Integrated Dynamic and Static Tactile Sensor: Focus on Static Force Sensing

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ABSTRACT

Object grasping by robotic hands in unstructured environments demands a sensor that is durable, compliant, and responsive to static and dynamic force conditions. In order for a tactile sensor to be useful for grasp control in these, it should have the following properties: tri-axial force sensing (two shear plus normal component), dynamic event sensing across slip frequencies, compliant surface for grip, wide dynamic range (depending on application), insensitivity to environmental conditions, ability to withstand abuse and good sensing behavior (e.g. low hysteresis, high repeatability). These features can be combined in a novel multimodal tactile sensor. This sensor combines commercial-off-the-shelf MEMS technology with two proprietary force sensors: a high bandwidth device based on PZT technology and low bandwidth device based on elastomers and optics. In this study, we focus on the latter transduction mechanism and the proposed architecture of the completed device.

In this study, an embedded LED was utilized to produce a constant light source throughout a layer of silicon rubber which covered a plastic mandrel containing a set of sensitive phototransistors. Features about the contacted object such as center of pressure and force vectors can be extracted from the information in the changing patterns of light. The voltage versus force relationship obtained with this molded humanlike finger had a wide dynamic range that coincided with forces relevant for most human grip tasks.

1. INTRODUCTION

While signal processing and machine vision have achieved revolutionary improvements, tactile sensing has not yet risen to the challenges of increased integration, better performance, and lower cost. The detection of payload slip and surface roughness by touch has been particularly challenging. The importance of tactile information is obvious in clinical cases where patients suffering peripheral nerve damage to their hands are able to initiate, but not maintain stable grasp due to lack of sensory feedback from cutaneous sensors [1]. Neurophysiologists have identified that rapid reflexive adjustment of grip is essential for handling objects and depends on tactile feedback via the spinal cord [2]. Engineers developing telerobotic manipulators have also improved performance when force and vibrotactile feedback was provided via “haptic displays” to the operator’s hand [3].

The proposed research overcomes these challenges by developing a multi-modal tactile sensor suite that incorporates four sensors. This project will refine existing designs into self-contained commercializable modules. In order for a tactile sensor to be useful for grasp control in unstructured environments, it should have the following properties [4]; one of our goals is to show how this sensor meets the following requirements: 1) tri-axial force sensing, 2) compliant surface for grip, 3) wide dynamic range (depending on application), 4) insensitivity to environmental conditions/able to withstand abuse, 5) good sensor behavior (e.g. low hysteresis, high repeatability), 6) slip and incipient slip detection. Based upon a review of the psychophysical literature and existing sensors, we have devised a suite of sensors that can sense all relevant signals for manipulation and meet these...
requirements: tri-axial forces (optical-elastomer), microvibration for slip and texture (piezoelectric and accelerometer) and proprioception (accelerometer and gyro). Kuchenbecker et al. [5] and Sukhoy et al. [6] have also used accelerometers on the surface of robotic end-effectors to extract microvibration data; a similar strategy could be employed here.

Table 1: Sensing modality summary

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Sensing Modality</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical-Elastomer</td>
<td>3D Force</td>
<td>USC – Further development contained herein</td>
</tr>
<tr>
<td>IntelliVibe – embedded piezoceramics</td>
<td>Dynamic Strain</td>
<td>IPTRADE – Proprietary; short summary presented</td>
</tr>
<tr>
<td>MEMS Accelerometer</td>
<td>3D Acceleration</td>
<td>Commercially available</td>
</tr>
<tr>
<td>MEMS Gyroscope</td>
<td>3D Angular Velocity</td>
<td>Commercially available</td>
</tr>
</tbody>
</table>

Additionally, this results in a completely scalable (in price, quantity, size, application) modular sensing system. This fully integrated, inexpensive sensor package will occupy a single BOM item rather than a complex multi-component expensive sensing system that would take dozens of lines in a BOM and requires redesign to fit a new application.

In the next sections, we highlight the background of the various sensor elements and then focus on the new optical-elastomer force sensing modality: theory of operation of the device, the construction of a simple prototype, as well as preliminary characterization data.

