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Miniaturized Force-Torque Sensor Built in a Robot End-Effector for Delicate Tool-Tip Gripping Control

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***Abstract*—A robot end-effector or gripper must have the capability to endure both the weight and acceleration of the object in spite of its frequent movement while a robot uses the gripper to handle various objects and assists the tasks of a person. In this regard, it is essential to directly measure the amounts of gripping force and torque applied to the object by the gripper. This work presents the design and development of a miniaturized force-torque (FT) sensor built inside the gripper with a thickness similar to that of the human finger. It enables efficient use of the FT sensor for delicate tool-tip gripping control of the gripper in the packaging line of electrical devices such as mobile phones. The FT sensor is optimized for acquiring the 3-DoF force-torque information of a single-axis gripping tool. The performance of the FT sensor has been verified through characterization experiments and integrated tests on the gripper.**

***Index Terms*—Force-torque sensor, packaging line, robot end-effector, semiconductor strain gauge.**

I. INTRODUCTION

A robot end-effector is a device at the end of a robot arm or a manipulator that is used for a robot to handle various objects and to assist the tasks of a person. The robot end-effector or gripper must have the capability to endure both the weight and acceleration of the object in spite of its frequent movement. For enhancing the performances of these object manipulation functions, the recent researches and developments of robot end-effectors have been placing more emphasis on integration with sensor technology using various sensors. It is essential to directly measure the amounts of gripping force and torque applied to the object by the gripper. Force-torque (FT) sensors, which measure the multi-axial force-torque, are used to control the force-torque of the joints and end-effectors in robots [1]–[3]. Particularly in many branches of industry, delicate tasks that are generally handled by humans are now left to the robots, in order to achieve higher levels of automation and productivity. It has become more important for FT sensors to be embedded in the joints and end-effectors to enable the robots to deliver precision in delicate human tasks.

Among these sensor technologies, the FT sensor has been applied by adjusting its function and size according to the purposes in various fields ranging from industrial robots to medical robots [4]–[9]. Currently, numerous and various commercial FT sensors have been developed. The representative small-size FT sensor products are Nano17 of ATI [10] and FT-Nano-17 of SCHUNK [11], where both sensors have a diameter of 17 mm and use semiconductor strain gauges. For applying such FT sensors to delicate manipulation tools or robot hands, miniaturization and optimization are necessarily required.

In this regard, this work presents a miniaturized FT sensor that is built in the gripper and optimized for acquiring the 3-degree-of-freedom (DOF) force-torque information of a single-axis gripping tool. The gripper is devised for exclusive use in the packaging line of electric devices such as mobile phones. The remainder of this paper is organized as follows. Section II presents the requirement and specification of the sensor frame and the data acquisition (DAQ) board for the FT sensors embedded in the robot end-effector. The design and implementation of the FT sensor are described in Section III. The experimental results and performance analyses are discussed in Section IV. Finally, the conclusions are presented in the last section.

II. REQUIREMENT AND SPECIFICATION OF A MINIATURIZED FORCE-TORQUE SENSOR

For determining the optimal and stable gripping of the two-finger grippers generally used in the robot working process, it is necessary for the gripper controller to acquire the deterministic gripping force and torque. In the case of the two-finger gripper, the gripping force F_z and torque T_z in the gripping direction and the torque T_x in the vertical direction of the gripping operation are sufficient for such determination as depicted in Figure 1. In addition, it is essential to use a limited number of strain gauges and glue them on the faces of the flat beams with high precision in order to simplify the assembly process inside the tiny sensor frame. The FT sensor used in this work has a limitation in the planar dimension of 14 mm × 14 mm because the gripper jaw with the similar thickness of a human finger is required for delicate handling of individual components in a speedy and automated packaging line of electronic devices such as mobile phones, and the devised sensor should be applied inside the gripper jaw. From this standpoint, we tried to show

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the feasibility of our devised FT sensor.

