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High-Sensitivity and High-Stiffness Force Sensor Using Strain-Deformation Expansion Mechanism

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1. Introduction

In order to grasp and manipulate an object controllably and dexterously with a multifingered hand of robot, the sensing of fingertip force is required. To these operation, for making the controllability higher and making force sensor be proof against unexpected collisions or weights, not only the sensor's sensibility but also its stiffness are desired as high as possible.

For sensing a force acting on a force sensor, in general, some sensing elastic bodies is equipped in the force sensor. When a force is applied on the sensor, the force will pass through the sensing elastic bodies and make the bodies deform linearly so that it can be measured from the strain-deformations on the elastic bodies. So far, many researches [1]~[7] [9] consider making the sensed force all passed through the sensing elastic bodies for force sensing. To this situation, if we want to make the sensibility higher, the stiffness of the sensing elastic bodies have to be reduced for making their deformations larger. Conversely, if we want to make the stiffness higher, the sensibility of the sensing elastic bodies will be reduced since their deformations become to small because of the higher stiffness. Thus by using the previous sensing structures, it is hard to realize the force sensing with both of high-stiffness and high-sensitivity.

For instance, about torque sensing, some strain gauges are put on an arm joint shaft to sense the torque deformation on the shaft [1]. In this way, to make the sensitivity higher, reducing the stiffness of joint shaft, for instance, using an elastic shaft as a portion of joint shaft [2], was considered. On the other hand, a joint shaft and an arm link was fixedly connected in series by an elastic body and its elastic deformation was used for joint torque sensing [3]. However this method will reduce the joint stiffness, too. Also, double-cross structure [7], double-membrane structure [6] [8] were proposed for force sensing or acceleration sensing. But these methods will reduce the sensor's stiffness if higher sensibility is required. In general, increasing the sensitivity of joint torque sensing by reducing the joint stiffness, is not desired.

This paper proposes a novel mechanism called *Strain-Deformation Expansion Mechanism* for 3-axis force sensing. By the force sensing mechanism, the small strain-deformation used for force sensing can be expanded while the sensor stiffness will not be reduced but will be heightened. In this paper, the force sensing principle is addressed by analyzing the

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deformation of the sensing mechanism and the forces acting on the sensor theoretically. Then, the sensitivity of the sensing mechanism and its expansion rate of sensitivity are defined, and a design method for realizing the sensing mechanism with high sensitivity is discussed. Lastly, some experiments are performed to show the basic characteristics and the effectiveness of the proposed force sensing mechanism.

