Abstract — This paper proposes a one-body optical torque sensor. The proposed sensor has advantages of anti-slip and low cost due to the simple one-body structure. Simulations for stress and strains analysis are accurately performed. To demonstrate the performance of proposed design, experiments were also carried out to compare it with a commercial force/torque sensor (Mini45, ATI).

Keywords— optical torque sensor; one-body structure; low cost; home-based rehabilitation robotic systems; easy to design; easy to manufacture; photo interrupter;

I. INTRODUCTION

Muscle rehabilitation therapy routinely requires muscle exercise to be carried out on a repetitive basis, typically for 15-30 minute periods, 2 to 5 times a week. However, the number of therapists is insufficient compared with the number of patients needing rehabilitation resulting in insufficient training for majority of the patients.

As a remedy for this problem, robotic systems have been developed[1-3]. Especially, home-based rehabilitation robotic systems[4,5] including tele-rehabilitation robots[6-8] are also developed. Widespread clinical acceptance of robotic systems is slowed in part by the relatively high cost of current commercially-available systems (for example, the $180,000 ARMinIII [1], or the $52,000 Armeo [2]). These robots enable force-feedback between patient and robot using expensive force/torque sensor.

[9] reports that the intensity of training affects recovery. If patients can receive enough training in hospital and their home by robotic systems, the recovery of patients will be enhanced. Commercialized rehabilitation robotic systems should be

a) easy to use for patients to rehabilitate by themselves
b) safe in home environment without an assisting therapist
c) provided at a low cost to be economically competitive especially in comparison to the outpatient treatment.

To meet these requirements, low cost force/torque sensor is an essential element. Force-feedback is widely used in rehabilitation robots to ensure its safety[10]. Strain-gauge type sensor is often used due to high sensitivity. However, it is expensive and noisy. In addition, it is always used with an amplifier due to small signal levels[11]. Commercial torque sensor, therefore, is expensive to apply to rehabilitation robotic systems.

To reduce the cost of torque sensor, an optical torque sensor is developed in [12] whose contribution is its implementation of impedance control using the optical torque sensor at each joint instead of a highly expensive 6DOF force/torque sensor at the end effector. However, it has slip-problem especially when used in vibrational or high speed plants due to its assembly structure.

This paper proposes an anti-slip and low cost torque sensor based on optical sensors. Since the proposed design has a simple one-body structure, it has advantages of ease of design and manufacture. The contents of the paper is organized as follows. Chapter II briefly overviews existing design and describes its slip-problem; Chapter III introduces proposed design in detail including simulations; Chapter IV deals with experiments to demonstrate the performance of prototype based on proposed design; Finally, Chapter V is a conclusion to the proposed design.

II. SLIP-PROBLEM IN EXISTING DESIGN

A. Conceptual design of existing optical torque sensor.

The conceptual design of existing optical torque sensors consist of three elements and an optical sensor as shown in Fig. 1. One element is an elastic structure which is a torsional spring varying with the applied torque. The other two elements are a mounting side and a tool side. To transmit the applied torque, the mounting side is fixed to the mechanical component that is connected with an actuator or drive shaft. And next link or driven shaft is attached to the tool side.

\[ \tau = k(\theta_i - \theta_f) = k \Delta \theta \]

Figure 1. Conceptual design of existing optical torque sensor
The issue is how the variance of elastic element, angles between the mounting side and the tool side, can be measured. An optical torque sensor proposed in [12] measures the angle using a photo interrupter which is a type of optical sensor. Output voltage of the photo interrupter varies according to the position of the interrupter as shown in the Appendix 1 which is an extract from a catalog for the photo interrupter (CNA1311K, Panasonic).

B. Detailed design of existing optical torque sensor

[12] introduces the development of optical torque sensor. In this section, the design process of the existing method is described with a focus on the slip-problem.

1) Elastic element

To design the elastic element, stress and strain analysis should be performed. More details are in chapter III.

2) Other two elements

The mounting side holds the rim of the elastic element, while the tool side holds the center of the elastic element, and vice versa. Perfect fit between each element is very important. Since the order of measurement range of photo interrupter is about ten micrometers, even a minute slip between the elastic element and the tool side causes large measurement error. To prevent this slip-problem, the elastic elements mounted with the photo interrupter and the tool side mounted with the interrupter are shaped to fit each other as shown in Fig. 3; It has a pick and hole, or key and lock structure. Although each element has a special shape, the existing sensor cannot avoid the slip-problem due to manufacturing errors from limitations in manufacturing accuracy in each element and bolts.