Figure 1 illustrates the conceptual design and modeling of the proposed FT sensor frame for a robotic gripper. The sensor frame structure has a basic dimension of 14 mm × 14 mm × 5 mm, and the structure with a Maltese cross shape makes it possible for the force-torque sensor to be built in the tool-tip of the gripper. The basic material of the sensor frame should satisfy the following conditions: (1) good workability, (2) large heat capacity and low coefficient of thermal expansion, (3) low density, (4) high corrosion resistance, and (5) high yield strength. The feasibility of the sensor frame devised for signal acquisition of 3-DoF (F_z, T_z, and T_x) has been evaluated through the finite element method (FEM) analysis based on the modeling of the sensor frame, as shown in Figure 2. The 3-DoF analog signals acquired from the sensor frame are processed through analog-to-digital conversion (ADC), digital filtering, decoupling, and calibration. The DAQ board should be implemented to provide a sampling rate of 500 Hz. After the FT sensor prototype is built in the tool tip of the gripper and the entire sensor system is integrated, the reliability assessment should be performed through various performance verifications.

Generally, the robotic gripper must have the capability to endure both the weight and acceleration of the object in spite of its frequent movement during packaging process. The force required to grip the object is obtained by the following well-known formula

$$F = \frac{m(g+a)\cdot S}{2\cdot «}, \quad (1)$$

where F is the force of a two jaw gripper required to grip the object, μ is the coefficient of friction, a is the maximum gripper acceleration in the gripper, and m is the weight of the object [12]. Here, S stands for the safety factor. The safety factor of 2 is recommended for gripping force in normal transportation. When remarkable acceleration, deceleration and/or impact occur at work part transportation, stronger inertial force is applied to a work part by gravity so that the sufficient safety rate should be considered [13]. By considering the general gripping force requirement of the robotic gripper, the FT sensor devised in this work should exhibit the performance to measure a maximum force of 30 N and a maximum torque of 500 mNm.

A semiconductor strain gauge for this work has been selected among various strain gauges. The strain sensitivity coefficient of the semiconductor strain gauge is tens of times greater than that of general metal gauges, and the output is large such that it is suitable for fine strain measurement. Despite these advantages, this strain gauge is brittle, particularly hard to handle wiring and sensitive to temperature so that extremely careful attention is required to handle it. Therefore, “U”-shaped semiconductor strain gauge from Micron Instruments is used as the FT measurement strain gauge along with the sensor frame design. The selected model is a semiconductor strain gauge with a total length of 0.060 in, an active length of 0.033 in, and a nominal resistance of 2000 Ω ± 100 Ω at 78°F. This model is convenient and moderate to be disposed on the top and bottom surfaces of the flat beams in the miniature sensor frame. Figure 3 shows that the selected strain gauges are affixed to the surfaces of a simple cantilever frame with one hole and the primary feasibility is evaluated by the experimental strain measurement.

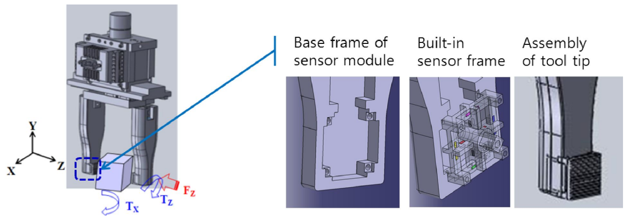


Fig. 1. Conceptual design and modeling of a force-torque sensor frame for a robotic gripper.

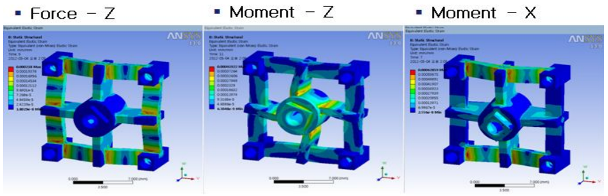
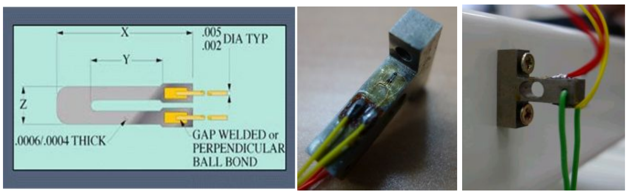


Fig. 2. FEM of a 14-mm multi-axial sensor frame.