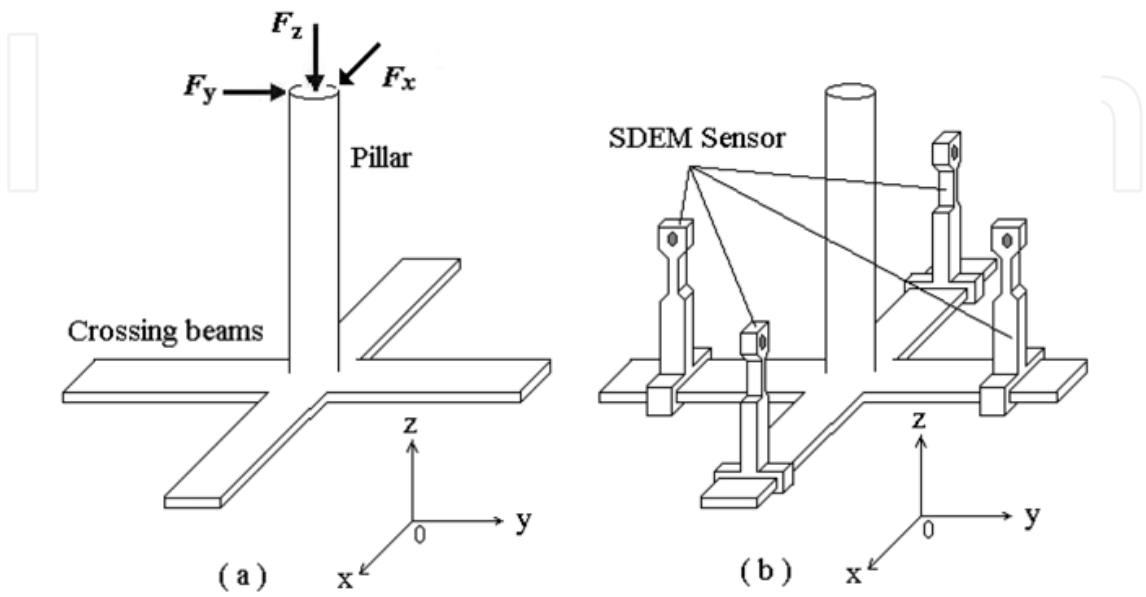


Fig. 1. Proposed force sensing mechanism

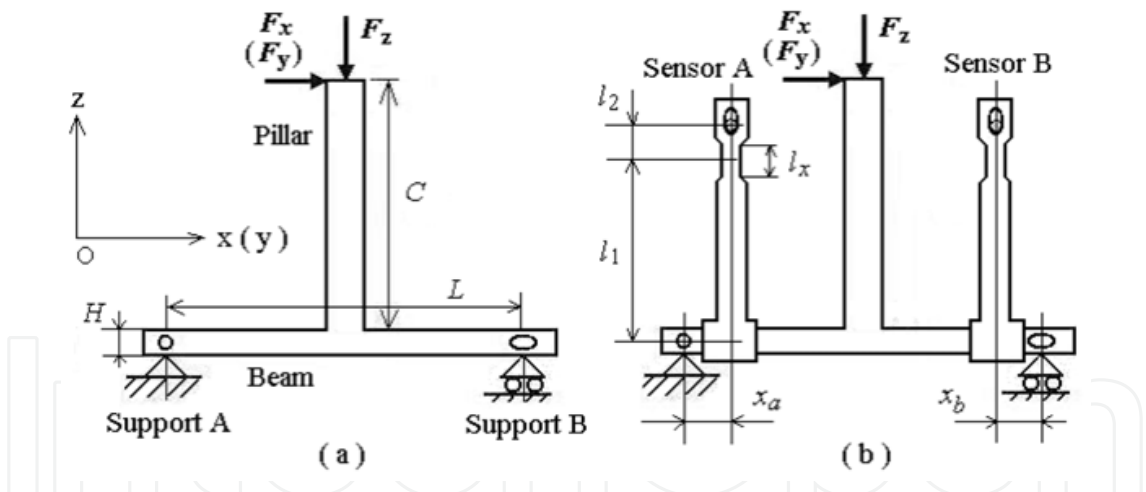


Fig. 2. Side view of proposed force sensing mechanism

2. Force sensing principle

A. Bending deformation on a beam

Fig. 1(a) shows a typical structure of previous 3- axis force sensor, which consists of one pillar and two beams crossing one and another at right angles. 3-axis forces to be sensed will act at the top of the pillar top, and the forces will be sensed by the strain deformations yielding on the crossing beam of the structure. For convenience, let us consider a side view of the sensing structure with height C , where the beam with length L , thickness H and width B is put on a hinge support and a support on rollers (see Fig. 2(a)). If a vertical force or a

lateral force is loading on the pillar top, the reactions to the loads at two supports will be upward or downward, so that the beam will be bent and strains will yield on the beam surface. The relation between a strain-deformation ϵ_c at a position x from the support A and the vertical force F_z or the lateral force F_x will be

$$\epsilon_{cz} = -\frac{F_z x}{E_c I_c} \cdot \frac{H}{8}, \quad (1)$$

$$\epsilon_{cx} = \frac{F_x C x}{L E_c I_c} \cdot \frac{H}{2}, \quad (2)$$

where E_c and $I_c (= BH^3/12)$ represent the modulus of longitudinal elasticity (Young's modulus) and the second moment of area of the beam respectively. From the equations, the relation between F_z (or F_x) and ϵ_{cz} (or ϵ_{cx}) is linear and F_z (or F_x) can be measured if ϵ_{cz} (or ϵ_{cx}) is known. Hence, strain gauges can be stuck on the beam surface for measuring the forces from the strain-deformation on the beam.

By this method, however, for making the sensitivity of the sensing structure higher, from eqs. (1) and (2) we can know that I_c (or B and H) of the beam must be reduced, so that the stiffness of the sensing structure will be lower. It is hard to make its sensitivity and stiffness higher in the same time. To this problem, this paper proposes a novel force sensing mechanism, by which the small strain-deformation on the beam can be expanded for the force sensing while the beam stiffness is increased but reduced.

B. Force sensing principle

When a force Φ_z (or Φ_x) acts on the pillar top, the beam will be bent and at a position x there is a bending angle Φ_z (or Φ_x)

$$F_z = \frac{4E_c I_c}{x^2 - L^2/4} \cdot \Phi_z, \quad (3)$$

$$F_x = \frac{2LE_c I_c}{C(x^2 - L^2/12)} \cdot \Phi_x, \quad (4)$$

and the strain at x will vary with Φ_z (or Φ_x). From the above equations, the relation between F_z (or F_x) and Φ_z (or Φ_x) is linear. The novel mechanism in this paper will use the bending angle Φ to realize a high-sensitivity and high-stiffness force sensing.

Fig. 1 to Fig. 3 show the principle of the proposed mechanism, which has four beam-like elastic bodies (sensor hereafter) on two crossing beams for force sensing. For one of two crossing beam, two sensors of the mechanism are fitted on the two side of the beam shown as Fig. 2(b) and Fig. 3. The sensor construct of the mechanism is designed as Fig. 3. We set that the longitudinal direction of the beam-like sensor crosses the beam at right angles, and is parallel with the longitudinal direction of the pillar when no deformation yields. One end of the sensor is fixed on the beam, while another end can displace in the longitudinal and rotational directions of the sensor but on the sensor laterals the end is constrained by the fixtures fixed on the wall around the mechanism.

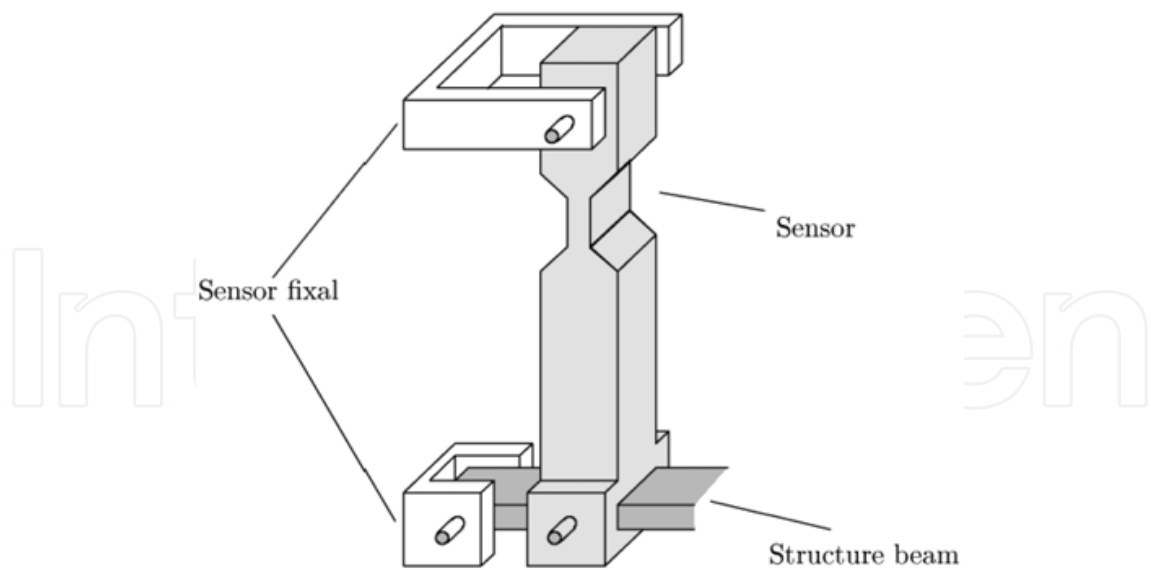


Fig. 3. Proposed force sensor construct

Let l_x denote the length of the narrow portion (whose thickness is h , width is b) of the sensor, l_1 denote the length from the beam connection of the sensor to the middle of l_x , l_2 denote the length from the middle of l_x to the fixtures (see Fig. 4(a)). The portions except the narrow portion are designed enough thickly for checking their deformations. Thus, shown as Fig. 4(a), the sensor's deformation can be focused on the narrow portion when the l_1 portion is displaced rotatively together with the bending angle Φ .

