

A Highly Sensitive Multimodal Capacitive Tactile Sensor

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Abstract—As technology develops, manufacture process becomes more and more automated using robots. There is demand for high performance tactile sensor which can support robotic grippers in manipulation tasks especially for unstructured flexible objects. Despite the efforts that have been spent, the fabrication process of those functional sensor remains complicated due to their requirement of specialized materials and equipment. The proposed multimodal sensor overcomes the difficulty by enhancing the electrical and mechanical design therefore simplifying the manufacture steps. In this version, static and dynamic sensing are integrated in the same layer of capacitive sensor with direct written microstructured dielectric. This structure allows it to have large range of force sensing as well as the ability of detecting contact events such as slippage or losing of contact.

I. INTRODUCTION

Robots have become more important to manufacturing processes in parallel with the greater automation enabled by technology. From the beginning of the robotic era, robotic grippers were used in straightforward manufacturing tasks like car assembly. But today robotic grippers must do more than just grasp the same item repeatedly: when handling complex objects involving unstructured fabrics [1], fragile materials, or a multitude of different shapes [2], robots must have some “sense” of how to accomplish the task without damaging the object.

The human hand, with its various mechanoreceptors, remains the best-functioning “device” for object-manipulation tasks. In an attempt to replicate these functions robotically, researchers have developed tactile sensors based on numerous different sensing principles, including piezoresistive rubber [3], [4], conductive ink [5], piezoelectric material [6], conductive fluid [7], [8], and change in capacitance [9], [10]. Most of these approaches are about measuring contact pressure, however the human sense of touch also includes senses of vibration, temperature and shear loading, among others. These other modalities allow us to recognize surface texture, detect slippage, and perceive other complex events. With this in mind, some researchers in robotics are now building multimodal tactile sensors in hopes of giving robots a sense of touch that is closer to the human one. Along with detecting pressure localization and magnitude, these modern sensors can also detect contact events like vibration. For example, Choi *et al.* [5] developed a variable resistor ink sensor that can also detect incipient slip thanks to the use of PVDF. The framework of the CloPeMa project [11] presented also a

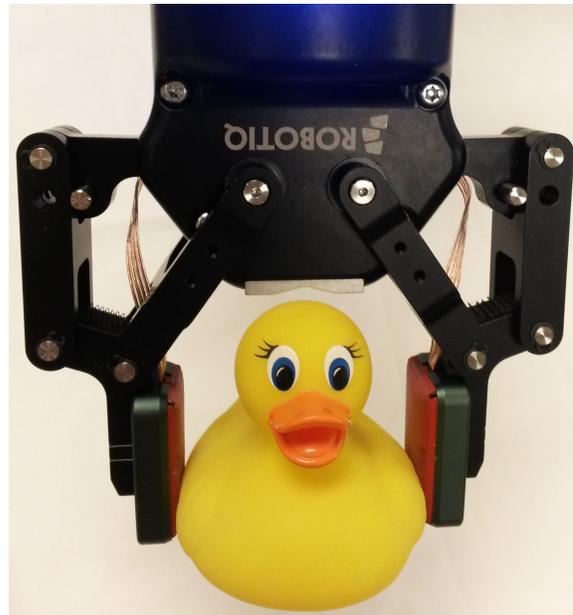


Fig. 1. Multimodal tactile sensors on Robotiq gripper

multimodal sensor for fabric manipulation and classification. But probably the most well-known multimodal sensor is the commercially-available BioTac from SynTouch[12] that can measure vibrations in addition to temperature and pressure. As these works have shown, sensors for grasping applications need more than simply the ability to sense forces. However, the aforementioned sensors are not ideal because their special materials and complex structures make them inconvenient to fabricate. In particular, the BioTac needs to replace a whole phalange in order to be integrated with a robotic hand.

Capacitive sensors appear to be a suitable candidate due to their simplicity and easy-to-implement properties. The performance of a capacitive sensor depends on its electrical circuit and the electro-mechanical characteristics of its dielectric. Capacitive sensors can now perform both static and dynamic sensing, because new integrated circuits (ICs) enable the sensor’s electronic circuit to process the additional data needed for dynamic sensing. As a result, such sensors can now classify contact events [13].

