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EVALUATION OF A COMMERCIAL FORCE SENSOR FOR REAL TIME APPLICATIONS

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Abstract. *A commercial piezoresistive FlexiForce sensor can be of great interest in biomedical robotic applications due not only to its advantageous material which will not be affected by metallic and ferromagnetic materials but to its dimension as well. In this paper, the evaluation of FlexiForce sensor is performed in the case of grasping robotic hand glove for medical application. The evaluation method is done through a dynamic calibration based on three experimental tests which are performed with different calibration features to accurately identify the behaviour of force sensor over time. Our empirical evaluation shows that the method used is computationally efficient, and that it has advantages over the traditional method. Quantitative results show and identify the characteristics of the force sensor pattern including the systematic errors such as lack of linearity, hysteresis and non-repeatability. The proposed method is a useful approach for evaluating the performance of any measurement force sensor in real time environments.*
Keywords: Force sensor, Real time applications, Force measurement system, Grasping robotic hand, Evaluation, Dynamic calibration

1. **Introduction.** In various robotics applications especially, in grasping robotic hand, force measurement is required to ensure safety and comfort in human and robot interaction [1]. For example, the force distribution is essential in most human movements such as grasping, writing and walking. An increasing number of medical robotics applications are involved by human/robot interactions and force control. For these applications, high accurate force measurement system is becoming very necessary.

Different technologies produce various types of force sensors which have been used and applied in several fields and applications [2]. Piezoresistive force sensor such as FlexiForce A201 (1-617-464-4500) with a standard force range of 0-25 lb (110 N) is one of the famous sensors widely used in force control tasks [3]. The evaluation of such sensors to determine its performance for real time or dynamic applications is important. For a growing number of medical applications involving the robotic hand glove for real time grasping purpose, these sensors seem to be well adapted to force-control tasks [4,5]. In literature, many researchers have proposed a characterization of piezoresistive force sensors using traditional calibration. Most of them have focused on static evaluation but only a few researchers have considered their response to dynamic loading [6]. However, the traditional calibration process for the FlexiForce sensor is a time-consuming task because it is usually

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done through manual and repetitive identification. In addition, a traditional computational method of FlexiForce sensor is inadequate for solving the problem of systematic errors since it is extremely difficult to resolve the mathematical formula among multiple confounding pressure variables [7]. Particularly, during the grasping object using robotic hand glove, the sensor loading will vary due to the patient hand movements and thereby inaccurate force measurements appear. Accordingly, adequate dynamic evaluation of the low-cost piezoresistive force sensors offers an interesting solution for force measurement in this context, because of successful identification force patterns including the systematic errors such as lack of linearity, hysteresis and non-repeatability.

In this paper, the focus is put on the dynamic evaluation of the multi commercial low-cost piezoresistive sensors (FlexiForce). The existence of nonlinearities, non-repeatability and hysteresis in their dynamic response is outlined, and the opportunity to compensate these systematic errors is suggested.

2. **Problem Statement.** The advantages of FlexiForce sensors include low cost, interesting dimensions with a very small thickness, easy to integrate and insensitive to magnetic fields which can be of great interest in biomedical applications [1]. Nevertheless, in real time applications, as time elapses, the FlexiForce sensor parameters change its characteristics due to its material creep and cause measurement errors leading to nonlinearity output [7-10]. These negatively affect the calibrated output data and as a result, inaccurate force measurements appear. Furthermore, the elastic modulus and hardness that leads to the creep effects of material are dependent on holding time, maximum load, and loading/unloading rates for nanoindentation in polymer. Therefore, an appropriate set of calibration method to dynamically evaluate the force sensor is necessary to avoid such measurement error. In addition, it is considered as a first step towards successful sensor compensation.

3. **Sensor Evaluation.** In this work, a piezoresistive FlexiForce sensor was utilized to be evaluated. This sensor relies on the resistive method where the resistance is inversely proportional to applied force. It can emit signals within millivolts range; therefore an amplification is needed. However, prior to the evaluation tests, all FlexiForce sensors were calibrated in real time environments.

3.1. **Calibration.** To evaluate how the FlexiForce sensor behaves over time, a dynamic calibration was performed using the CT3 Texture Analyser machine as demonstrated in Figure 1. It can be observed that different hardware components incorporated together in the construction of a force measurement system in order to successfully calibrate the multi force sensors. The components used are load cell with strain amplifier to be used as a reference signal, data acquisition device (DAQ) to calibrate signal from load cell, FlexiForce sensor's adapter to amplify sensor's signal, readout circuit to extract sensor's signal, trigger circuit using Arduino to synchronize between two signals (sensor and load cell signals). In experimental setup, there are two signals to be extracted and the components are connected accordingly. The hardware connections were as follows. In sensor signal, the FlexiForce sensor was connected to the adapter. The output of adapter was connected to the input of readout circuit which was connected to the PC through USB connection. On the other hand, the load cell signal (reference) is extracted by connecting the load cell with the strain amplifier which amplified the signal output and then transmitted to the analogue input of DAQ connected to the PC. The Arduino is used to synchronize between two signals by applying a trigger circuit which enhances the calibration accuracy and acquires only the signals in the area we need. In addition, it can save hardware bandwidth and memory. LabVIEW program was used to acquire the calibrated signals to be evaluated.