(a) (b) (c)

Fig. 3. Primary test of a semiconductor strain gage on a simple cantilever frame: “U”-shaped semiconductor strain gauge from Micron Instruments (a), affixation(b), raw signal acquisition(c).

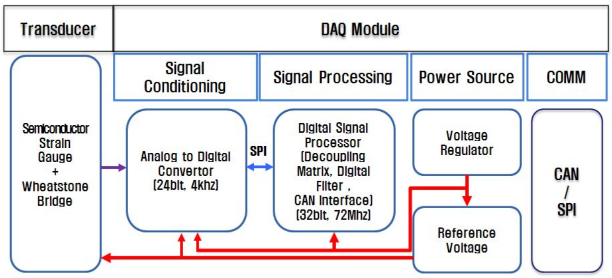


Fig. 4. Block diagram of the DAQ board for signal acquisition from the strain gauge.

Figure 4 shows the configuration of a DAQ board for signal acquisition from the strain gauge. The DAQ board acquires raw signals from the semiconductor strain gauges instead of the signal amplifiers. The use of the semiconductor strain gauge is feasible from the point of view that the output signal of the semiconductor strain gauges is 40~50 times larger than that of the existing metal thin film strain gauges. The DAQ has been configured with three major components: an analog-digital converter for signal conditioning, a microprocessor for signal processing, and a power supply for reference power. The size and performance of those components are the most important point of consideration in satisfying both the dimension limitation and the target specification of the FT sensor module to be built inside the jaw of a gripper. This implies that the FT sensor developed in this work should accept the dimension of 14 mm by 14 mm and exhibit the performance to measure a maximum force of

30 N and a maximum torque of 500 mNm with a force resolution of 7 mN and a torque resolution of 0.1 mNm.

III. DESIGN AND IMPLEMENTATION OF THE MINIATURIZED FORCE-TORQUE SENSOR MODULE

As mentioned in the previous section, the proposed FT sensor should satisfy the requirement and specification of the gripper devised for the exclusive use in the packaging line of electrical devices such as mobile phones. The mechanical and electronic design of the prototype of the proposed sensor module and its implementation are described in this section.

The mechanical structure of the miniaturized multi-axial sensor frame has a modified Maltese cross shape with a dimension of 14 mm × 14 mm × 5 mm. The basic structure has a regular quadrilateral frame with an internal cross-shaped beam as shown in Fig. 5. The external frame consists of four pillars with a square of 2.5 mm and four horizontal connection beams of 2 mm × 1 mm. The internal cross-shaped beam has four vertical connection beams of 4 mm × 1 mm and a cylinder pillar for fastening a tool-tip where the gripping force is exerted, as shown in the second row of Fig. 5. The basic material of the sensor frame is stainless steel SUS304 (18 % Cr-8 % Ni), which is known as a material of good solidity and elasticity.

The sensor frame with this simple and intuitive geometry is machined by end milling with high precision. Its finishing operation is necessarily required for lowering the roughness of each connection beam surface on where the strain gage will be attached. Twelve semiconductor strain gauges are disposed on the top and bottom surfaces of the flat beams of the sensor frame. Figure 6(a) shows the complex wiring connection of the calibration jig caused by many signal wires from the strain gauges. The complex wiring of the multiple signal wires is more effectively conducted by using a wiring board specifically devised for more easy and convenient wiring, as shown in Fig. 6(b). The sensor frame module after completing the wiring is shown in Fig. 6(c).