By cleverly designing the dielectric, the sensor’s sensitivity can be greatly enhanced. Several researchers have succeeded in improving the sensitivity of their capacitive sensors by using dielectrics made of elastomer foam [9], [14], [10] and microstructured rubber [15]. Another research group from our lab attained extremely high sensitivity using a microstructured dielectric made of nanoparticle-filled elas-

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tomers [14]. However, although all these researchers created sensitive capacitive sensors, their methods are not ideal because of the inconvenient and time-consuming nature of the specialized dielectric fabrication processes.

This paper proposes a multimodal sensor that is suitable for typical manipulation tasks and simple to fabricate. With the design of the microstructure of the dielectric and the electrical circuit board, this sensor is sensitive to a broad range of forces ($0 - 50N$) and is also able to perceive dynamic events. By using an intricate design of dynamic taxel with static taxels thanks to a special geometry, we have been able to exploit the *fringe capacitance effect* [16] to not only improve the sensitivity, but also enhance the spatial uniformity of the response. Static and dynamic sensing are achieved with the same layer of the capacitor by using a direct laser written microstructured dielectric. This allows us to simplify the manufacturing process. Moreover, with its modular design, this sensor can be easily integrated with different kinds of robotic grippers over any phalange.

The paper will proceed as follows. Section 2 presents the novel dielectric and its fabrication process. Section 3 describes the improved multimodal capacitive sensor, its operating principle and the packaging method. The functionality of the sensor is validated and the results of the experiments are given in Section 4. Section 5 concludes the paper.

II. DIRECT WRITING MICROSTRUCTURED DIELECTRIC

A. Microstructured dielectrics and capacitive sensors

The dielectric plays an important role in the performance of capacitive-based sensors. Its contribution to the capacitance value can be expressed in eq. 1:

$$C = \epsilon_0 \epsilon_r \frac{A}{d}, \quad (1)$$

where C is the capacitance value, ϵ_0 is the electric constant, and A is the overlap area of the two electrodes. The other two parameters reflect the electro-mechanical properties of the dielectric.

The ϵ_r is the relative permittivity and its value depends on the materials. The most common elastomers used for dielectrics do not have as high ϵ_r as is desired, which has motivated researchers to find improvements. A typical solution is mixing high permittivity fillers such as PMN-PT or titanate with the base elastomer [9], [14]. A good mixer is necessary to create a uniform compound that can be cast and cured in dielectric sheet. This process includes mold design and fabrication, and casting and curing of the elastomer liquid.

The distance between two electrodes, d , represents the thickness of the dielectric. When pressure is applied, the dielectric deforms, changing its thickness and therefore the capacitance of the sensor. The displacement of the dielectric is determined by the applied pressure and the hardness of the dielectric. In order to increase the displacement given a certain pressure, soft dielectrics and elastomer foams have

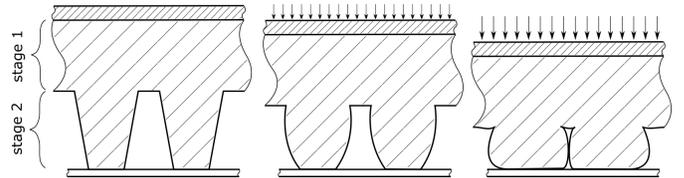


Fig. 2. Microstructured dielectric

been used (both open [9] and closed cell [10]). Using these types of dielectrics, one can obtain an extremely sensitive sensor since its thickness changes even when pressure is only slightly applied. As a result of the high deformation rate, the dielectric should be thick so it does not get saturated quickly. This means we face a tradeoff between a bulky design and a low range of force sensitivity when designing a sensor.