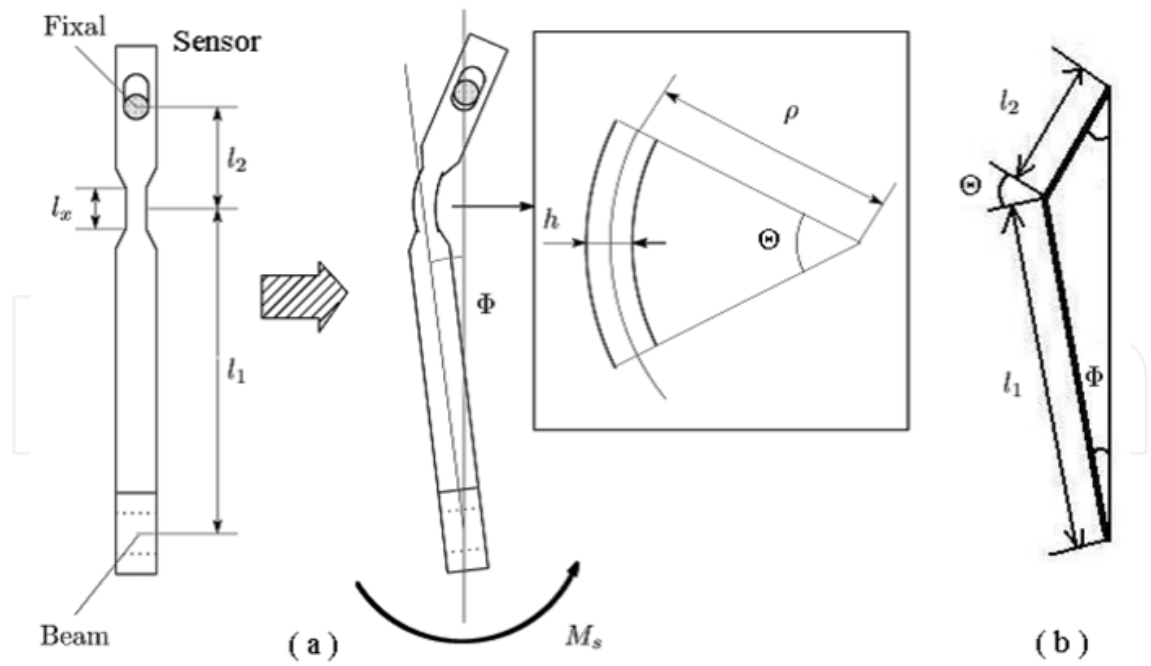


Fig. 4. Force sensor behavior

Fig. 4 gives figures with a side view in Fig. 3, which shows the behavior and characteristic of the proposed sensor. When a vertical force is applied to the pillar top, the force will be delivered to the middle of beam, so that the beam will be bent shown as Fig. 5 and a

bending moment will act at the connection between the beam and sensor. From the beam's bending deformation the l_1 portion of sensor will be rotated, if the stiffness of shaft is hard while the narrow portion of sensor is flexible. Then, because the both laterals of the l_2 portion are constrained, bending deformations like Fig. 5 will occur at the deformable l_x portion, and the two sensors on beam's two sides will be bent with opposite rotation. In the same way, if a lateral force is applied at the pillar top, the l_x portion of two sensors will also be bent but their bent behaviors will be the same rotation (see Fig. 5). By measuring the bending deformations of sensor, it is possible to sense the bending deformation of beam.

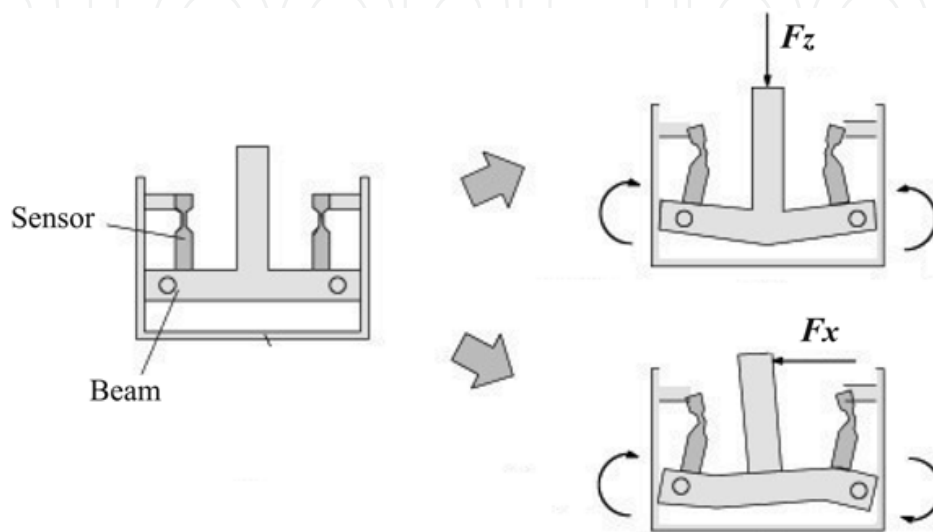


Fig. 5. Behaviors of force sensor

C. Forces acting on beam

When a force is applied on the pillar top, for a beam without the proposed sensing mechanism, two reactions from two beam supports will yield to act against the applied force. For a beam with the proposed sensing mechanism, besides the two support reactions, two reactions at the two sensor's l_2 portions will also yield because of the bending deformation of beam as shown by Fig. 4 and 5. Accordingly, by using the proposed sensing mechanism, part of the applied force will branch off to act on the sensors to yield a bending deformation for force sensing.

