Fibre Optic-Based Force Sensor for Bio-Mimetic Robotic Finger

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***Abstract*—A novel optical-based fingertip force sensor, which is integrated into a bio-mimetic finger for robotic and prosthetic manipulation is presented. This is used to obtain tactile information during grasping and manipulation of objects.**

Unlike most devices the proposed force sensor is free of any electrical and metal components and as such is immune to electromagnetic fields. The sensor is simple and very compact, has extremely low power consumption and noise levels and requires no additional hardware. It is based on a cantilever design combined with fiber optics and is integrated into the distal phalanges of a robotic finger.

The unique design of the sensor makes it ideally suited for use in messy or harsh environments that may be prone to electromagnetic fields, granular or liquid intrusion, may include combustible gasses or be subject to radiation

Keywords*—*Robot Sensing Systems; Tactile Sensors; Intelligent Sensors; Manipulator Dynamics

I. INTRODUCTION

Current robotic manipulation of objects is relatively clumsy. It is becoming increasingly apparent that providing a sense of touch, to be able to feel objects, is a natural way to glean additional data from the environment. However additional touch sensors often greatly add to the complexity and physical bulk of the manipulator. Optical sensors provide an elegant and efficient way to provide a sense of touch. Optical based force and torque sensors has been designed for different applications [1, 2]. This work introduces design and integration of optical based fingertip force sensor into, bio-mimetic anthropomorphic robotic fingers. The robotic finger has the same shape, arrangement, length and proportion as a human hand phalanges [3,4]. The integrated sensor provide tactile information during physical interaction .

II. DESIGN

A laser-scan model of human finger bone was used from Thingiverse (www.thingiverse.com) [5]. The original Stereo Lithography (STL) file was customized so as to introduce additional structural components (i.e. cantilever, holes and groove) in the model (Figure 1). The mesh size of the file was reduced using Autodesk Mesh mixer (Autodesk, Inc). Finally Finite Element Analysis (FEA) of the finger model has been done using Solid Works (Dassault Systmes Solidworks Corp.). The distribution of applied load over the cantilever is shown by the diffrent colours (i.e. red being higly loaded and blue-unloaded) in the FEA simulation (Figure 2). It is apparent from the simulation that the maximum applied force (i.e. 5[N], mean maximum external finger force [6]) on the cantilever is significantly lower than the yield strength of the material selected for manufacturing the real finger (i.e. ABS plastic) [7]. Therefore the load dosen't produce mechanical failure or damage to cantilever integrated in the phalange.

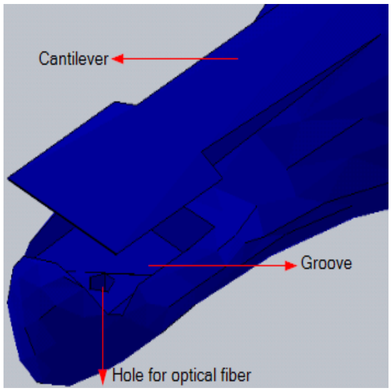

Fig. 1. Customized Distal Interphalangeal Phalange(DIP)

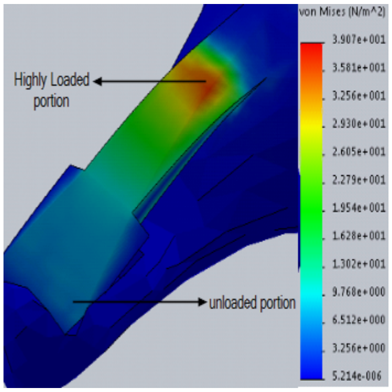

Fig. 2. FEM simulation of the cantilever (ABS material, load of 5[N])

III. FABRICATION

The distal phalange of index finger was manufactured using HP 3D printer machine using ABS plastic (Figure 3). The light beam was projected onto the mirrored cantilever beam by fiber optic cable (i.e. the emitter), a fraction of the reflected beam is received by the second optic fiber (i.e. the receiver) which are in close proximity [4] (Figure 3). The applied force modulates intensity of the reflected light and produces different voltage outputs.