2. BACKGROUND

Numerous transduction methods have been previously implemented in an effort to meet the needs of mechatronic robots and prosthetics. Transduction mechanisms such as optics, capacitance, piezoresistance, ultrasound, and conductive polymers have all yielded viable solutions, but only for limited environments or applications. For example, most MEMS sensors provide good resolution and sensitivity, but lack the robustness for many applications outside the laboratory. Finally, individual sensors from a variety of suppliers suffer from prohibitively high cost and/or implementation challenges. Therefore we have combined several sensing modalities into a single unit; reviews of tactile sensing can be found in [7-9].

2.1. Dynamic Force Sensing: IntelliVibe

By incorporating dynamic piezoelectric sensors (PZT based IntelliVibe, IPTRADE), we can sense the acoustic spectra microvibrations associated with incipient slip and sliding over textured surfaces. The IntelliVibe technology involves the incorporation of lead zirconium titanate (PZT) wafers into a printed circuit board (PCB) substrate (Figure). PZT wafers are commercially available in various thicknesses, typically ranging from 1/8 to ½ of a millimeter. They are sputtered with nickel or silver on their top and bottom surfaces to facilitate electrical connection. Unfortunately, they are extremely brittle and cannot be soldered to or easily handled. This necessitates packaging that will provide mechanical robustness and an easy way to make an electrical connection [10, 11]. The result is an extraordinarily sensitive, low-cost, robust, and simple to use strain sensor that does not require any external power input or signal conditioning. These sensors are extremely mechanically and electrically robust, do not require any maintenance, and have operating temperatures between -50 and 100 degrees Celsius.

Table 2: IntelliVibe Properties

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Sensitivity</td>
<td>55 mV/µε</td>
</tr>
<tr>
<td>Range</td>
<td>2000 µε</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1 to 40kHz</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>&lt; 1.0 %</td>
</tr>
</tbody>
</table>
2.2. Static Force Sensing: Optical-Elastomer Sensor

The use of optics in tactile sensor is not new; several attempts have been made to use either camera based or electro-optic modalities in tactile sensing. The camera based approaches generally involve tracking patterns or the position of landmarks on the inner surface of an elastomer [12-15]. Other approaches involve modulating the signal between a light emitting element and a light sensor [16, 17] or coupling optical waveguides [18]. The approach presented in this work is closest to [15] and [17] where modulation of the mean free path of photons to a receiver modulates the beam. The design presented here differs from [15] and [17] in two major ways: 1) the sensing elements are housed and recessed within a protective core, away from the environment and 2) The device uses apertures to the phototransistors to affect light intensity.

The need for this new sensor is to overcome robustness and sensor limitations previously mentioned: its strengths are an integrated, compliant covering, robust design and tri-axial force sensing for grip control. It presents many of the benefits of the BioTac® [19], a conductive fluid based sensor: an integrated “skin” for grip and appearance (already accounting for the low-pass spatial-temporal filtering effect of said skin). The core is durable and hardy to withstand the everyday human environment. The skin is also designed to be easily and quickly replaced if damaged: the media that are cycled during use are an inexpensive rubber and light. The optical transduction system is also electromagnetically robust towards noise. While it lacks thermal flux and microvibration sensing modalities, strategies to overcome this are presented below. The main advantage is that it avoids the requirement for a conductive fluid and the attendant risk of leakage in the event of a puncture to the inflated skin.

3. THEORY OF TRANSDUCTION – OPTICAL-ELASTOMER SENSOR

A phototransistor placed away from a light emitting diode (LED) will change its output current as the intensity of incipient light changes. In the prototype described herein, a set of three recessed phototransistors was placed within a rigid core of acrylic (configuration described later). An LED was located nearby and the device was coated in two layers of elastomer – one that is very easily deformed and translucent and one that is reflective, opaque and harder, to protect the softer elastomer. The reflective and opaque nature of the outer layer keeps out ambient light (Fig. 3).