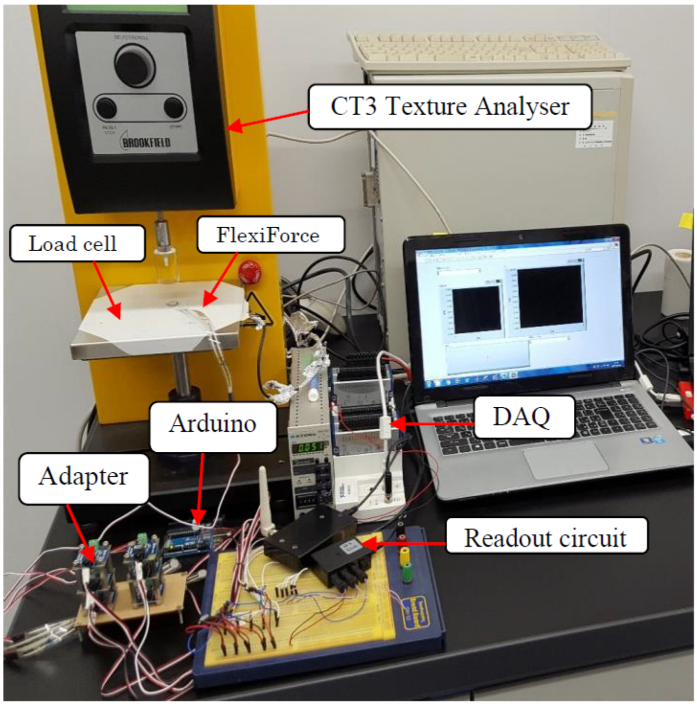

Figure 1. Dynamic calibration of FlexiForce sensor using CT3 Texture Analyser

Subsequently, the calibration process was done by using CT3 Texture Analyser machine to apply compressive loads to the sensing area of FlexiForce sensor. However, in order to ensure the compatibility of the proposed calibration method with the desired application which is grasping robotic hand glove, three experimental calibration tests were performed. During each test, different loads of maximum pressure and holding times were applied. By this calibration method, the features of force pattern are effectively identified and the relationship between applied load and sensor output is sufficiently established. Table 1 explains the differences between three calibrations executed. Based on these experiments, the dynamic evaluations of multi force sensors were investigated.

Table 1. The calibration of FlexiForce sensor based on the three experiments

Experiment No.	**Calibration**			
	Applied force (N)	Holding time (sec)	Data points	No. of cycles
1	0∼44.13	10	132,243	28
2	0∼19.61	5	130,990	39
3	> 30	–	122,149	83
Note	Sampling rate is 100 Hz			

In the first experiment, a dynamic load ranging from zero to 44.13 N was applied to each of the FlexiForce sensor via standard cylinder probe (diameter 52.4 mm, sized to fit within the active area of the sensors (9.53 mm) and the puck (8.75 mm)). The puck put between the probe and the sensor's active area as well as the cylinder probe made from plastic clear acrylic were inserted to ensure that the load was evenly distributed across the active sensing area, avoiding local high pressures at edges, for example. The larger load values were chosen because the typical maximum finger force produced by humans is no higher than 30 N [11].

Consequently, and similarly, with previous calibration, the experiment was repeated but with different applied forces and holding times. In the second experiment, an applied force from zero to 19.61 N was loaded while more than 30 N was performed in the third experiment as a random applied force. A set of holding times was also selected to imitate the desired robotic hand grasping as well as to find an optimum holding time limit for the material of sensor. The selected holding times were 10, 5 and zero sec at maximum load for experiments 1, 2 and 3 respectively. The sensor output was recorded by readout circuit at 100 Hz with multiple load-unload cycles tests run on each FlexiForce sensor. Simultaneously, the load cell output (reference) was recorded by DAQ at the same sample rate to match the sensor output. Then the sensor output was aligned with the applied load. During each experimental test, load-unload cycles were applied and repeated with more than 20 min and the data points output were recorded as outlined in Table 1.

4. **Results.** In this section, we present the real time calibration data of the force sensor and its evaluation. Figure 2 shows the calibrated data of force sensor obtained from three experiments within one hour of calibration as discussed previously. The blue, green and red colours were related to the data of experiment 1, experiment 2 and experiment 3 respectively. It can be observed that the force patterns were clearly different from experiment 1, experiment 2 and experiment 3 due to the dissimilar features of applied forces and holding time. Indeed, different input force patterns and holding times for the same sensor enhance the accuracy and efficiency towards identification of the behaviour of force sensor over time so that it is easy to compensate the systematic errors in later process.