In the previous researches [1]~[7], an elastic body for sensing is fitted between a sensor's top and its base in series, so that the whole applied force will pass through the elastic body for yielding a deformation. And for obtaining a higher sensitivity, the beam stiffness should be reduced. In this paper, sensing elastic bodies (sensors) are connected with beams in parallel, so that the applied force will be divided into two parts, one passes through the beams to beam's hinge supports and another passes through the sensors to sensor's fixtures. Thereby, only a part of applied force is required for yielding a sensor deformation. And, considering that the sensors and beams are arranged in parallel, the stiffness of this mechanism can be made higher than that only using the beams.

For the case when the sensors and the beams are arranged in parallel, since the sensors have lower stiffness and the beams have higher stiffness, a bending deformation of beam can make a bending deformation on the sensor. On the other hand, the sensors will give their

resistances to the beam bending. Accordingly, the beam stiffness added the sensor stiffness makes the whole stiffness of the mechanism. If we make the sensor stiffness higher, the mechanism stiffness will become higher. For a certain applied force, however, the bending deformation of sensor will become smaller because of its higher stiffness. Conversely, if we make the sensor stiffness lower, its bending deformation will be larger, while the mechanism stiffness will be still higher somewhat than the beam stiffness. Meanwhile, the branched force for bending deformation on sensors will become smaller. Therefore, only by smaller branched forces, we can make a larger bending deformation on sensors for force sensing without reducing the beam stiffness.

3. Analysis of force sensing principle

A. Geometric analysis on sensor deformation

Fig. 4(b) shows a deformed sensor, which is simplified from Fig. 4(a). Since the bending angle of beam Φ is very small, the length of the triangular long-side in Fig. 4(b) is considered as l_1 , the length of shortside does l_2 . At first, let us consider expressing angle Θ by angle Φ . Noting that only the l_x portion is bent on the deformed sensor, about angles Φ and α , we get

$$l_1 \sin \Phi = l_2 \sin \alpha, \quad (5)$$

$$\alpha = \sin^{-1} \left(\frac{l_1}{l_2} \sin \Phi \right). \quad (6)$$

Thus, Θ can be expressed as

$$\Theta = \alpha + \Phi = \sin^{-1} \left(\frac{l_1}{l_2} \sin \Phi \right) + \Phi. \quad (7)$$

Then, let us consider obtaining the surface strain ε_{l_x} on the bent l_x portion. Shown as Fig. 4(a), let ρ ($= l_x/\Theta$) denote the radius of curvature and Δl denote the deformation of length on its surface. Since the thickness is h and the length of neutral surface is l_x , we have

$$\varepsilon_{l_x} = \frac{\Delta l}{l_x} = \frac{(\rho + h/2) \Theta - \rho \Theta}{l_x} = \frac{h}{2l_x} \Theta. \quad (8)$$

According to eq. (5), ε_{l_x} can be expressed by Φ as

$$\varepsilon_{l_x} = \frac{h}{2l_x} \Theta = \frac{h}{2l_x} \left\{ \sin^{-1} \left(\frac{l_1}{l_2} \sin \Phi \right) + \Phi \right\}. \quad (9)$$

Hence, from eq. (9) and $\sin \Phi \approx \Phi$, $\cos \Phi \approx 1$ since Φ is very small, there exists

$$\Phi \left(\frac{l_1}{l_2} + \cos \frac{2l_x \varepsilon_{l_x}}{h} \right) = \sin \left(\frac{2l_x \varepsilon_{l_x}}{h} \right). \quad (10)$$

Considering that the strain ε_{l_x} is 10^{-3} orders of magnitude, we have $\sin(2l_x \varepsilon_{l_x}/h) \approx (2l_x \varepsilon_{l_x}/h)$ and $\cos(2l_x \varepsilon_{l_x}/h) \approx 1$ if $(2l_x \varepsilon_{l_x})/h$ is designed small enough. Thereby, ε_{l_x} can be obtained as

$$\varepsilon_{l_x} = \frac{(l_1 + l_2)h}{2l_x l_2} \cdot \Phi. \quad (11)$$

Accordingly, the strain ε_{l_x} on the bent l_x portion has a linear relation with the bending angle of beam Φ .

B. Sensor deformation and forces

About the bent l_x portion of a sensor shown as Fig. 4, the relation between an bending moment acted on the sensor M_s and the radius of curvature ρ can be described as

$$\frac{1}{\rho} = \frac{M_s}{E_s I_s}, \quad (12)$$

where, E_s denotes the modulus of longitudinal elasticity (Young's modulus) of the sensor's material, I_s denotes second moment of area, which is $I_s = bh^3/12$ when the cross section of the l_x portion is rectangular. From eqs. (6), (12) and $l_x = \rho\Theta$, we have

$$\varepsilon_{l_x} = \frac{h}{2\rho} = \frac{6}{E_s b h^2} \cdot M_s. \quad (13)$$