The novel dielectric is presented in Fig. 2 with two stages: the first stage is full sheet of material and the second stage is constructed by a number of frusto-conical shaped protrusions. With such a structure, the first stage has higher stiffness and permittivity compared to the second one. The stiffness k and relative permittivity ϵ_r of the dielectric are the non-linear combinations of these values of the two stages. When pressure is applied, the response of this microstructured dielectric can be described as follows: At low pressure, a set of corresponding protrusions are quickly deformed and they expand. When they have totally filled the surrounding area (as in Fig. 2), the response reaches the second phase where the dielectric acts as a full sheet of elastomer. The capacitance at a given pressure p is

$$C_p = \epsilon_0 \epsilon_{rp} \frac{A}{d_p}, \quad (2)$$

with

$$\epsilon_{rp} = f(p, \epsilon_{rStage1}, \epsilon_{rStage2}), \quad (3)$$

and

$$d_p = g(p, k_{Stage1}, k_{Stage2}). \quad (4)$$

While $\epsilon_{rStage1}$ and k_{Stage1} are determined by the producer, $\epsilon_{rStage2}$ and k_{Stage2} are defined by the microstructure pattern. By changing the pattern, one can control the behavior of the dielectric and thereby the response of the sensor.

B. Direct laser structuring of the dielectric

Rana et al. presented a fabrication method of using invert molding to cast the dielectric out of liquid elastomer filled with nanoparticles [14]. They succeeded in making a highly sensitive sensor that can be integrated with a robotic gripper. However, their method is time-consuming due to the invert molding process. In this study, we tried a straightforward approach where the microstructure is written directly on the dielectric. Doing so can accelerate the processing time of the dielectric, so that it takes mere seconds rather than days. A standard laser cutter (Trotec Speedy 300) is used to engrave the frusto-conical protrusion and to cut the dielectric out of the sheet of material. It can be challenging to find a precasted sheet of soft polymer that can be engraved with a good

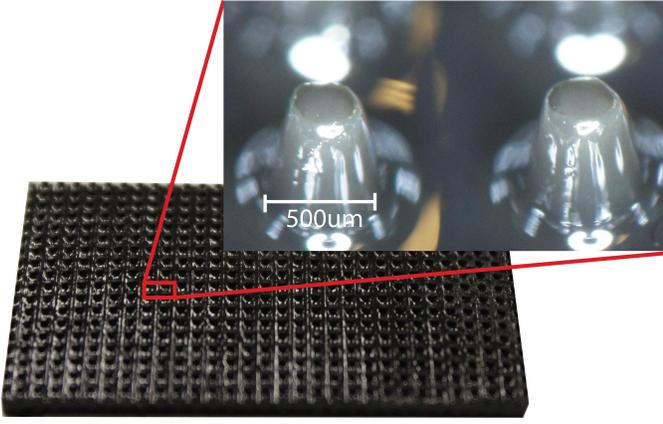


Fig. 3. Microstructured dielectric

accuracy directly by a standard CO₂ laser engraving machine and that fit the application. This sheet must have a good dielectric permittivity ($\epsilon_{rStage1}$), an adequate thickness and a relatively low hardness k_{Stage1} . Since nanoparticles are not used, the higher the $\epsilon_{rStage1}$, the better the sensor's response will be. Also, as the sheet gets softer, the measurement precision rises but the saturation threshold is lowered. A number of material such as delrin, nylon, polyurethane (PU) foam, and PU itself were tested in search of the most suitable one. At 12 – 120W laser power, the results showed that PU gave the best performance in term of how accurately we can transfer a given pattern on it.

The geometry of the dielectric sheet, and the disposition, shape, and dimensions of the protrusions, are critical to its behavior under pressure. In this prototype, the protrusions are equally distributed on the dielectric sheet with the distance or pitch between each protrusion measuring 1.2mm. Each protrusion has a base measuring 0.6mm in diameter, a flat tip measuring 0.3mm in diameter, and a height measuring 0.5mm (Fig. 3). Using this dielectric, the sensor can detect pressure of up to 390kPa. However, those parameters can vary depending on the desired sensor performance or sensitivity. For instance, using a thinner dielectric would reduce the working range of the sensor to 230kPa yet increase the sensitivity at low levels of applied pressure. Moreover, the shape and dimensions of the dielectric material must be adapted to the shape and dimensions of the capacitor electrode. The laser power setting and speed allow us to control the diameter, pitch, and height of each protrusion.

