A Whisker Tracing Sensor for Manufacturing Application

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Abstract

This paper discusses a whisker sensor composed of a flexible beam anchored at the base with torque sensor, and an actuator for moving it. A sufficient condition for detecting the surface shape by using a whisker sensor is summarized. It is shown that a straight-lined whisker sensor with one axis torque sensor can achieve the requirement irrespective of contact friction, while a curved whisker can not do it. We show an application example where the sensor is utilized for detecting the effective length of screw after tapping.

Key words: *Whisker Sensor, High Sensitivity, Surface Probing, Surface Tracing*

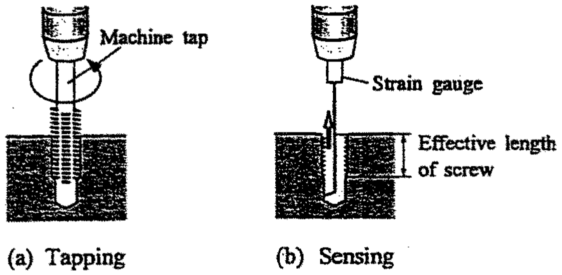
1 Introduction

Background

In automobile companies, each mechanical part is finished through various machining process, such as cutting, welding, pressing, lathing, reaming, drilling, and tapping before assembling them. After tapping process, the effective length of screw should be carefully checked to keep the quality of the product. So far, the measurement of the length has often been done manually by utilizing a specially designed scale. To speed up the sensing procedure, recently we have started a project where we develop a sensing system capable of measuring the effective length of screw automatically. While the diameter of the screw hole widely changes among parts, a difficult situation appears especially for a small hole since it is hard to insert a sensor head into the hole. Under such a situation, a whisker sensor as shown in Fig.1 can be a good candidate because of its slender shape and flexibility. The sensor is first inserted into the hole until the tip reaches the prescribed length and then the sensor tip is moved until it detects the effective height of screw. The flexibility of the whisker is also effective for avoiding any damage to mechanical parts while the whisker sensor is contacting them.

Goal of this work

Knowing of the necessity of whisker sensor, our goal is to design and develop a whisker sensor head capable of implementing it in a tool exchanger system as shown in Fig.2. The whisker sensor is composed of a flexible beam anchored at the base with strain gauges, and an actuator for moving it. Due to such a surprisingly simple structure, we can construct the sensor system with low cost.



(a) Tapping (b) Sensing

Fig. 1: Sensing of effective length of screw

After briefly reviewing conventional works, we consider a sufficient condition for a whisker sensor to detect a surface shape and show that a straight-lined whisker sensor with one-axis torque sensor can detect the surface shape irrespective of the contact friction, while a curved whisker can not achieve it under one-axis torque sensor. Through preliminary experiments, we verify that even a straight whisker can detect surface irregularities with pretty high sensitivity (< 5 [μm]), which is sufficient for applying to the measurement of the effective length of screw. A slightly modified sensor is designed and developed for detecting the effective length of screw. The experimental results are also shown.

2 Related Works

A simple flexible beam sensor can take the form of a short length of spring piano wire or hypodermic tubing anchored at the end. When the free end touches an external object, the wire bends and this can be sensed by a piezoelectric element or by a simple switch [1]. A more elaborate sensor is described by Wang and Will [2]. Long antennae-like whisker sensors were mounted on the SRI mobile robot Shakey [3] and on Rodney Brock's six-legged robot insects [4]. Hirose and others discussed the utilization of whisker sensors in legged robots [5]. The sensor system is composed

