheme. In this case, the elastic element functions as a device that converts the effect of force into displacement—the vertical movement of the mirror which is caused as a result of the exerted force induces a change of the reflected light signal intensity. Operating based on this principle, the sensitivity of the sensor much depends on the stiffness of the elastic element.

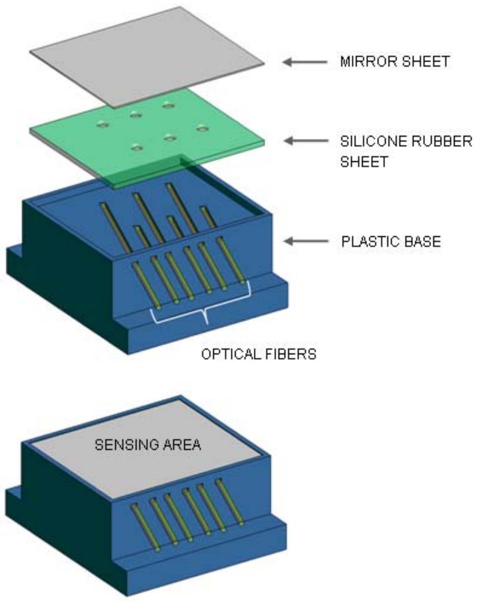

Fig. 6. Exploded view of the sensor assemblies.

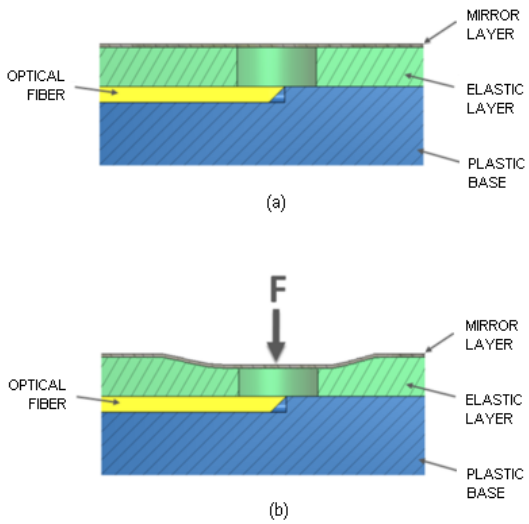

Fig. 7. (a) Cross-sectional view of the sensor at no load. (b) Cross-sectional view of the sensor being loaded.

III. SENSOR PROTOTYPE

A. *Tactile Sensor Array Fabrication*

To evaluate the feasibility of applying prismatic-tip optical fibers for force and tactile sensing, a 3×2 sensor array prototype is fabricated. Fig. 6 shows the prototype sensor assembly which consists of three layers—the optical fiber layer, the elastic layer, and the mirror layer. In the optical fiber layer, six prismatic-tip optical fibers are placed in parallel leaving a distance of 7 mm between each other in the same row and 11 mm between each other in the same column. The fibers are all integrated in an ABS (acrylonitrile butadiene styrene) plastic base made by a rapid prototyping process. This rigid plastic base fixes the fibers in a specific orientation that shows highest sensing ability

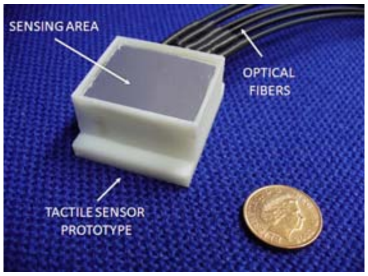

Fig. 8. Tactile sensor array prototype.

while avoiding movements that could cause errors in the measurement. Fig. 7 illustrates the proper alignment of an optical fiber such that it allows light to emit towards the mirror. In this prototype, the optical fibers employed are multimode plastic optical fibers of 1 mm diameter with a 45° angled cut that has been fine-polished. The fibers are glued to the plastic base using epoxy resin.

Another layer of the tactile sensor array is the elastic layer which is made of a silicone rubber sheet with a 3×2 array of 5-mm-diameter holes. The holes are aligned with the optical fiber tips allowing the light to transmit upright and strike the mirror in the upper layer. Based on the sensing characteristic shown in Fig. 5, the elastic layer is designed to have a 2.5-mm thickness. This thickness is chosen since it appears to demonstrate good sensitivity while offering sufficient space for the mirror to move closer to the fiber tip when a maximal force load is applied.

The topmost layer of the sensor (shown in Figs. 6 and 7) is the flexible mirror layer made of a silver-colored Melinex^{TM} sheet. Having a thickness of 0.2 mm, this mirror sheet is deformable. When a certain amount of force is applied to the sensor, the mirror moves downwards and the elastic sheet located underneath is deformed. Hence, the mirror's reflective surface moves closer to the fiber tip and, thus, leads to a change of voltage at the photodetector that receives the light from the fiber. Fig. 8 depicts the fully assembled tactile sensor array prototype.