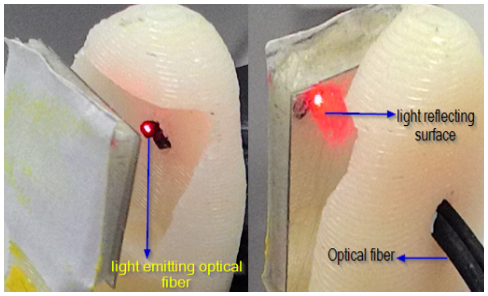

Fig. 3. Fingertip fiber optic cable and mirror arrangement

IV. CALIBRATION

To use the designed sensor,accurate calibration is vital. As such a specific testrig was constructed for this purpose [2].

A. *Calibration test-rig*

The main components involved in this test-rig are Keyence FS-N11MN Digital Fiber Optic Amplifier, IIT-FT17 force and torque (F/T) sensor, NI USB-6000 DAQ board (National Instruments Inc.) and a fixing vice [8]. The phalange is attached to fixed jaw of the vice and IIT-FT17 F/T sensor is attached to the moving jaw. The handle at the end of moving jaw enables to manually control force applied to the phalange (Figure 4).

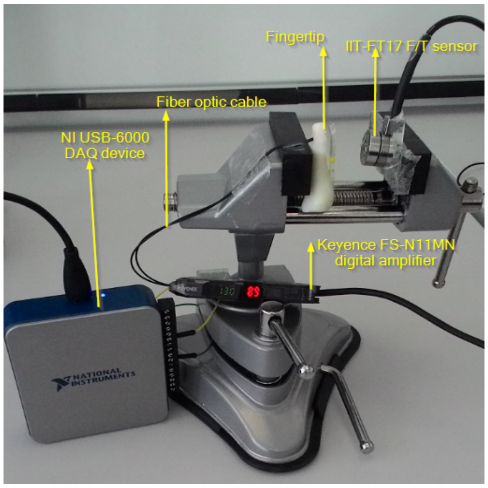

Fig. 4. Force sensor calibration setup

The signal line of the FS-N11MN is connected to one of the analogue pins of NI USB-6000 DAQ device to measure the output voltage. A LabVIEW Virtual Instrument (VI) program, which can measure the output voltage from the DAQ device in real-time and export the data to excel was developed. A program in C++ was then used to measure the force components of the IIT-FT17 F/T sensor. These measurements are read by another LabVIEW VI program and exported to Excel. The two sets of data (i.e. voltage and force) are finally used for regression analysis in order to highlight correlations between data sets.

B. *Calibration procedure*

IIT-FT17 F/T sensor was used to apply and measure the force to the sensing element of the fingertip (Figure4). The loading and unloading of the force was done at different force values and the corresponding voltage output from the fiber optic sensor was measured. Fifteen different input force values were used during loading and unloading experiments. The NI USB-6000 (National Instruments) data acquisition board was used to log the voltage from the sensors at frequency of 500 Hz.

C. *Calibration curve*

After collecting data using procedures explained above, the data was exported to excel to further analyze and quantify the relationship between force and voltages. Applying simple linear regression technique, it was possible to find the relationship between voltage and corresponding force by fitting a linear equation to the observed data [9]. This way the output voltage from the optical fibers is associated to normal force (i.e. Fz where z is the ortogonal axis) applied to the fingertip. The calibration curve is shown in Figure 5. The fitted liner equation from linear regression analysis is:

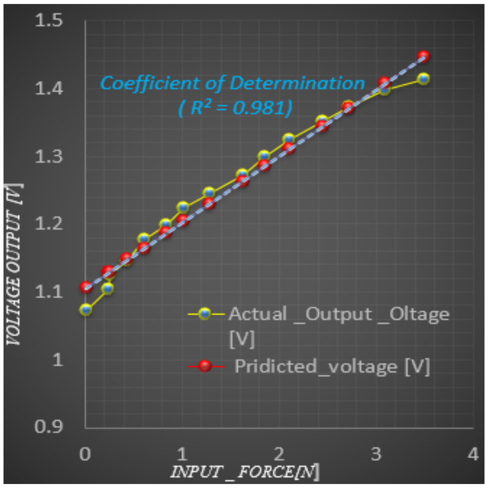

Fig. 5. Calibration curve of force sensor

$$OutputVoltage = 0.0978 * Appliedforce + 1.1045 \quad (1)$$

Applying Eq. (1) the force can be measured once the output voltage from the sensor is known.