III. MULTIMODAL CAPACITIVE SENSOR

Tactile sensing can be classified into two groups: static and dynamic sensing. The former corresponds to the localization of pressure (normal pressure and shear force) while the latter relates to all contact events such as slippage or object recognition.

In this design, the static sensing is composed of an array of 28 tactile pixels (taxels) arranged on a printed circuit board (PCB) of 22mm × 37mm. The arrangement reflects the distribution of forces on the surface of the sensor. Each

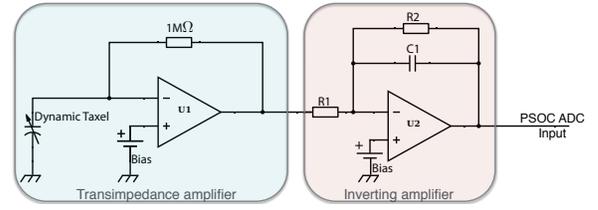


Fig. 4. Signal processing circuit for dynamic sensing

taxel is an individual square of 3.625mm × 3.625mm, as seen on the left side of Fig. 5. When contact happens, there is displacement of the dielectric at the contact area and change in the capacitance of the adjacent taxels (eq. 2). Mapping the capacitance values provides an image of the applied pressure. It allows the user to regulate the manipulation forces so they are appropriate for the grasping task at hand.

The dynamic sensing structure is similar to the static one, except there is only one taxel. This taxel uses the same dielectric as discussed previously. Together they form a capacitor, which is processed by an high gain transimpedance amplifier (Fig. 4) that measures the variation of capacitance rather than the capacitance itself. The variation can be evaluated by eq. 5:

$$\Delta C = C_p - C = \epsilon_0 A \left(\frac{\epsilon_{rp}}{d_p} - \frac{\epsilon_r}{d} \right). \quad (5)$$

An application of dynamic sensing can be found in the work of Roberge et al. [13], which used these data for classifying tactile events. Dynamic sensing has also been used to identify the texture of the contact surface [17].

A. How we achieve multimodal sensing with the same layer

The great advantage of this sensor is that both static and dynamic sensing are arranged on the same layer of the PCB. Unlike existing multimodal sensors such as [18], the dynamic and the static sensing here use the same principle of transduction (capacitance-based), which entails a simpler and more compact integration in embedded applications. The single dynamic taxel is integrated around the static taxels. Essentially, the dynamic taxel takes on a grid-like pattern, filling in the spaces between each individual static taxel. The only difference between the dynamic and static sensing mechanisms occurs at the processing stage. The static signal is processed by a capacitance-to-digital converter (CDC), whereas the dynamic signal is processed by analog amplifier circuits.

The CDC is based on the time measurement of a response of the capacitor to an excitation signal. Each of the 28 taxels will be measured to localize pressure at the surface of the sensor. The resolution and the response time of the taxels depend on the adopted CDC chip.

For the dynamic sensing, the variable capacitor is formed by the PCB, the microstructured dielectric and its grounded layer. The variable capacitor responds to any dynamic activities at the surface of the sensor. A small vibration is

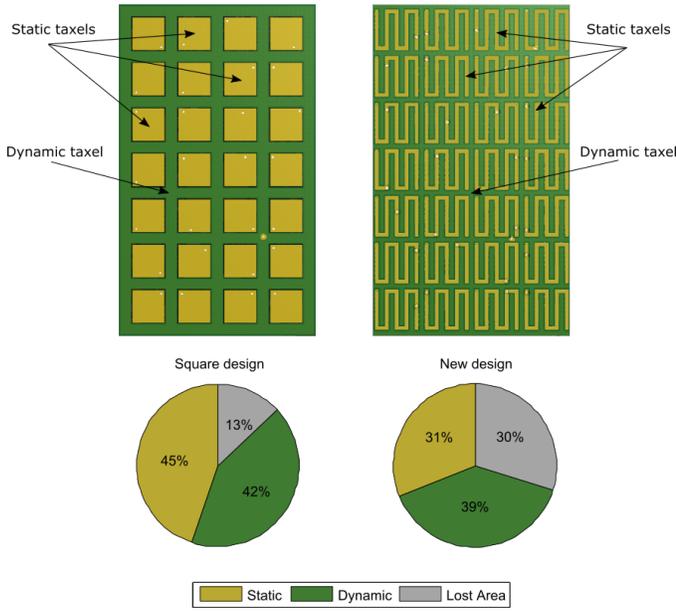


Fig. 5. Static and dynamic sensing in the same layer

reflected by a movement of charges due to a change of capacitance [19]. This change is processed with a transimpedance amplifier (current-to-voltage converter) with a high gain.