If the simulation result of the elastic element and the fit of each element are acceptable, the next step is manufacturing a prototype. The prototype 1 was machined from each piece of material - brass, aluminum alloy, and steel- using wire Electrical Discharge Machining (EDM) cutting to eliminate hysteresis and guarantee high strength [12]. The EDM method satisfies tight tolerance but is very expensive. However despite such costs, EDM cutting is needed to manufacture the elastic element with complex structures, including the fitting shape. The prototype 1 based on existing design is shown in Fig. 4.

III. THE PROPOSED DESIGN

A. Conceptual design of the proposed design

Since the fundamental slip-problem is derived from assembling each element with bolts, this paper proposes a simple one-body structure unifying the three elements as explained in Chapter II.

For effective variance of the elastic element, various structures are suggested in [13]. To adopt these structures, one side of the body can be machined as shown in left side of Fig. 5; however, EDM cutting is needed to manufacture a complex structure; such as spoke or hexa form. To meet the low cost criteria the proposed design adopts a cylinder type structure shown in right side of Fig. 5. It can be manufactured by lathe and milling machine without EDM cutting.

B. Detailed design of proposed design

The proposed design is divided into two parts based on their roles. One is a sensor body part with an elastic element such as a torsional spring, and the other is a measurement part to measure the variance using a photo interrupter.
1) Sensor body part

The stiffness depends on the structure of the sensor and property of the material, so-called design variables. Firstly, the material of sensor body, based on desired capacity, is chosen. If the desired capacity is larger than 200Nm, steel alloy is chosen, otherwise aluminum alloy or brass is usually selected. Then the structure with one-body is designed, namely, an outer diameter, an inner diameter, and a thickness as shown in Fig. 6 are determined.

In a typical sensor design, as the sensor placement is already determined, the size and numbers of holes attached to the sensor placement are determined. In addition, the outer diameter is also decided on. (Note that the proposed sensor is designed to substitute Mini45 in the hand rehabilitation robot explained in Chapter V. The desired capacity Td is 10Nm) Therefore, design variables to be designed are only two variables, \(d_1\) and \(t_1\). The stiffness of the sensor is increased with larger \(d_1\) and smaller \(t_1\). To determine the \(d_1\) and the \(t_1\) appropriately, the stress and strain simulation should be performed. The simulation is carried out with SolidWorks 2010(Dassault Systèmes SolidWorks Corp.)

a) Strain Analysis

As mentioned in Chapter II, the measurement range of photo interrupter is the order of ten micrometers. The photo interrupter used in prototypes is CNA1311K, whose measurement range is 50 \(\mu\)m. Since the desired sensor capacity(Td) is 10Nm, the variance by +10Nm is about +25\(\mu\)m(half of the measurement range of the CNA1311K), and the variance by -10Nm is also about -25 \(\mu\)m. It can be checked from strain analysis using FEM shown in Fig. 7.

b) Stress Analysis

When a torque within \(-T_d \sim +T_d\) is applied to the sensor, the variance should be derived from the elastic deformation. The stress of sensor by applied torque, which is in the capacity of sensor, \(-10Nm \sim +10Nm\), is lower than maximum yield stress. It can be checked from stress analysis using FEM.

If the simulation result satisfies the design goal, a prototype can be manufactured. The prototype 2 is manufactured as shown in Fig. 8. Then we have two prototypes. The prototype 1 is based on existing design, and the prototype 2 is proposed design.

2) Measurement part

The measurement part consists of a photo interrupter and an interrupter. Since the output voltage of the sensor is proportional to the blocking area of interrupter, the interrupter should be designed as a right rectangle. In the prototype 2, the interrupter is made of aluminum alloy. A mount for the interrupter is designed to adjust the position of interrupter for adjustment. To measure both directions of torques within \(-10Nm \sim +10Nm\), position of the interrupter should point out of the center of the photo interrupter. 3D CAD model of the interrupter and the mount of interrupter are shown in Fig. 9.
IV. EXPERIMENTS

Before experiments with the prototype to test performance, the interrupter should be located on the center of the photo interrupter, checking the output voltage of the photo interrupter using an oscilloscope or an analog to digital converter (ADC). If the sensing area is open (empty), the voltage of photo interrupter is high, if closed the voltage is low. In other words, voltage is proportional to the blocking area of interrupter as shown in Appendix 1.