When the light is emitted from the LED, it will undergo diffuse reflection (as opposed to specular reflection from a mirror) off the surfaces of the core and the outer elastomer. Diffuse reflection results in omnidirectional reflection angles due to the surface irregularities in the materials. The light will also undergo intensity loss due to absorption and scattering as it transmits through the various lengths of materials (elastomer and air). As objects are contacted, the path of light from the LED to the phototransistors is deformed, changing its intensity. These changes in intensity will contain information about the contacted object such as its center of pressure and force. This change in intensity is governed by the two previously mentioned optical phenomena and the configuration of the sensing elements, core and elastomer. As forces are applied above the device, the soft elastomer is squeezed into the air gap. This leads to the next phenomenon surrounding the system: aperture size. As the size of the recession above the area changes, this changes the amount of force to occlude the transistor. If the volume of the recession is comparable to the volume of elastomer above it, then lower reaction forces will increase sensitivity of the device to incipient forces. Depending upon the application, large recessions could be used for sensitivity or very small diameter fiber optic cabling can be used for increased resolution.

Figure 3: Left) Diagram relating position of phototransistors, LED and elastomeric skin of device. Arrow indicates possible light path. Right) Qualitative illustration showing effect of altering aperture size during incipient forces.
As the light travels to a phototransistor, it is affected by absorption. Because the core and outer elastomer are largely reflective and the inner elastomer is translucent, we consider this a weakly absorbing system. In this system:

This results in attenuation of:

\[ I = I_0 e^{-ax} \]  

Where:

- \( I_0 \) = the intensity of the light passing through a medium
- \( a \) = the absorption coefficient of the material (wave length dependent): \( \frac{-k \chi''}{n} \), where \( k \) is the wave number and \( n \) is the index of refraction
- \( x \) = the distance the light must travel through a given material

And \( \chi'' \) is the imaginary component of susceptibility and \( \chi' \) is the real component.

\[ \chi'' \ll \chi' + 1 \]  

For example, consider Fig. 3, when no force is present the light takes a given path to reach the phototransistor and undergoes one interaction with the core and one with the outer skin. A force causes the path to be altered causing two interactions with the core and skin. Although this is a contrived illustration, it demonstrated how these surfaces may interact with the light path. While a small amount of the light is absorbed and converted to heat, the primary effect of the translucent elastomer on the light path is scattering. Several types of scattering occur in non-crystalline solids, including Raleigh scattering, represented by elastic collisions and Raman scattering, resulting in inelastic collisions; these are described further in [20-22]. As the soft elastomer is deformed; the amount of rubber the light is required to travel through to the phototransistor will change, causing a change in intensity at the phototransistor as well.

Having considered these points, we move to consider a set of design features for the materials and geometry of the core that take advantage of these previously described physics:

- The inner elastomer is translucent and very compliant
- The outer elastomer is opaque and reflective
- Phototransistors are arranged facing all planes of action (X, Y, Z) to sense forces in these dimensions

By orienting the phototransistors in a unique fashion, normal and tangential forces can be extracted from contacted objects.

![Figure 4: Behavior of sensor to forces: Right) Normal forces bulge the inner elastomer outwards away from lateral phototransistors while compressing above lower phototransistor, the fingernail (“Nail”) pins the “skin” in place; Left) Normal and tangential forces interact to cause compress and bulge effect featured](image)

In summary, several effects are combined to reduce illuminance when objects contact the sensor, resulting in a non-linear response: scattering, absorption and phototransistor occlusion. Due to this complex, but hypothesized monotonic response, we utilize machine learning algorithms to show normal and tangential force data are embedded in the phenomenon. Precise effects on how each law, elastomer and object contact parameters are related to one another remain to be characterized in future work. For example cross-axis effects from forces are anticipated: the sensor output for tangential forces will depend on the amount of normal force applied as the skin is depressed (as in Fig. 3). However the sensor is calibrated by training a machine learning algorithm with a variety of moments, forces and object designed to capture such effects. Our emphasis is currently not placed on a particular algorithm or accuracy in surpassing commercial sensors in predicting forces. This is for two reasons: 1) the focus is on a robust device that senses percepts relevant to object handling; 2) it is not entirely clear how the data will be utilized by a mechatronic or other system for such handling. For example, humans do not explicitly calculate forces at the fingertip while object handling, yet our brain and spinal cord are trained to make use of this data.
4. METHODS