B. *Optoelectronics*

In order to measure the intensity of the light signal and perform signal processing, a six-channel optoelectronic circuit is used. Six high-intensity LEDs (light-emitting diodes, SFH756V) are employed to generate light for six prismatic-tip optical fibers, and six photodiodes are deployed for reading the light intensity. Each LED is current-regulated to prevent fluctuation in the light signal. This is realized by using a current driver which operates based on a current regulator (L200C). Photodiodes (SFH250V) are used to detect the light intensity at the end of each optical fiber. Instrumentation amplifiers (INA122) and filters are employed for the optoelectronic circuitry for signal conditioning and amplification. After the light signal is detected, the electrical signal generated at the photodiode is amplified (with a gain factor of approximately 28,800). It is then filtered for noise suppression with an active low-pass filter (16-Hz cut-off frequency) and finally read out by a 16-bit data acquisition device (NI USB-6211). The schematic diagram of the photodiode and its signal processing circuitry is shown in Fig. 9.

IV. TESTING METHODS AND EXPERIMENTAL RESULTS

A. *Loading/Unloading Test*

After assembling the sensor array, it was tested for force measurements. A standard force/torque sensor (ATI Nano

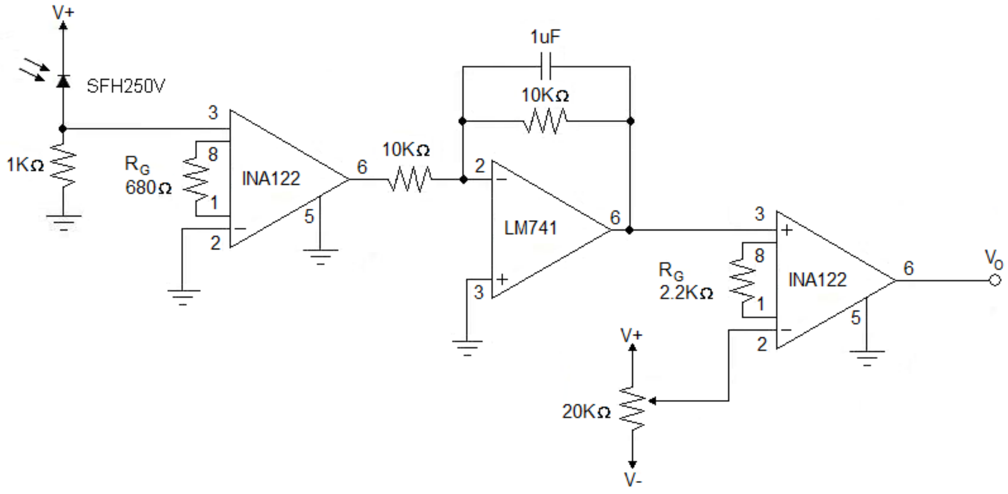

Fig. 9. Schematic diagram of a photodiode and associated circuitry.

17) installed on a robotic manipulator (Mitsubishi RV-6SL) was used to apply and measure forces simultaneously at particular locations of the sensor array (see Fig. 10). A roller which is mounted at the tip of the standard force/torque sensor was used to concentrate the applied force to a specific testing location. This roller also enables continuous force loading to be performed over the sensing area of the tactile sensor array.

To conduct the initial test, the tactile sensor array prototype was placed on a rigid stationary support. The robotic manipulator, which held the standard force/torque sensor in a straight vertical orientation, then maneuvered down to press the tactile sensor array at a point over a prismatic-tip fiber. After fully loading the sensor with a maximum designed loading force of 4.8 N, the roller was gradually removed. During the test, the output responses of the standard force/torque sensor and the tactile sensor array were recorded. Fig. 11 shows the output response of a tactile sensing element to the applied force loads. The response is relatively linear; however, hysteresis is observed. This is caused mainly due to the intrinsic viscoelasticity of the silicone sheet applied to assemble the sensor components. To reduce the hysteresis level, the operating force range should be reduced. An elastic material that possesses better elastic property should replace the silicone sheet. The sensor dimensions and specifications would also need to be optimized for future practical uses.

B. Sensitivity Distribution Test

The same setup that was used to carry out the initial test was also used to identify the sensitivity distribution of each sensing element. To verify the sensitivity distribution, a 2-N force was applied to the tactile sensor array by pressing the roller against the sensor array at a point above an optical fiber tip. While keeping the vertical position constant, the roller was translated horizontally away from the initial pressing position. The variation in the voltage output response of the tactile sensing element was recorded during the experiment. The outcome of this experiment led to the identification of the force responsive area around the tactile sensing element. Fig. 12 illustrates the variation in the output response of a tactile sensing element over a radial distance of 4 mm. It can be seen that the output level decreases as the distance from the center of the sensing element increases.