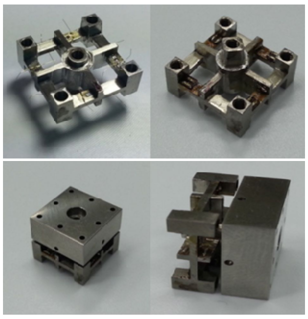
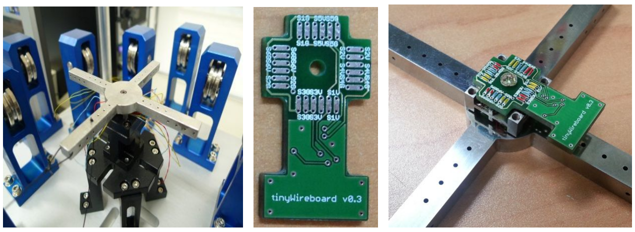


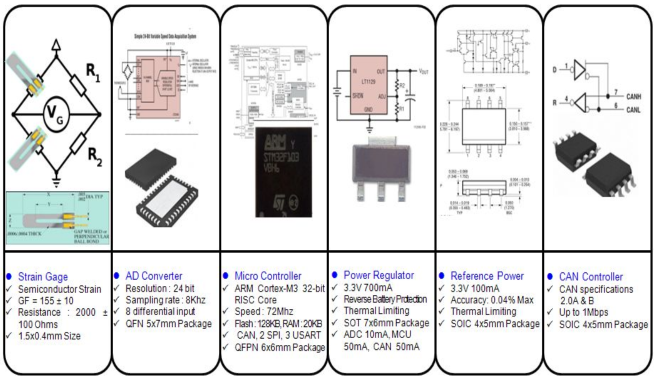
Fig. 5. Fabrication of multiple-axis sensor frame with handling semiconductor strain gauges.



(a) (b) (c)

Fig. 6. Calibration jig connected by many signal wires (a), a wiring board for more easy and convenient wiring (b), and a sensor frame module wired by using the wiring board (c).

The DAQ board is customized to miniaturize the dimension with satisfying the target specification of the FT sensor, such as measuring range, resolution, and sampling rate. It is extremely important for the DAQ board to be well-designed for effective signal data processing. The DAQ electronic parts were selected by conformity assessment. It consists of 12 sets of semiconductor strain gauges, an A/D converter with 24-bit resolution, a 32-bit RISC Core Microcontroller, a power regulator and a power reference, and a CAN controller. The configuration and specification of the DAQ hardware parts are summarized in Figure 7. In order to realize the specified resolution of force and torque measurement, we implemented the electrical design of FT sensor DAQ module which can acquire 5,000 divisions of raw signal output from the strain gage by using the ADC signal processing unit with 24 bits resolution. Furthermore, the firmware of the DAQ board has been developed by implementing and updating the following functions: ADC, digital filter for noise removal, decoupling matrix for mutual interference compensation, zero offset for zeroing, sensor calibration, and CAN communication for DAQ data transmission. The design and development of the DAQ board prototype have been updated through three times of revision. Figure 8 shows all the versions of the prototype



- Strain Gage
  - ✓ Semiconductor Strain
  - ✓ GF = 155 ± 10
  - ✓ Resistance : 2000 ± 100 Ohms
  - ✓ 1.5x0.4mm Size
- AD Converter
  - ✓ Resolution : 24 bit
  - ✓ Sampling rate : 8Khz
  - ✓ 8 differential input
  - ✓ QFN 5x7mm Package
- Micro Controller
  - ✓ ARM Cortex-M3 32-bit RISC Core
  - ✓ Speed : 72Mhz
  - ✓ Flash : 128KB, RAM : 20KB
  - ✓ CAN, 2 SPI, 3 USART
  - ✓ QFPN 6x6mm Package
- Power Regulator
  - ✓ 3.3V 700mA
  - ✓ Reverse Battery Protection
  - ✓ Thermal Limiting
  - ✓ SOT 7x6mm Package
  - ✓ ADC 10mA, MCU 50mA, CAN 50mA
- Reference Power
  - ✓ 3.3V 100mA
  - ✓ Accuracy: 0.04% Max
  - ✓ Thermal Limiting
  - ✓ SOIC 4x5mm Package
- CAN Controller
  - ✓ CAN specifications 2.0A & B
  - ✓ Up to 1Mbps
  - ✓ SOIC 4x5mm Package

Fig. 7. Configuration and specification of the DAQ hardware parts by conformity assessment.