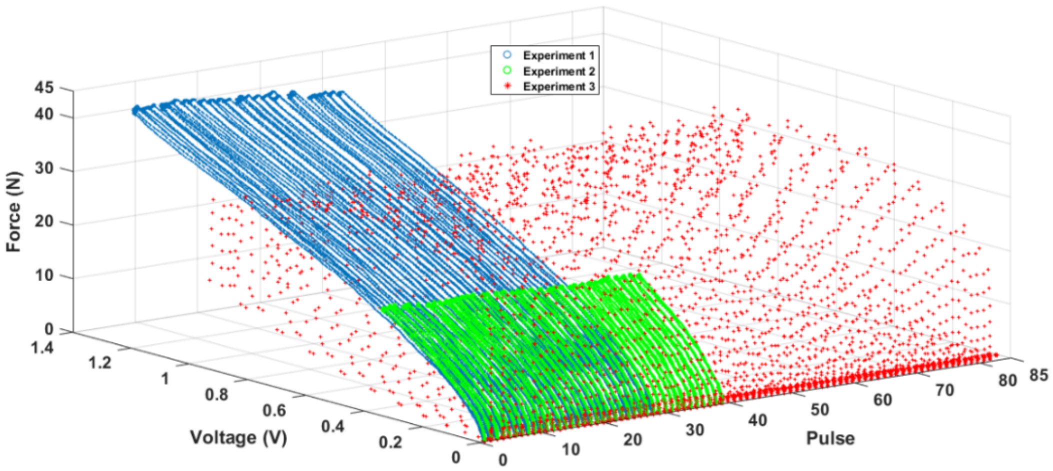

FIGURE 2. The calibration data output of FlexiForce sensor based on three experiments in real time

Evaluation. To additionally clarify the evaluation of FlexiForce sensor over time, Figure 3 represents the behaviour of sensor output and its corresponding load cell reference based on experiment 2 as example. Throughout the repeated load-unload cycles tests, a decrease with fluctuation in the output voltage over time was observed even the same pressure forces were applied in each cycle. This causes the systematic errors that would be evaluated in this paper. On the whole, for evaluation and performance purpose of calibration method, the Mean Absolute Deviation (MAD), Mean Square Error (MSE), Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) were 0.288, 0.098, 0.313 and 79.07% respectively. The results were based on the calibration data of experiment 2 while 39 cycles tests were repeated. However, the compensation of systematic errors for FlexiForce sensor can be found in the paper published in [7] under the same author.

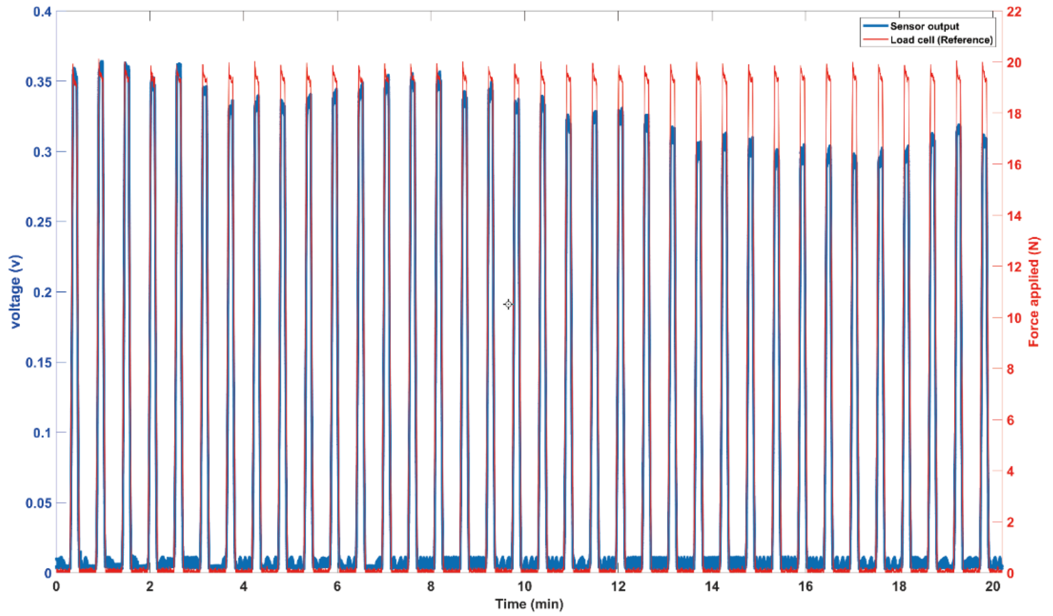

FIGURE 3. The relative measured voltage changes in the sensor over time based on experiment 2