4.1 Circuitry

The prototype circuitry for the optical elastomeric tactile sensor was built with discrete parts hand assembled into the mold. Phototransistors were small enough to fit in the housing yet responsive over the range of expected luminance (silicon NPN phototransistors: Vishay Semiconductors BPW16N). As the illumination changes, the phototransistor will function as a variable resistor when driven by a dc signal. In order to measure the changes in the transconductance of the phototransistors, the circuit in Figure 4 was implemented.

\[
\begin{align*}
V_{cc} &= 5V \\
R_D &= 330\Omega \\
\text{LED} \\
L_0 &= \text{Light Source} \\
R_{L1} &= 50k\Omega \\
R_{L2} &= 50k\Omega \\
R_{Ln} &= 50k\Omega \\
V_{out1} \\
V_{out2} \\
V_{outn} \\
\text{Common Emitter Amplifier Array}
\end{align*}
\]

Figure 5: Tactile Sensor Circuit Diagram (Left) LED interfaces with surface of the core (Right) three phototransistors are housed within the core

The common-emitter amplifier circuits in Fig. 5 generate “n” voltage outputs which transition from a high to a low state when light in the visible light range of 400nm to 700nm is detected by the phototransistor’s base. Each output voltage in the array is produced by connecting a resistor between the voltage supply and the collector of the phototransistor. The output voltage is read at the terminal of the collector. Since the configuration acts as an amplifier, the phototransistor magnifies this current to useful levels that can be measured. The result is that the voltage outputs of each of the phototransistors in the array change from higher values to lower values (and vice-versa) depending on the amount of visible light detected on the base terminal. Collector-emitter current for the transistor depends on the incipient light as well as the collector-emitter voltage (fixed at +5VDC).

The LED must provide sufficient illuminance over relevant pressure levels of the device; hence a relatively bright white LED (Lumex: LXHL-BW02) was chosen with a normal operating power of 45mW. For a voltage supply $V_{cc} = 5V$ and detectable initial current of 100µA (acquired from the phototransistor data sheet), the transresistance of the phototransistor should be approximately 50kΩ. The load resistance, $R_{Ln}$, was chosen to be 50kΩ in our voltage divider circuit to maximize circuit sensitivity. The parallel array of common-emitter phototransistor circuits were all subsequently set to the same values ($R_{L1}= R_{L2}= \ldots= R_{Ln}=50k\Omega$).

4.2. Prototype Construction

The body of the device was formed from a wax mold that was machined by a CNC mill using a geometry generated in Inventor and MasterCam X. The empty mold and a blank positive are featured in Fig. 6.

Figure 6: Left) Negative wax mold to create sensor core and Right) Positive blank showing sensor shape and illustration to highlight locations of LED and phototransistors (PXtor): located 10mm away in each direction from the LED

The internal circuitry was soldered together and placed within the core. The LED was held in place with cyanomethacrylate bonding agent. The positions of the phototransistors were predetermined and holes were drilled to house the silicone tubing plugs. These plugs fit to the ends of the phototransistors and act to create the necessary recesses, as well as hold them in place during fabrication; the phototransistors were recessed by 2mm.
Once all of the necessary components were in place, the mold was cast with commercial dental acrylic (*Hygienic Perm Reline & Repair Resin*). Two screws were placed in the mold to act as anchor studs for the “fingernail” that will act to control the deformation of the elastomer, such that the elastomer is not loose and free to slip. The electronic core was removed from the mold and then coated in elastomers.