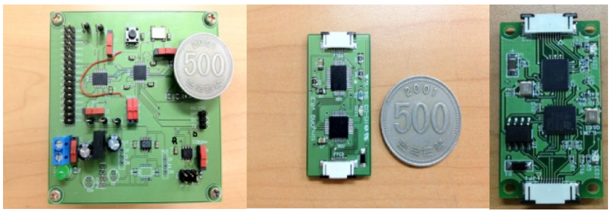


Fig. 8. First version (left), second version (middle), and third version (right) of the prototype.

It is ideal that a force sensor responds to only the force acting in the direction of measurement, but not to the other directional forces. However, the actual force sensor responds to the other forces exerting in the undesired direction. It is called the mutual interference (crosstalk). The coupled signals should be separated by implementing an experimental decoupling matrix, which is computed according to the least square method, to compensate for such mutual interference of signals:

$$F^T = S^T \times R^T, \tag{2}$$

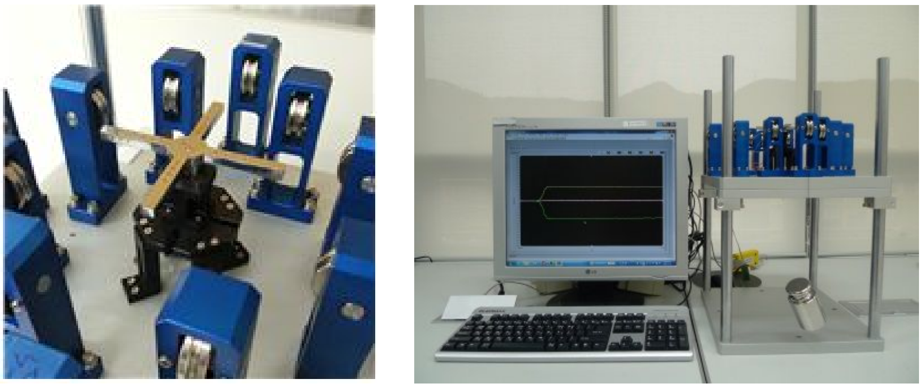
$$(S \times S^T)R^T = S \times F^T, \tag{3}$$

$$R^T = (S \times S^T)^{-1} \times S \times F^T, \tag{4}$$

where F, R, and S denote the force-torque vector, decoupling matrix, and measured signal vector, respectively.