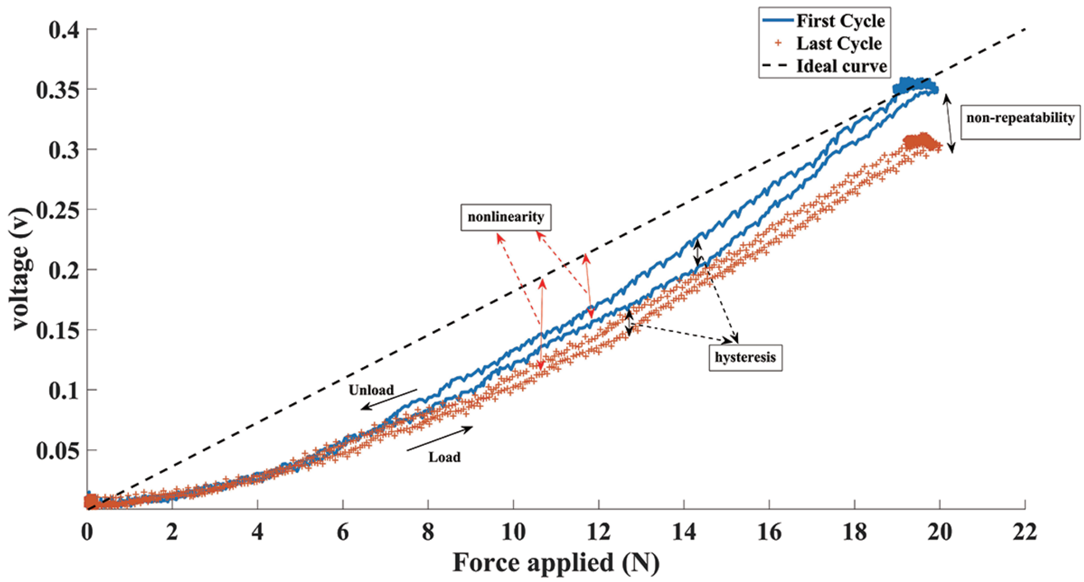

FIGURE 4. Measured sensor versus applied force for hysteresis, nonlinearity and non-repeatability calculation

Figure 4 investigates the evaluation of FlexiForce sensor including the repeatability, hysteresis and linearity. The first and last load-unload cycles of sensor calibration over time are presented in order to evaluate the sensors behavior under a full scale.

1) *Repeatability*. The repeatability refers to a sensor's ability to give identical output for the same input. It is evident from the results that, the FlexiForce has a lack of repeatability under the same applied force and experimental conditions. Indeed, the characteristics of first and last cycle were totally different especially after 5 min of sensor calibration. The mean and SD of the readings for 39 cycles test based on experiment 2 at maximum applied force (19.61 N) were 0.3299 and ± 0.02, respectively. Furthermore, the coefficient of variation was 6.44%.

2) *Linearity.* Linearity is a measure of the proportionality of the sensor's response to the applied load over the range of loading [12]. The mean and SD of the readings for 39 cycles test at 5, 10, 15 and 19 N were 0.039 ± 0.002, 0.109 ± 0.011, 0.211 ± 0.020, 0.307 ± 0.029, respectively. In addition, the coefficient of variation for 5, 10, 15 and 19 N was 4.74%, 10.35%, 9.32% and 9.45% respectively. The quantitative results proved that the FlexiForce has a lack of linearity over the range of loading.

3) *Hysteresis.* It is the difference in the sensor output response during increased loading and decreased loading at the same force [12]. Similar to previous evaluation, the sensor was examined based on procedures of experiment 2 under 39 repeated cycles test. The hysteresis of first and last cycles of the sensor output was calculated at the midpoint in voltage measurements and the result was 3.273% and 2.282% respectively. Furthermore, the mean $\pm$ SD of the maximum difference in output for increasing and decreasing loads in first and last cycles was 0.221 ± 0.021 and 0.317 ± 0.026 respectively. A typical example of the data is shown in Figure 4.

5. **Conclusions.** From this study, we can conclude that the evaluation of a commercial FlexiForce sensor for real time applications is crucial in order to accurately identify the behaviour of sensor over time. This method definitely helps to overcome the issue of the systematic errors which negatively affect the calibrated output data. Quantitative results of three experimental tests were performed. The evaluation results show the lack of linearity, non-repeatability and hysteresis in the FlexiForce sensor. Furthermore, a fluctuation in output force over time was detected even the same experimental conditions were applied. With this evaluation method, other sensor measurement systems can be evaluated. Nevertheless, the sensor provided useful force data, adding to the knowledge of what happens at the grasp during a robotic hand glove.

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