The sensor was first pour-coated with a very soft silicone elastomer: Ecoflex 0010 (hardness: Shore 00-10A, Smooth-On Inc), then heat cured with a 750F heat gun for 10 seconds before pour-coating in Silastic E (hardness: Shore A 35, Dow Corning Inc) by the same process. The Silastic E bonds to the Ecoflex in the curing process forming a single skin; average thickness of the Ecoflex was 2.5mm, average thickness of the Silastic was 1mm. Ecoflex’ translucence was arbitrarily chosen for this study and precise optical characterization remains [23], though scattering and refractive properties are changeable in polymers by using the proper dopants [24]. After complete curing, an aluminum “fingernail” was installed to complete the final device (Fig. 7).

**Figure 7: Elastomeric optical tactile sensor alpha prototype**

4.3. Characterization

4.3.1. Dynamic Range and Repeatability

To characterize the quasi-static behavior of the prototype shown in Figure 6, we applied forces to the ventral, distal phototransistor of the device. A linear drive (Nippon Pulse America; PFL35T-48Q4C (120) stepper motor and NPAD10BF chopper drive) was used to advance a probe: 20 mm diameter (10 mm radius of curvature). Normal force was measured using a six-axis force-plate (Advanced Mechanical Technology; HE6X6-16) positioned below the vise holding the device (Fig. 8). This was repeated 10 times and an integral generate over force versus output voltage using the Trapezoidal Rule; sample rate was 100Hz. Error rate was calculated by comparing the integral of subsequent trials versus the first (Eqn. 3); mean and standard deviation of error were generated.

**Figure 8: Experimental set-up for quasi-static characterization: A) clamp B) sensor C) probe D) stepper motor E) 6-DoF force plate; coordinate frame shown in upper left corner**

\[
\text{Error} = 100\% \times \frac{\int \text{Trial 1} - \int \text{Trial X}}{\int \text{Trial 1}}
\]  

(3)

4.3.2. Force Vector Extraction

Additionally, the sensor was also subjected to manually applied lateral “push-pull” forces to explore the normal to tangential force response of the device (bi-axial forces only). We constructed a training set consisting of several pressing and sliding movements applied on the skin of the device while it was bolted to a vise atop the previously described 6-DOF force-plate. Spearman correlation coefficients between tangential-facing phototransistor and force and normal phototransistor and forces were calculated.
To explore if normal and tangential force data are embedded in sensor response, a three-layer back-propagation perceptron was used. It is capable of approximating any given nonlinear relation when a sufficient number of neurons are provided in the hidden layer [25]. MATLAB’s Neural Network Toolbox 6.0.4 was used; data for each voltage channel were preprocessed by subtracting the mean and dividing by the variance. This software employed the Levenberg-Marquardt backwards propagation algorithm [26] to tune the weights and biases of the artificial neural network (ANN) to maximize the correlation between the model predictions and the recorded data. Hidden and output units used hyperbolic tangent and linear activation functions, respectively. Hidden layer size was chosen at 15 (significantly > the number of inputs, [27]); over-fitting was managed by using early stopping and Bayesian regularization.

Prior to ANN training, the primary data sets were divided into three sets: 1) a working set (70%), with which the ANN was trained via back-propagation; 2) a validation set consisting of 15% of randomly chosen data to prevent overfitting; and 3) a test set of 15% randomly chosen data used to measure the ANN’s ability to generalize after training. Standardized mean square error (SMSE) and correlation coefficient were reported.

4.3.3. Dynamic Response

A primitive experiment was performed to estimate the frequency response of the sensor. We applied a vertically oscillating flat probe (a tuning fork attuned to C₃ = 130.8 Hz) to the fingertip while recording the vertical force and output voltage of the distal sensor. Response was simultaneously recorded from the previously mentioned force plate. The frequency response of the sensor and associated electronics should be fast enough to preclude significant delays in a grasp control system relative to the speed of the actuators.

5. RESULTS

5.1. Dynamic Range and Repeatability

Results for the normal force-voltage experiment are shown in Fig. 9. The device represents a wide dynamic range of forces and appears to not saturate yet near 10N. Fig. 9 shows that the sensor was responsive over physiologically relevant grip force ranges with high repeatability observed: 2.11 +/- 1.35%.