B. Improvement

Most capacitive tactile sensors use square taxels. However using that shape with a multimodal sensor, where two different types of taxels coexist, lead to a non uniform sensitivity through space. Indeed, a same vibration applied at two different places can generate two different dynamic responses. In order to minimize this drawback we designed our sensor with comb-shaped taxels that allow to interlace the two sensor modalities. This proposed shape presented at Fig. 5 allow a better distribution through space of our dynamic and static taxels, thus leading to a more uniform sensitivity. Moreover, this design also has the benefit to increase the perimeter to area ratio for each taxel, something that maximise the fringe field in the capacitor. The conventional capacitance equation (see eq.1) ignore the curved field that exist at the edges of the plates, something that is a direct function of the perimeter of the capacitor. Maximizing this *usually neglected* field can greatly increase the sensor response as shown in Fig. 6. Indeed, despite the fact that both areas of static and dynamic sensing were decreased (from 45% to 31% and from 42% to 39%), the interlaced design has a higher variation output than the original one.

In addition, this version also integrates an Inertial Measurement Unit (IMU). In many applications of robotics, the spatial orientation of the sensor is relevant to detecting events such as an underactuated grasp or a change in grasping. This is achieved by filtering data from the IMU in order to get the quaternion and Euler's angles. The accelerometer and gyroscope data are sampled and integrated in a Madgwick and Mahony algorithm [20] to measure any change of orientation of the sensor. Using an IMU brings other advantages: thanks

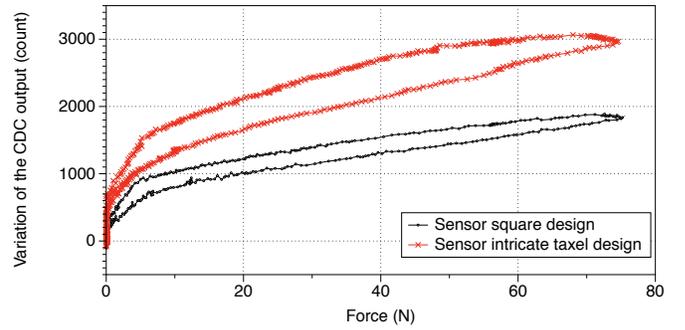


Fig. 6. Square taxel design vs. intricate design

to the third accelerometer contents inside the chip, the sensor is able to detect dynamic events such as micro-vibration, movements of the robot, and external perturbations. The complementarity of these two dynamic sensing abilities (analog and IMU) makes the sensor a tool that fully capable of detecting many different dynamic events. For instance, it can enable differentiation between an object slipping in the gripper's grasp and the perturbations that are due to the movements of the robot. Although there was not enough data to be presented in Section IV, preliminary tests showed that IMU has high potential in manipulation and perception tasks.

C. Packaging

Fig. 7 presents the structure and the prototype of a capacitive tactile sensor. The PCB, accommodated electronic components, and ICs act as the first side of the static and dynamic capacitors. The PCB has a case to protect it from bending while pressure applied. The dielectric is placed over the PCB with the microstructured pattern facing towards the taxels. Right on top of the dielectric is the conductive fabric that works as the second plate of these capacitors. The whole stack is shielded from environmental electrical noise using the same flexible conductive fabric. Finally, a layer of silicone rubber completely covers the sensor for protection. Thanks to the crisscross texture of that layer the contact friction is increased which supports the manipulation tasks. The aluminum interface is designed with a customized flange so the device can be easily integrated with different