V. RESULT AND DISCUSSION

From regression analysis result, the two data sets (i.e. Output voltage and Input force) have linear behaviour with coefficient of determination ($R^2 = 0.981$). This means 98.1% of sensor's output (i.e. voltage) is due to its input (applied force). The proportion of variability of sensor's output can be explained by the variability of its input [9].

A. *Sensor Performance*

The most important performance measuring parameters of the designed sensor have been analysed.

1) **Accuracy**: measure of how close are actual sensor readings (i.e. output voltage from KEYENCE FS-N11MN) from their corresponding predicted voltage

value (i.e. voltage data obtained from the fitted linear equation during calibration procedure).The designed sensors accuracy is measured mainly by its relative and absolute errors. Based on the data obtained from the calibration procedure, the calculated value for percentage of sensors maximum relative error is 2.6% of sensor's actual reading. This small deviation shows sensor's better accuracy [10].

2) **Span**: The designed sensor works over an input range between 0[N] and 5[N]. Beyound specified design range, it result in permanent damage or destruction of sensor.
3) **Resolution and Sensitivity**:the senor can discriminate input force values above 0.02[N] and it has sensitivity value of 0.098 V/N.
4) **Saturation**: Beyond its input range (i.e. 5[N]) the sensor reaches its saturation limit. This means , any further increment of input force will no longer increase output voltage [10].
5) **Mechanical Hysteresis Error**: caused by induced mechanical stress in the component causing deflection of the cantilever beam less at a given value of force when force is increasing than when it is decreasing [10]. Based on the data collected during calibration, the hysteresis error of the sensor is shown in Figure 6.

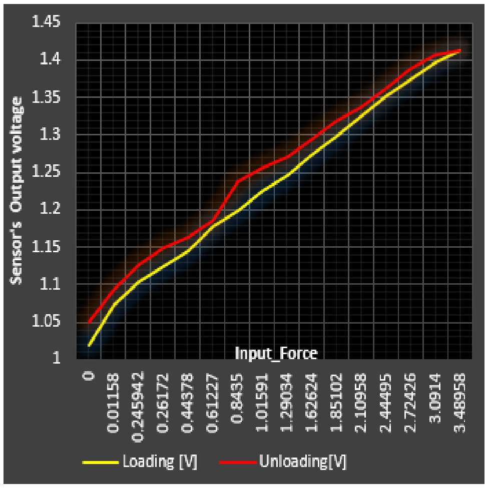

Fig. 6. Sensor Hysteresis curve

The percentage of the hysteresis is the ratio of maximum difference between the loading and unloading curve and the output range of the sensor. Therefore the maximum calculated hysteresis error is 8.5%. This means each sensor measurements during unloading will be 8.5% greater from each loading measurement (Figure 6). Lower value of hysteresis error is also another good indication of sensors performance.

VI. CONCLUSION AND FUTURE WORK

Fabrication, calibration and performance analysis of an optical based fingertip force sensor was conducted. A mechanically simple and low cost optical based fingertip force sensor was used in a biomimetic anthropomorphic phalange. The sensors calibration result shows high correlation (i.e. R= 0.99) between applied force and corresponding voltage output from the digital fiber optic sensor. Output from regression analysis indicates better value of coefficient of determination ($R^2 = 0.981$). This means variability of output voltage can be explained by the variability of the fingertip force. The calculated values of sensors relative and hysteresis errors are small and are good indicators of sensors excellent performance. These results linked with the sensors inherent resilience to harsh environments indicate that such a device will be able to be used for numerous applications, for example: surgical manipulation; handling toxic or radioactive materials; for extraterrestrial probes; in environments where combustion is a problem, for example is gas pipe lines; or be used in environments where there is a danger of electromagnetic interferences, for example when working in close proximity to large machinery such as MRI scanners, NMR spectrometers, and so on. Future work will focus on optimizing structural components and the location of the sensors. In addition the use of different sensors, the deployment of fiber optic cables, the shape of both the reflective surface and structure of built-in cantilever beam are also possible areas where further improvement can be made.

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