Figure 9: 10x Repeated Normal Force Characterization of Single Phototransistor

5.2. Force Vector Extraction

A second experiment was performed to explore the sensor’s ability to resolve tangential as well as normal forces. Spearman correlation for Y tangential force were 0.441 (p <0.0001) and 0.491 (p < 0.0001) for Z. Each force was resolved via two separate ANNs with input from only two phototransistors); results are presented in Fig. 9 and Table 3.

Table 3: ANN s Statistical parameters for predicted versus novel data

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Y</td>
<td>0.345</td>
<td>0.814</td>
</tr>
<tr>
<td>Z</td>
<td>0.416</td>
<td>0.766</td>
</tr>
</tbody>
</table>

Figure 10: ANN interpretation of Y-tangential forces (top) and Z-normal forces (bottom) compared to actual, novel data
5.3. Dynamic Response

However it seems that as the tuning fork’s amplitude decreases (after 2.4 sec and shown by decreasing force plate response); the sensor shows a loss of response as stimulus amplitude decreases as well, indicating amplitude dependency. Additionally, a spectrogram (FFT) is shown below capturing the second harmonic of the tuning fork (middle C, $f = 261.6$ Hz). This shows there is potential for amplitude dependent dynamic representation of stimulus. The temporal details of the mechanical input were well-represented over the range of loads tested informally.

![Figure 11: Top Row) Phototransistor output; Bottom Row) Force plate output Left Column) Global view; Right Column) Zoom view of onset](image)

6. DISCUSSION

This development of the elastomeric optical force sensor was successful in that a new prototype was built and tested with promising results. We note that the sensor is sensitive to forces over a wide dynamic and physiologically relevant range with good repeatability. Sensor response does not yet saturate at the upper end of forces (upper test range limited by jig). An ANN was used to show that features like forces can be extracted from the device. It is important to note the ANN only used two inputs. Future prototypes will feature many more sensing elements and higher tolerances of construction.

The dynamic experiment shows there is faithful reproduction of high frequency components in the elastomer, suggesting low hysteresis at these frequencies. Though these limits were not determined, it is not likely this modality will be used to sense high frequency data due to the amplitude dependence. Further characterization of the device (e.g. hysteresis) is also required, but problems are not anticipated due to design and material.

7. CONCLUSION

We now return to the list of sensor requirements and evaluate the status of this device and how it meets those requirements. The device showed proof-of-concept in being able to extract normal and tangential forces from only two inputs using a compliant grip surface. This ability will be increased with a more robust set of phototransistors. The device also showed a highly repeatable voltage-force profile over a physiologically relevant dynamic range. Hysteresis, drift and robustness remain to be tested but are not considered to be problematic given the design and availability of materials for the device. Next steps for this project include fabricating a beta version, specifically:

- Integrating the electronics into a printed circuit board to facilitate electrode placement and consistency
- Characterizing what design parameters are required for which applications, such as skin thickness, colorization (for both layers), number of phototransistors vs. LEDs and location. For example, this will depend on:
  - Environmental robustness requirements (e.g. wear rates vs. ambient light entry)
  - More thorough frequency response to support short latencies of grip control
  - Resolution/low-pass spatial filtering for feature discrimination
- Validation of the whole system and algorithms on a mechatronic gripper platform
Several improvements must also be considered for the device. Components can also be miniaturized and small fiber optic cable can be routed to the surface of the core recessions, precluding the presence of the phototransistors near the surface at all. This can greatly increase robustness and support higher resolution. The next generation device will sense acceleration, jerk, angular velocity, dynamic strain and its derivative as well as sample a multitude of phototransistors via the Cypress Programmable System on a Chip 5.0. A high-level circuit diagram and CAD model are presented below for the next beta prototype.

![High-level circuit lay-out of beta-prototype](image1)

![45-degree view of a CAD model of the sensor](image2)

![Side view of CAD drawing](image3)

**Figure 12: Left) High-level circuit lay-out of beta-prototype Upper Right) 45-degree view of a CAD model of the sensor featuring screwed in base-plate; Lower Right) Side view of CAD drawing; high stiffness rubber core is shown in yellow, surrounded by soft elastomer layer (grey) and hard, opaque elastomer layer (black).**

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