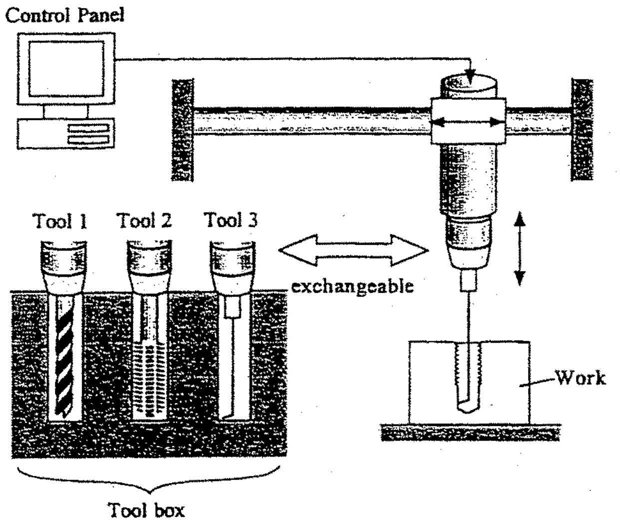


Fig. 2: Process machine with tool exchanger

of an electrode and a whisker whose end is fixed at the base. This sensor unit has been arranged in an array around each foot of the legged robot, TITAN III, so that it can monitor the separation between each foot and the ground. This sensor is also conveniently used to confirm which part of the foot is in contact with the ground. Similarly shaped whisker have been considered for legs of the Ohio State University active suspension vehicle [6]. Russell has developed a sensor array [7] and succeeded in reconstructing the shape of convex object followed by the whisker. Wilson and Mahajan [8], Snyder and Wilson [9] have designed the whisker probe system composed of a piano wire with strain gauge sensors and the base sweep actuators made of two polyurethane tubes that bend when pressurized with air. Wilson and Chen [10] have reported experimental results that demonstrate the precision and accuracy of the whisker probe system in detecting and displaying solid boundaries enclosing areas up to 40 by 50 [cm]. These works assume that the whisker tip always makes contact with the object. Kaneko, Kanayama and Tsuji [11] have proposed the Active Antenna that can localize a contact point between a flexible beam and environment through a pushing motion. Tsujimura and Yabuta have addressed an object shape detection system using a force/torque sensor and an insensitive flexible probe [12]. In our former work[13], we have discussed the basic principle of tracing type whisker sensor.

3 Working Principle [13]

3.1 Basic working principle

Now, let us consider a general whisker model as shown in Fig.3, where $\tau = (\tau_x, \tau_y, \tau_z)^t \in R^{3\times1}, M = (m_x, m_y, m_z)^t \in R^{3\times1}$, and $f = (f_x, f_y, f_z)^t \in R^{3\times1}$ are torque at the base, moment and force at the tip of the beam, respectively. For simplifying our discussion, we set the following assumptions.

Assumption 1: The deformation of whisker is small enough to ensure that we can apply classical beam theory.

Assumption 2: The elongation of a straight-lined whisker due to a unit axial force is negligibly small compared with the deflection due to a unit bending force.

Assumption 3: The whisker tip (or close to the tip) always makes contact with the environment to be sensed.

Assumption 1 guarantees the following linear relationship between force(moment) and displacements.

$$\begin{bmatrix} d\delta \\ d\theta \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \begin{bmatrix} f \\ M \end{bmatrix} \tag{1}$$

where $d\delta = [\delta_x, \delta_y, \delta_z]^t \in R^{3\times1}$, $d\theta = [d\theta_x, d\theta_y, d\theta_z]^t \in R^{3\times1}$, $D_{ij} \in R^{3\times3} (i = 1,2; j = 1,2)$ denote the displacement vector, the angular displacement vector, the block compliance matrix, respectively. Since we can generally neglect the moment M at the contact point, we can focus on the relationship between $d\delta$ and f.

$$d\delta = D_{11} f \tag{2}$$

Additionally, we have the following relationship between τ and f.

$$\tau = J^t f \tag{3}$$

where J^t is the Jacobian matrix mapping from f to τ. We now examine whether $d\delta$ can be estimated by measuring τ. Suppose that there are three torque sensing axes around x, y, z, respectively. Since $J^t \in R^{3\times3}$ under such an assumption, the inverse of J^t exists if $det\,|J^t| \neq 0$.