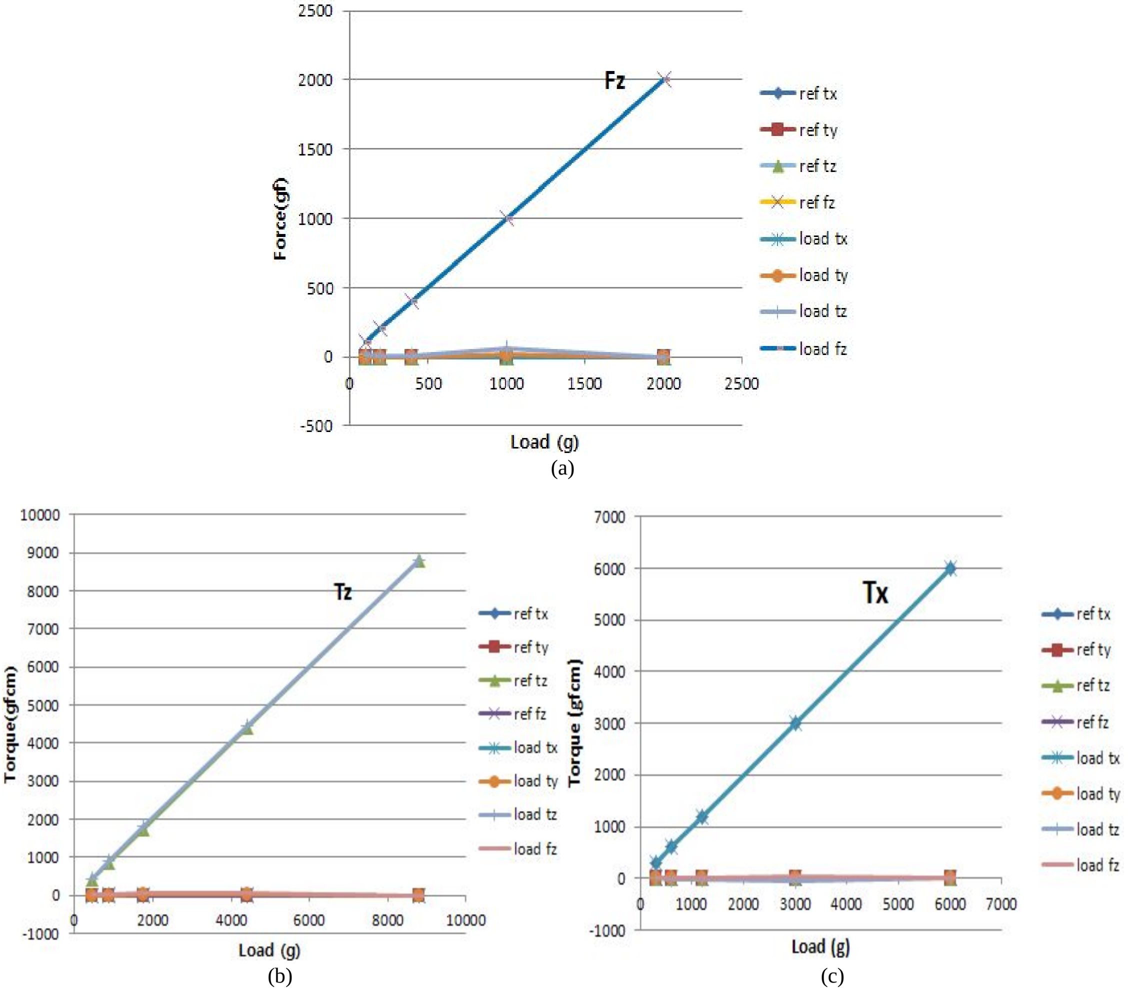
IV. EXPERIMENTAL RESULTS AND DISCUSSION

For the configuration of an experimental environment to evaluate the performance of the developed sensor module, a calibration unit and precision reference weights are devised and prepared as shown in Fig. 9. A crossbar jig is used for easily conducting the loading and unloading of different masses along the x, y and z directions. The DAQ board collects six raw signals from the sensor frame. The raw signals are converted into 3-DoF force-torque (F_z, T_z, and T_x) through the following processes: ADC, digital filtering, and decoupling matrix. According to the development specification, the measuring range is satisfied with a maximum force of 30 N and a maximum torque of 500 mNm. The linearity test is conducted by loading and unloading at each different load along the *x-y* and *z* directions. The linearity measurement of the F_z, T_z, and T_x reference loads shows that the maximum nonlinearity errors are less than 0.25 %, 0.72 %, and 0.13 % on full scale, respectively, as shown in the plots in Fig. 10.



(a) (b)

Fig. 9. Experimental environment configuration for sensor evaluation: calibration unit (a) and precision reference weights (b).



(a)

(b) (c)

Fig. 10. Measurements in the linearity test for the sensor module.

V. CONCLUSIONS

A miniaturized FT sensor for acquiring the 3-DoF force-torque information of a single-axis gripping tool has been designed and fabricated for the purpose of delicate tool-tip gripping control of a robot end-effector for a dual-arm robot application. Furthermore, the DAQ board for signal acquisition from the strain gauges of the FT sensor has been implemented by configuring the signal processing board in the FT sensor and accessing the conformity of its components. For the feasibility verification of the sensor performance, the linearity and repeatability of the sensor have been evaluated through the experimental results. For full reliability evaluation, additional tests like hysteresis, drift, and durability are required.