After the interrupter setting, the prototype is mounted with a delicate commercial sensor, Mini45, on the test bed for the calibration of the prototype shown in Fig. 10. Then two signals can be extracted; one is the output voltage of the photo interrupter, while the other is the torque value of the Mini45. The over-all data acquisition processes are shown in Fig. 11. From the result of strain simulation, the variance ($\Delta \theta$) is proportional to the applied torque ($T$). And the output voltage ($V$) is proportional to the variance ($\Delta \theta$). The torque ($T$), therefore, is proportional to the output voltage ($V$) as expressed in (1). (2) is also derived from the relation in (1).

\[ V \propto \Delta \theta \propto T. \quad (1) \]

\[ T = aV + b. \quad (2) \]

Constants, $a$ and $b$, are determined by the least square method. After 10 repeated experiments, $a$ and $b$ is obtained with 6.534 and -11.641 respectively. A raw data of $V$ and $T$ from photo interrupter and Mini45 are shown in Fig. 12. After calibration of raw data using (2), the estimation is almost the same as the torque value of Mini45 as shown in Fig. 12. RMS error which is the root-mean-square of deviation from torque value of Mini45 is 0.0016Nm. Notice that the proposed design is better than existing design compared to Appendix 2.
V. CONCLUSION

Performance of proposed design is verified by experiments of comparison with Mini45 and the existing design. It is simpler, costs less, and weighs less compared to Mini45 and the existing design.

In the case of commercial torque sensor, since the size is standardized, its application to service robots, such as rehabilitation robotic systems is limited. In contrast, the proposed design has advantages because it is easier to design as desired, and easier to manufacture without EDM cutting. Note that the cost of prototype 2 including photo-interrupter is only 100 USD.

When comparing the proposed design and the existing design with respect to performance, RMS error of the prototype 2 is only about 3% of the prototype 1. The prototype 2 achieves the anti-slip structure with one-body. Even if bidirectional torques are applied, the estimation of torque using the prototype 2 is almost the same as the torque value of Mini45.

In order to demonstrate the proposed design, the prototype manufactured is inserted in the KAIST hand rehabilitation robot in place of Mini45. The accuracy of the prototype 1 is lower than that of Mini45; however, this does not affect the implementation of impedance control. From the results of experiments, it is expected that implement of impedance control using the prototype 2 is also performed successfully. The proposed design will be applicable to various service robots using force/torque feedback scheme.

Mechanical specifications of each sensor are listed in Table I, where w/ means with, w/o means without. Linearity is defined the % error of constant a in (2). RMS error is defined the root-mean-square of the deviation from the torque value of Mini45.

<table>
<thead>
<tr>
<th>TABLE I. MECHANICAL SPECIFICATION OF EACH SENSOR.</th>
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<tbody>
<tr>
<td>Commercial (Mini45)</td>
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<tr>
<td>Material</td>
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<tr>
<td>Method of manufacture</td>
</tr>
<tr>
<td>Photo interrupter</td>
</tr>
<tr>
<td>Load capacity(Nm)</td>
</tr>
<tr>
<td>Outer diameter(mm)</td>
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<tr>
<td>Thickness (mm)</td>
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<tr>
<td>Weight(g)</td>
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<tr>
<td>S/N</td>
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<tr>
<td>Linearity(%)</td>
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<tr>
<td>RMS error(Nm)</td>
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<td>Cost(USD) w/o amp.</td>
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ACKNOWLEDGMENT

This work was supported by Technology Innovation Program (Innovation Cluster Program) through the Korea Innovation Cluster Foundation funded by the Ministry of Knowledge Economy (MKE, Korea) (No. 1415113260).

APPENDIX

A. Appendix 1

![Figure 14. The output of the photo interrupter is varies according to the position of the interrupter. The linear property is observed in d=1.3mm ±25μm due to the measurement range of CNA1311K. Its catalog can be obtained from www.alldatasheet.com](image1)

B. Appendix 2

![Figure 15. The RMS error of the prototype 1. This results show that large deviation from the Mini45 compared to prototype 2 as shown in Fig. 13](image2)

REFERENCES