$$d\delta = D_{11} [J^t]^{-1} \tau \tag{4}$$

Therefore, we can estimate $d\delta$ through the measurement of τ. Now, we consider whether a fewer numbers of torque sensors can successfully estimate the displacement(or height) or not. Suppose that only z-axis torque sensor is available. This component can be picked up by multiplying a selection vector $s = (0, 0, 1)^t$ for eq.(3). Namely,

$$s^t \tau = s^t J^t f \tag{5}$$

where $\tau_z = s^t \tau$. Under the assumption, we have the following relationship,

$$f = (J_1^t)^\sharp \tau_z + [I_3 - (J_1^t)^\sharp J_1{}^t]\xi \tag{6}$$

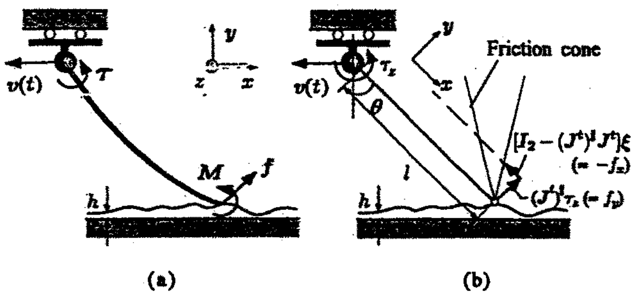


Fig. 3: Analytical model of whisker sensor

where ${J_1}^t = s^t J^t$, $I_3 \in R^{3\times3}$, $\xi \in R^{3\times1}$, and $\sharp$ denote the Jacobian matrix from f to τ_z, the unity matrix, an arbitrary vector, and pseudo-inverse matrix, respectively. The first term of f is the force component that can be measured by the torque sensor and the second term is the one that can not be evaluated by the sensor. Eq.(6) means that the contact force f can not be uniquely determined for a measured torque τ_z. In other words, the force component $[I_3 - (J_1^t)^\sharp J_1^t]\xi$ perpendicular to $(J_1^t)^\sharp\tau_z$ varies depending upon the friction at point of contact. Substituting eq.(6) into eq.(2), we obtain

$$d\delta = D_{11}({J_1}^t)^\sharp\tau_z + D_{11}[I_3 - (J_1^t)^\sharp {J_1}^t]\xi \qquad (7)$$

Due to the existence of a null space in eq.(7), in general, we can not uniquely determine $d\delta$ through the measurement of τ_z alone.

Let us consider a straight lined whisker as shown in Fig.3(b), where the whisker is slightly pressed on the surface and the inclined coordinate system is considered for simplifying the discussion. Note that if the displacement is assumed to be the order of 100 [μm], we can regard that the beam with the length of a few centimeters still keeps a straight line even under such a pressed phase. For such a 2D model, D_{11} and ${J_1}^t$ are given by

$$D_{11} = \begin{pmatrix} \frac{l}{EA} & 0 \\ 0 & \frac{l^3}{3EI} \end{pmatrix},\ {J_1}^t = (0, l) \qquad (8)$$

where l, E, A, and I are the beam length, the elasticity, the cross sectional area, and the second order moment of cross section of the beam, respectively. Substituting eq.(8) into $D_{11}({J_1}^t)^\sharp\tau_z$ and $D_{11}[I_2 - ({J_1}^t)^\sharp {J_1}^t]\xi$, we obtain

$$\begin{aligned} D_{11}(J_1^t)^\sharp\tau_z &= \begin{bmatrix} \frac{l}{EI} & 0 \\ 0 & \frac{l^3}{3EI} \end{bmatrix} \begin{bmatrix} 0 \\ l \end{bmatrix} \tau_z \\ &= \begin{bmatrix} 0 \\ \frac{\tau_z l^2}{3EI} \end{bmatrix} \qquad (9) \\ D_{11}[I_2 - (J_1^t)^\sharp {J_1}^t]\xi &= \begin{bmatrix} \frac{l}{EA} & 0 \\ 0 & \frac{l^3}{3EI} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} \\ &= \begin{bmatrix} \frac{l\xi_1}{EA} \\ 0 \end{bmatrix} \qquad (10) \end{aligned}$$