The main contributions of this work are summarized:

1. The FT sensor devised in this work has been designed and fabricated by satisfying the limitation in the planar dimension of 14 mm × 14 mm because the sensor should be built in the gripper with a thickness similar to that of the human finger in order to enable more delicate and efficient use of the sensor in the packaging line of electric devices such as mobile phones.
2. An optimized configuration of the wiring board and DAQ board has been proposed and implemented in order to facilitate the fine wiring of semiconductor strain gauges and to maximize the strength of the signal acquisition, despite such dimension limitation.
3. The sensor performance assessment satisfies the requirement and specification of the FT sensor for the robot end-effector of the dual-arm robot application in the packaging line.

Our further work is to integrate the developed FT sensor into the robot end-effector of the dual-arm robot and to guarantee the real-field reliability through tool-tip gripping control for delicate handling of the electric devices.

REFERENCES

[1] B. H. Lee, J. W. Joo, “Design of six-component F/T sensor with flexible fixed ends”, *Korean Society of Mechanical Engineers, KSME Journal A*, vol. 34, no. 6, pp. 771–780, 2010. [Online]. Available: http://dx.doi.org/10.3795/KSME-A.2010.34.6.771

[2] M. S. Ko, I. J. Ha, B. H. Lee, N. Y. Ko, “The output analysis of wrist force/torque sensor for SCARA type robots”, *Korean Institute of Electrical Engineers Journal*, vol. 37, no. 8, pp. 570–578, 1988.

[3] M. Fontana, S. Marcheschi, F. Salsedo, M. A. Bergamasco, “A three-axis force sensor for dual finger haptic interfaces”, *Sensors*, vol. 12, no. 10, pp. 13598–13616, 2012. [Online]. Available: http://dx.doi.org/10.3390/s121013598

[4] C. G. Kang, “Performance improvement of a 6-axis force-torque sensor via novel electronics and cross-shaped double-hole structure”, *Int. J. Control Autom.*, vol. 3, no. 3, pp. 469–476, 2005.

[5] G. J. Garcia, J. A. Corrales, J. Pomares, F. Torres, “Survey of visual and force/tactile control of robots for physical interaction in Spain”, *Sensors*, vol. 9, no. 12, pp. 9689–9733, 2009. [Online]. Available: http://dx.doi.org/10.3390/s91209689

[6] T. Liu, C. Li, Y. Inoue, K. Shibata, “Reaction force/torque sensing in a master-slave robot system without mechanical sensors”, *Sensors*, vol. 10, no. 8, pp. 7134–7145, 2010. [Online]. Available: http://dx.doi.org/10.3390/s100807134

[7] J. Lee, “Apply force/torque sensors to robotic applications”, *Robotics*, vol. 3, no. 2, pp. 189–194, 1987. [Online]. Available: http://dx.doi.org/10.1016/0167-8493(87)90007-6

[8] M. Sorli, S. Pastorelli, “Six-axis reticulated structure force/torque sensor with adaptable performances”, *Mechatronics*, vol. 5, no. 6, pp. 585–601, 1995. [Online]. Available: http://dx.doi.org/10.1016/0957-4158(95)00039-8

[9] J. Zhenlin, G. Feng, Z. Xiaohui, “Design and analysis of a novel isotropic six-component force/torque sensor”, *Sensors Actuat. A-Phys.*, vol. 109, pp. 17–20, 2003.

[10] F/T Sensor: Nano17. [Online]. Available: http://www.ati-ia.com/_products/ft/ft_models.aspx?id= - Nano17

[11] FT-Nano_017_EN.pdf. [Online]. Available: http://www.schunk.com/_schunk_files/attachments/FTNano_017_EN.pdf

[12] G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk, *Robot Grippers*. Berlin: Wiley, 2007, pp. 88–89.

[13] Selection Guide (Gripping Force). [Online]. Available: http://www.intelligentactuator.com/partsearch/robocylinder/appndx74_Model_Selection_by_RCP2_Gripper.pdf