Thus, if we make the thickness h and width b on l_x portion smaller, in the same material, a certain strain ε_{l_x} is able to be realized with a smaller M_s . By eq. (13), the moment M_s for realizing a strain ε_{l_x} can be written as

$$M_s = \frac{E_s b h^2}{6} \cdot \varepsilon_{l_x}. \quad (14)$$

For a beam with the proposed sensing mechanism, the relations among an applied force F_z (or F_x), the sensor's bending moment M_{sa} and M_{sb} , and the beam's bending angle Φ_a and Φ_b at the connecting positions x_a and x_b , can be written as follows, that is,

$$\Phi_a = \frac{F_z(x_a^2 - L^2/4)}{4E_c I_c} - \frac{M_{sa}(x_a - L/2)}{E_c I_c}, \quad (15)$$

$$\Phi_b = -\frac{F_z[x_b^2 - L^2/4]}{4E_c I_c} + \frac{M_{sb}(x_b - L/2)}{E_c I_c}, \quad (16)$$

for a vertical force F_z ;

$$\Phi_a = \frac{F_x C(x_a^2 - L^2/12)}{2LE_c I_c} + \frac{M_{sa}(2x_a^2 - x_a L + L^2/6)}{LE_c I_c}, \quad (17)$$

$$\Phi_b = \frac{F_x C(x_b^2 - L^2/12)}{2LE_c I_c} + \frac{M_{sb}(2x_b^2 - x_b L + L^2/6)}{LE_c I_c}, \quad (18)$$

for a lateral force F_x . From eqs. (11), (14) and the above equations, we have

$$F_z = \frac{4E_c I_c}{x_a^2 - L^2/4} \left[\frac{(l_1 + l_2)h}{2l_x l_2} + \frac{E_s b h^2 (x_a - L/2)}{6E_c I_c} \right] \varepsilon_{zal_x} \quad (19)$$

$$\triangleq B_a \varepsilon_{zal_x},$$

$$F_z = \frac{4E_c I_c}{x_b^2 - L^2/4} \left[-\frac{(l_1 + l_2)h}{2l_x l_2} + \frac{E_s b h^2 (x_b - L/2)}{6E_c I_c} \right] \varepsilon_{zbl_x} \quad (20)$$

$$\triangleq B_b \varepsilon_{zbl_x},$$

$$F_x = \frac{2LE_c I_c}{C(x_a^2 - L^2/12)} \left[\frac{(l_1 + l_2)h}{2l_x l_2} - \frac{E_s b h^2 (2x_a^2 - x_a L + L^2/6)}{6LE_c I_c} \right] \varepsilon_{xal_x} \triangleq A_a \varepsilon_{xal_x}, \quad (21)$$

$$F_x = \frac{2LE_c I_c}{C(x_b^2 - L^2/12)} \left[\frac{(l_1 + l_2)h}{2l_x l_2} - \frac{E_s b h^2 (2x_b^2 - x_b L + L^2/6)}{6LE_c I_c} \right] \varepsilon_{xbl_x} \triangleq A_b \varepsilon_{xbl_x}, \quad (22)$$

where ε_{zal_x} and ε_{zbl_x} are the strains on the sensors at x_a and x_b corresponding F_z , ε_{xal_x} and ε_{xbl_x} are those corresponding F_x .

For an applied force whose direction is between F_z and F_x , the corresponding strains ε_{al_x} and ε_{bl_x} on the two sensor of a beam will be

$$\varepsilon_{al_x} = \varepsilon_{zal_x} + \varepsilon_{xal_x}, \quad (23)$$

$$\varepsilon_{bl_x} = -\varepsilon_{zbl_x} + \varepsilon_{xbl_x}. \quad (24)$$

And since $|\varepsilon_{zal_x}| = |\varepsilon_{zbl_x}|$ and $|\varepsilon_{xal_x}| = |\varepsilon_{xbl_x}|$ for the proposed mechanism, we have

$$\varepsilon_{zal_x} = \varepsilon_{zbl_x} = (\varepsilon_{al_x} - \varepsilon_{bl_x})/2, \quad (25)$$

$$\varepsilon_{xal_x} = \varepsilon_{xbl_x} = (\varepsilon_{al_x} + \varepsilon_{bl_x})/2. \quad (26)$$

Therefore, an arbitrary force F_{xz} between F_x and F_z can be obtained by

$$\mathbf{F}_{xz} = \frac{1}{4} \begin{bmatrix} (A_a + A_b) & (A_a - A_b) \\ (B_a + B_b) & -(B_a - B_b) \end{bmatrix} \begin{bmatrix} \varepsilon_{al_x} \\ \varepsilon_{bl_x} \end{bmatrix}. \quad (27)$$

In the same way, we can obtain the relation between an arbitrary 3-axis force F and the strains $\varepsilon_{al_x}^X, \varepsilon_{bl_x}^X, \varepsilon_{al_x}^Y, \varepsilon_{bl_x}^Y$ on the 4 sensors of 2 crossing beams as following

$$\mathbf{F} = \frac{1}{8} \begin{bmatrix} 2(A_a^X + A_b^X) & 2(A_a^X - A_b^X) \\ 0 & 0 \\ (B_a^X + B_b^X) & -(B_a^X - B_b^X) \end{bmatrix}$$

$$\begin{bmatrix} 0 & 0 \\ 2(A_a^Y + A_b^Y) & 2(A_a^Y + A_b^Y) \\ (B_a^Y + B_b^Y) & -(B_a^Y + B_b^Y) \end{bmatrix} \begin{bmatrix} \varepsilon_{alx}^X \\ \varepsilon_{blx}^X \\ \varepsilon_{alx}^Y \\ \varepsilon_{blx}^Y \end{bmatrix} \quad (28)$$

where ε^X and ε^Y denote the beams respectively along X-axis and Y -axis. Thereby, we can know that there exist linear relations between an applied 3-axis force and the proposed sensor's strains.

According to eq. (28), the sensitivity and stiffness of the proposed sensing mechanism can be regulated within a certain extent by the designing of the sensor's dimensions and material.

C. Sensor's sensitivity and expansion rate of sensitivity

This subsection discusses the expansion rate of sensitivity of the proposed sensing mechanism for a certain applied force. For this purpose, the strain on the proposed sensor will be compared with the strain on the beam which was employed for force sensing in previous methods. In this paper, the sensitivity of joint torque sensor is defined as the magnitude of the strain for sensing for every unit force.