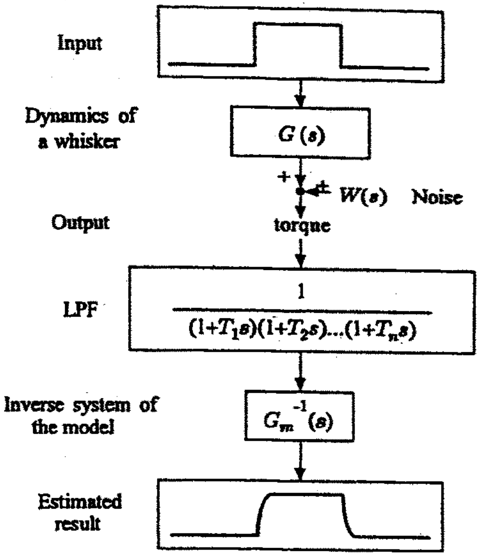


Fig. 4: Data processing flow

During a tracing motion, the contact force may appear on either boundary of the friction cone. Therefore, ξ_1 can not be an infinite value, and is limited as shown in Fig.3(b). For such a limited force, classical beam theory ensures that the longitudinal deflection $l\xi_1/EA$ is even smaller than the bending deformation $\tau_z l^2/3EI$ (Assumption 2). Thus, the displacement caused by the force in null space can be neglected. As a result, we can estimate the surface height h uniquely by

$$h = \delta_y \sin\theta = \frac{\tau_z l^2}{3EI}\sin\theta \qquad (11)$$

It should be noted that there exists one to one mapping between h and τ_z, even though a friction force makes the contact force shift within the null space.

[Remark]
Surface irregularities are observable under a straight-lined whisker with one-axis torque sensor, irrespective of the contact friction.

This is a great advantage for using a straight lined whisker, while we can not keep such robustness against friction under the utilization of a curved beam.

3.2 Incorporation of dynamic effect

As the tracing speed increases, dynamic effect will become dominantly. Such a dynamic effect produces mechanical vibration over the whisker and, as a result, vibration signals are also observed from the output of strain gauge in addition to a static drift. Under such dynamics effects, the relationship between input and output is expressed in the following,

$$T(s) = G(s)H(s) + W(s) \tag{12}$$

where $T(s)$, $H(s)$ and $W(s)$ are Laplace transformation of torque, the height from the base, and noise, respectively, and $G(s)$ is the transfer function between $H(s)$ and $T(s)$.

$W(s)$ can be removed by using an appropriate filter. Therefore, if $G(s)$ is given, we can obtain the height with respect to time,

$$h(t) = \mathcal{L}^{-1}\{G^{-1}(s)T(s)\} \tag{13}$$

where $\mathcal{L}^{-1}\{\cdot\}$ denotes the inverse of Laplace transformation. The signal processing for obtaining $h(t)$ is shown in Fig.4, where the Low-Pass Filter(LPF) is indispensable so that the inverse system may become proper. However, it is extremely difficult to obtain $G(s)$ in an exact form. No analytical formulation can be found in the literature treating flexible manipulators. Instead of using an exact form of $G(s)$, we utilize an approximated form $G_m(s)$, where $G_m(s)$ is the model with a spring alone and given by $G_m(s) = k_1$, where k_1 is determined from a preliminary experiment. Fig.4 shows the data processing flow, where $T_i(i = 1, ..., n)$ denotes the time constant for a low pass filter. For more pricise modelling, see [13].