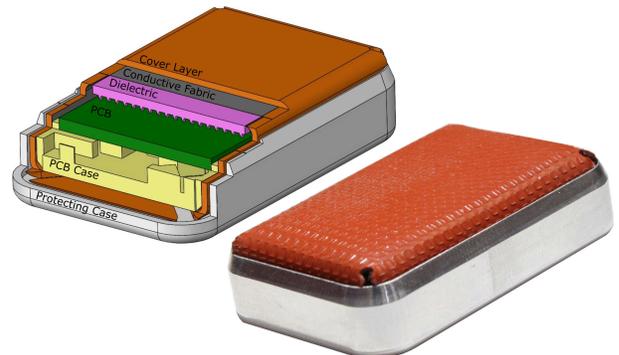


Fig. 7. Multimodal capacitive tactile sensor assembly.



Fig. 8. Experiment testbench

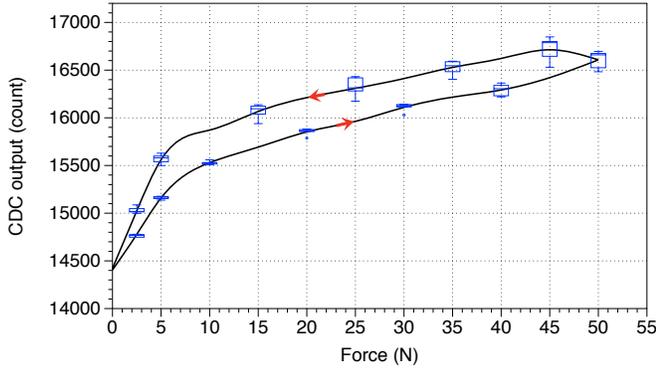


Fig. 9. Repeatability and hysteresis of the sensor evaluated on a given taxel.

robotic grippers. The modular design makes it easy for the user in case they need to maintain or replace the sensor. Moreover, all the utilized materials are off-the-shelf products which support the need for quality consistency.

IV. EXPERIMENT AND CHARACTERIZATION

The first set of experiments was performed in order to study the repeatability and hysteresis of the sensor. The test bench is presented in Fig. 8 with the pressure applied by the Mark-10 force gauge. Various type of indenters were used to simulate different contact scenarios, including point, line and planar contact. Normal force was applied and incrementally increased up to $50N$ and then gradually decreased to $0N$. Each sensor was tested ten times at two different positions giving the capacitance values of 28 static taxels.

As an example, the experiment results with the rounded indenter ($5mm$ in diameter) at one taxel is illustrated in Fig. 9. The red arrows show the direction of the force applied on the sensor. The two curves represent the responses of the

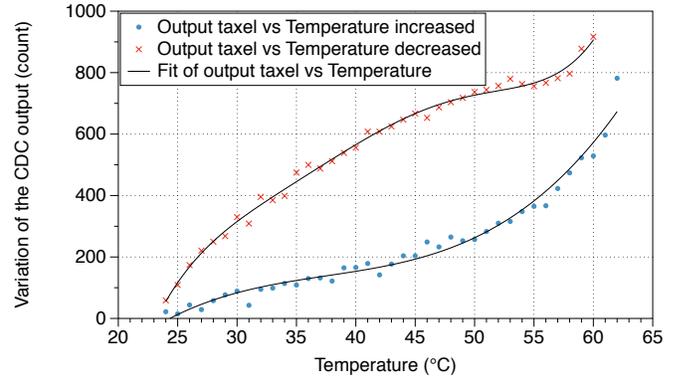


Fig. 10. Temperature drift

sensor in the loading and unloading cycles, respectively. Each curve can be divided into two parts with different slopes. As we can see, the response at the lower force range ($0-7N$) has a higher slope than the response at the higher one ($7-50N$). This behavior accords with the design of the dielectric as presented in Section II. The frusto-conical elements stage of the dielectric has low stiffness and is quickly deformed at low pressure. It follows from this that the sensor is sensitive at a low range of force while still functioning properly in higher ranges. Moreover, with the parameterized design, the working range of the sensor can be adapted to various types of application.