At first, about the previous method which directly sticks gauges on the crossing beams, the strains on beam ε_{cz} and ε_{cx} corresponding to forces F_z and F_x are represented as eqs. (1) and (2) respectively. Accordingly, their sensitivity can be expressed as

$$\frac{\varepsilon_{cz}}{F_z} = -\frac{xH}{8E_cI_c}, \quad (29)$$

$$\frac{\varepsilon_{cx}}{F_x} = -\frac{CxH}{2LE_cI_c}. \quad (30)$$

On the other hand, the sensitivity of the proposed sensor can be written as

$$\frac{\varepsilon_{lx}}{F} = \frac{\varepsilon_{lx}}{\varepsilon_c} \cdot \frac{\varepsilon_c}{F}. \quad (31)$$

From eqs. (19), (21) and (29), (30), $\varepsilon_{lx}/\varepsilon_c$ will be

$$\frac{\varepsilon_{lx}}{\varepsilon_{cz}} = \left[\frac{(l_1 + l_2)h}{2l_xl_2} + \frac{E_sbh^2(x - L/2)}{6E_cI_c} \right] \frac{L^2/4 - x^2}{xH}, \quad (32)$$

$$\frac{\varepsilon_{lx}}{\varepsilon_{cx}} = \left[\frac{(l_1 + l_2)h}{2l_xl_2} - \frac{E_sbh^2(2x^2 - xL + L^2/6)}{6LE_cI_c} \right] \frac{x^2 - L^2/12}{xH}. \quad (33)$$

When $\varepsilon_{lx}/\varepsilon_c$ is larger than 1, sensitivity ε_{lx}/F will be larger than ε_c/F . In this paper, $\varepsilon_{lx}/\varepsilon_c$ is referred to as *Expansion Rate of Sensitivity* relative to a strain on beams.

As the above discussion, by means of the proposed joint torque sensor, the applied force can be sensed by “expanding” the strain-deformation on beams. The sensor will be referred to as *SDEM (Strain- Deformation Expansion Mechanism) Force Sensor* hereafter.

4. Basic characteristics and implementation of SDEM force sensor

A. Experimental SDEM force sensor

Overview of a SDEM force sensor with size $\phi 18\text{ [mm]}\times 18\text{ [mm]}$ is shown in Fig. 6. The dimensions about the proposed sensor is shown in Table I. The materials used for sensors and beams are duralumin (A2014-T4) and austenitic stainless steel (SUS303) respectively. According to eqs. (32) and (33), the expansion rate of sensitivity of the sensor are 3.071 in x and y directions and 9.309 in z direction theoretically.

L	$10.0\times 10^{-3}\text{ [m]}$	l_1	$9.0\times 10^{-3}\text{ [m]}$
C	$15.3\times 10^{-3}\text{ [m]}$	l_2	$3.0\times 10^{-3}\text{ [m]}$
H	$1.5\times 10^{-3}\text{ [m]}$	l_x	$3.5\times 10^{-3}\text{ [m]}$
B	$3.0\times 10^{-3}\text{ [m]}$	h	$1.0\times 10^{-3}\text{ [m]}$
E_c	$20.6\times 10^{10}\text{ [Pa]}$	b	$2.0\times 10^{-3}\text{ [m]}$
E_s	$73.0\times 10^9\text{ [Pa]}$	x	$0.5\times 10^{-3}\text{ [m]}$

Table I. Dimensions of experimental force sensor

B. Evaluation of static characteristics

A series of forces in x (y) and z directions from -20.0 [N] to 20.0 [N] , and forces continuously and slowly changing in x (y) direction from 0 up to 6.2 [N] then down to -6.2 [N] and up to 0, in z direction from 0 up to 4.0 [N] then down to -4.0 [N] and up to 0 were respectively applied on the SDEM force sensor to confirm the linearity and hysteresis characteristics.

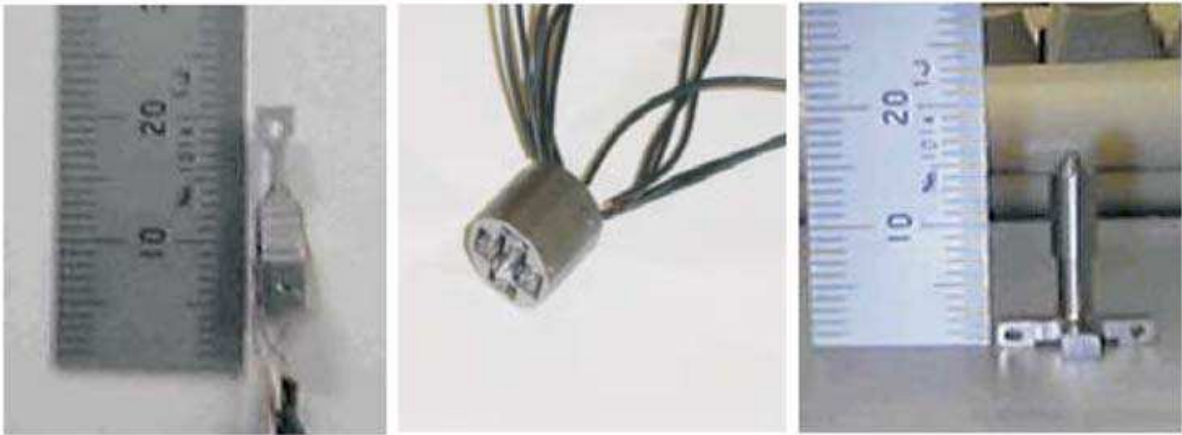


Fig. 6. Experimental SDEM 3-axis force sensor

Fig. 7 shows the experiment results on the linearity of the sensor respectively in x (y) and z directions, which plots the applied force values in abscissa and the SDEM sensor outputs in ordinate. According to the errors which are less than $\pm 0.004\text{ [Nm]}$, the degree of linearity ($100\times\text{error} / \text{measured range}$) is $\pm 0.95\text{ [\%]}$.

Based on the data from the SEDM force sensor and a Force Gauge (FGC-5N, made by Nihon Densan), Fig. 8 gives the graphs plotting the hysteresis characteristics, which plots the Force

Gauge outputs in abscissa and the SDEM sensor outputs in ordinate. The hysteresis differences in x (y) direction are less than 0.75 [N], those in z direction are less than 0.70 [N].