To visualize the sensitivity distribution over the sensing area of the tactile sensor array, a three dimensional (3D) graph is presented as shown in Fig. 13. This graph represents the combination of the responsive areas of all tactile sensing elements. As visualized by the graphical representation, the spatial resolution of the tactile sensor array still needs to be improved since the overlapping parts of individual plot are relatively low. Although this may suffice for some applications where high spatial resolution is not required, improvements that would lead to extended overlapping areas will be useful for delicate tactile sensing applications (e.g. finger-tip sensing). This can be achieved by reducing the distances between the optical fibers and also increasing the number of the sensing optical fibers.

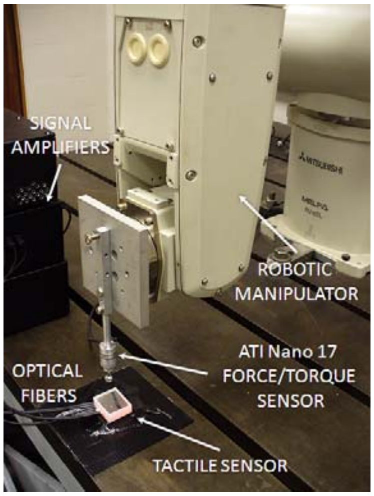

Fig. 10. Experimental setup.

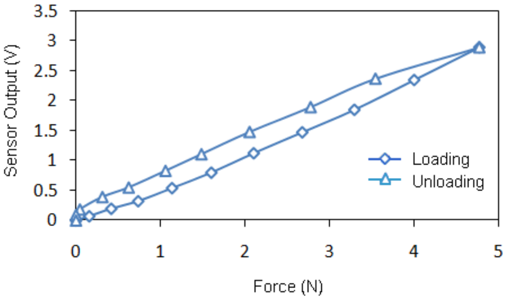

Fig. 11. Response of the sensor to a force loading/unloading cycle.

V. DISCUSSION

As described in the paper, a tactile sensor array prototype was developed with an objective to verify the feasibility of performing tactile sensing by using an array of prismatic-tip optical fibers. To our knowledge, this is the first time that the prismatic-tip optical fibers are used for tactile sensing application. The prismatic-tip fiber sensing configurations offer the distinct advantage of being able to perform sensing from the side, allowing a tactile sensor array to be easily fabricated in layers (as described in Section III) with the potential to be integrated in tactile skins. Although the specification and size of the current sensor prototype is still not optimized for the integration with a robotic hand (on a finger or palm), future research aims at developing a miniaturized sensor that incorporates smaller and more flexible optical fibers.

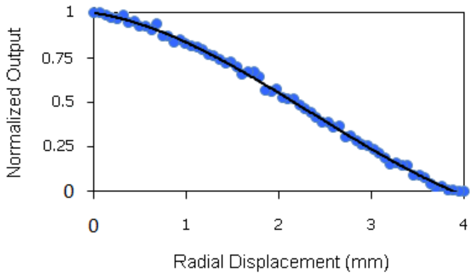

Fig. 12. Response of the sensor to a continuous pressing force applied over a radial distance of 4 mm from a sensing element.

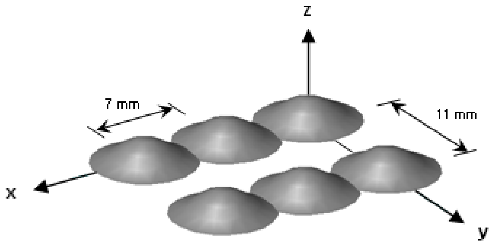

Fig. 13. Responsive areas of the tactile sensor array.

This sensor prototype with a 3×2 array of sensing elements is found to provide sufficient information about the force acting on the sensing area. However, to increase the sensor resolution for delicate sensing tasks, more fibers are required to be installed in a small area; hence, the number of optical detectors needs to be increased. As this is possibly not suitable for the development of a low-cost sensing device, future research will consider the employment of other effective means to measure the intensity of light signals. Several techniques on signal multiplexing and processing using a CCD (charge-coupled device) camera are also to be investigated.

VI. CONCLUSION

This paper describes a new approach of performing tactile sensing for dexterous robotic hands. The operating principle is based on prismatic-tip optical fibers arranged in a rectangular array. Such an array constitutes a matrix of sensing elements for uniaxial force measurements. A laboratory prototype with 3×2 sensing elements demonstrates that it sensitively responds to normal force loading. Since its sensing structure appears to be simple and compact, it can be easily miniaturized to the scale that is needed for a robotic hand. Also, because the optical-based sensing principle offers electromagnetic interference immunity, the sensor can be designed for uses in harsh environments where strong electromagnetic interference is occurring such as the power plants, electrical power stations, and magnetic resonance imaging (MRI) environments.

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