Capacitive sensor using soft dielectric are well know to be sensitive to temperature variation. Fig. 10 presents the results when a sensor was put in an environment with high temperature variation ($24^{\circ}C-60^{\circ}C$). The data were acquired from the sensor while the temperature first increased to the highest temperature in this range and then decreased to the lowest. This range of temperature is adequate for typical robotic grasping applications. The highest variation of the CDC output is about 900 (at $60^{\circ}C$) which is less than 6.5% of the smallest output of the sensor (14500 Fig. 9).

This capacitance-based tactile sensor has a good noise immunity thanks to numerous features. The CDC is made with a delta sigma modulator that offers superior noise-immunity performance against conducted and radiated external noise. Moreover, the conductive fabric ground and the aluminium case form a shield that protects the sensor from interference from the outside world. This enables it to have less than 100 counts of noise (see Fig. 11) for an average signal at 18000 counts.

The dynamic sensing function was tested by attempting to detect vibrations applied on the surface of the sensors. The vibrations were applied with a linear actuator, the Haptuator Mark II, which can vibrate at the exact frequency of the supplied sinus waveform within a range of $90Hz-1000Hz$. Fig. 12 shows the dynamic data when the actuator is placed between the two sensors on Robotiq gripper with a small normal gripping force at different frequencies ($125Hz$ (middle) and $450Hz$ (bottom)). The graph displays the Fast Fourier Transform spectrum analysis as well as in time domain

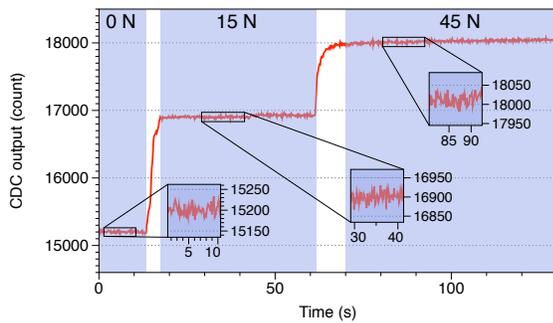


Fig. 11. Static signal-to-noise ratio for a given taxel at different forces

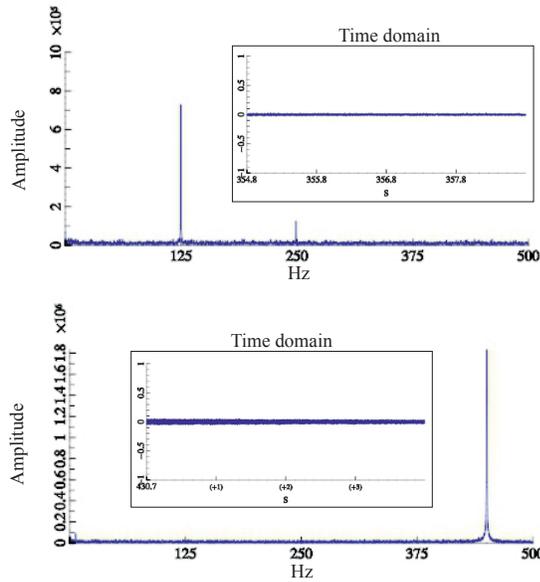


Fig. 12. Fast Fourier Transform spectrum analysis of different frequencies

showing that the dynamic sensor has correctly acquired the vibrations applied by the actuator.

V. CONCLUSION

Towards our goal of making simpler capacitive sensors that can handle typical manipulation tasks, we have improved the dielectric as well as the electronic circuit of our sensor. Thanks to the direct laser writing method, the microstructured pattern can be etched on the material sheet without time-consuming molding and casting procedures. This simplification means we do not need to embed nanoparticles to increase the dielectric permittivity the way previous researchers did. The performance of this sensor is enhanced by the novel design of the capacitor electrodes. The combination of static and dynamic sensing the same layer make this a compact yet capable sensor. The experiment results proved that it is a suitable solution for robotic applications. The research will be carried on in order to thoroughly exploit all the remain possibilities such as the IMU, dynamic sensing, etc. as well as all the scenarios where this sensor can be utilized.

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