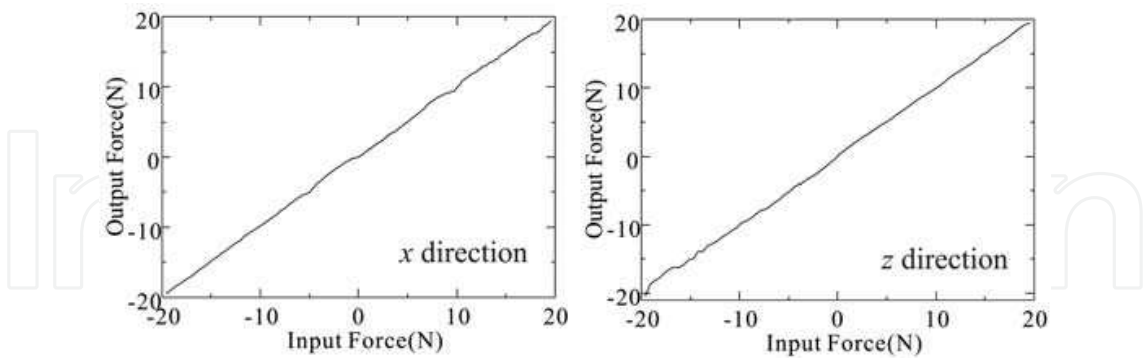


Fig. 7. Linearity between applied forces and sensor outputs

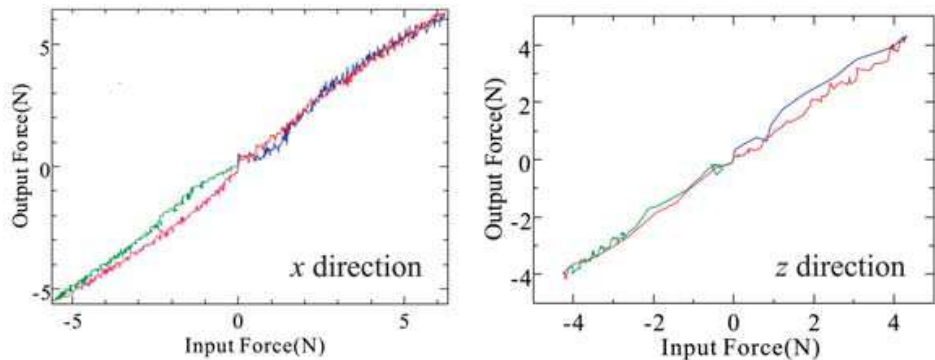


Fig. 8. Hysteresis characteristics

C. Evaluation of dynamic characteristics

The step response of the SDEM force sensor was examined. In the experiments of step response, the applied forces in x (y) and z directions were varied respectively from 0.5 [kgf], 1.0 [kgf], 2.0 [kgf] to 0 instantaneously. The results are shown by Fig. 9, where almost no overshoot or time lag appears.

D. Experimental verifications on expansion rate of sensitivity

In order to verify the expansion rate of sensitivity of the SDEM sensor experimentally, we use a previous crossing beam sensor without the proposed sensing mechanism. In the experiments, 3 forces of 0.5 [kgf], 1.0 [kgf] and 2.0 [kgf] were applied respectively in x (y) and z directions, and the SDEM sensor outputs and the outputs from the previous sensor were accumulated respectively. The 3 ratios of the two kind of outputs are plotted in Fig. 10.

According to the experimental results, the expansion rate of sensitivity of the SDEM force sensor is 3.195 about x (y) direction, 9.429 about z direction on the average. On the other hand, the expansion rate calculated theoretically is 3.079 about x (y) direction and 9.309 about z direction. The theoretical value and the experimental value are almost equal.

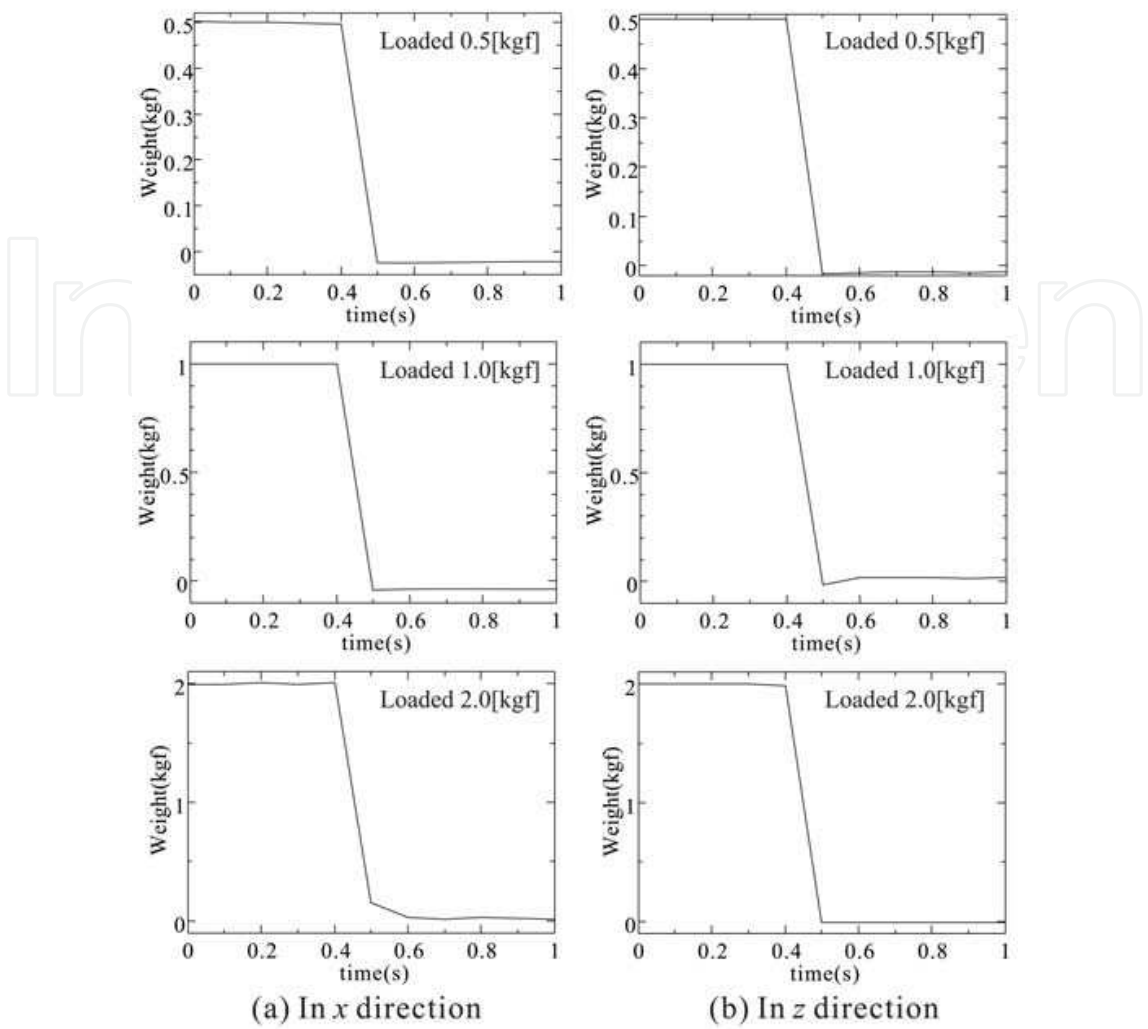


Fig. 9. Step responses

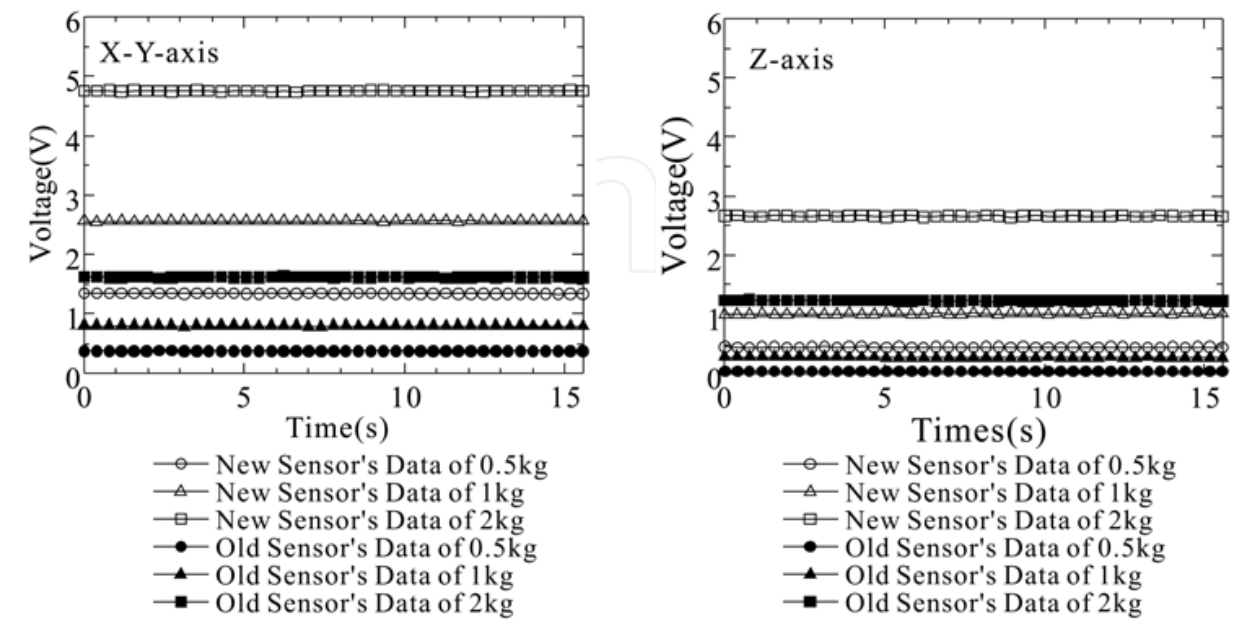


Fig. 10. Expansion rate of sensitivity

5. Conclusion

For dexterously performing object grasping and manipulation with multifingered hand of robot, sensing the fingertip forces with high-sensitivity and highstiffness is desired. In general, from previous sensing structures, if the stiffness of a sensor is made be high, its sensitivity will be reduced, so that It is hard to realize the force sensing with both of high-sensitivity and high-stiffness. This paper proposes a novel mechanism called *Strain-Deformation Expansion Mechanism* for 3-axis force sensing. By the force sensing mechanism, the small strain-deformation used for force sensing can be expanded while the sensor stiffness will not be reduced but will be heightened. In this paper, the force sensing principle was addressed by analyzing the deformation of the sensing mechanism and the forces acting on the sensor theoretically. Then, the sensitivity of the sensing mechanism and its expansion rate of sensitivity were defined, and a design method for realizing the sensing mechanism with high sensitivity was discussed. Lastly, some experiments with robot finger were performed to show the basic characteristics and the effectiveness of the proposed force sensing mechanism.

The proposed force sensing mechanism can be also applied to other cases besides robot and the like, for force sensing with high sensitivity and high stiffness.

6. References

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Sensors: Focus on Tactile Force and Stress Sensors

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This book describes some devices that are commonly identified as tactile or force sensors. This is achieved with different degrees of detail, in a unique and actual resource, through the description of different approaches to this type of sensors. Understanding the design and the working principles of the sensors described here requires a multidisciplinary background of electrical engineering, mechanical engineering, physics, biology, etc. An attempt has been made to place side by side the most pertinent information in order to reach a more productive reading not only for professionals dedicated to the design of tactile sensors, but also for all other sensor users, as for example, in the field of robotics. The latest technologies presented in this book are more focused on information readout and processing: as new materials, micro and sub-micro sensors are available, wireless transmission and processing of the sensorial information, as well as some innovative methodologies for obtaining and interpreting tactile information are also strongly evolving.

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