4 Preliminary Experiments

Now, let us consider a simple whisker sensor, where a straight lined whisker is anchored with a base equipped with a strain gauge. An interesting question that comes up to us is *How accurately such a sensor can reconstruct the surface shape with irregularities?*

To examine the sensing capability, we developed a whisker sensor by using a piano wire where the length and diameter are 100 [mm] and 1.4 [mm], respectively. The piano wire is connected with the base with a strain gauge. Fig.5 shows an experimental system where instead of moving the sensor, the surface is moved by the slider. A laser distance sensor as well as an electric dial gauge is also installed in the system for comparison. It is important to note that all sensors are placed in such a way that they may trace the same point as shown in Fig.5. In order to obtain the basic characteristic of the sensor, we prepare various materials for the surface, such as semi-transparent tape (STT), non-transparent tape (NTT), copy paper, and rubber. The contact friction is small for both STT and NTT, while it is not for paper and rubber. Fig.6 shows an experimental result for three different steps (60, 120, and 150 [μm]), where (a), (b), (c), (d), and (e) are the original input height, the direct torque sensor output without any filtering, the estimation results in our approach, the output from the electric dial gauge, and the output from the laser distance sensor, respectively, and the surface material used for each step is indicated in (a) with abbreviation form. Through this experiment we can see that the whisker sensor exhibits as high sensitivity as the electrical dial gauge with the sensitivity of less than 2 [μm]. Through more precise experiments, we found that the whisker sensor has less than 5 [μm] resolution even under conservative estima-

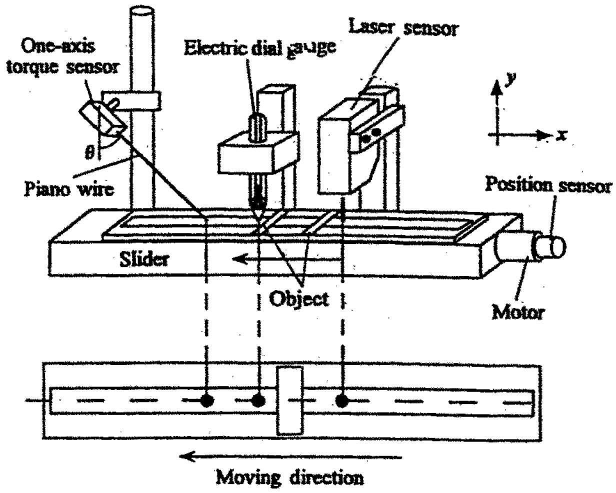
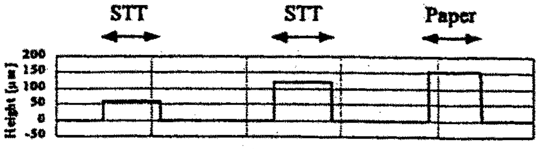
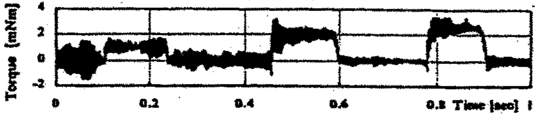


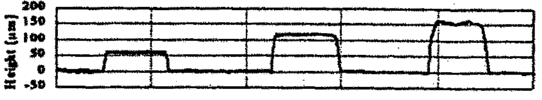
Fig. 5: Experimental system



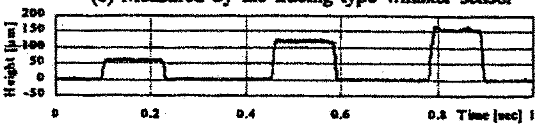
(a) Input shape



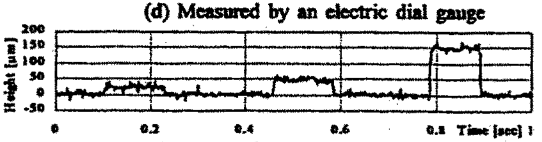
(b) Direct torque sensor output



(c) Measured by the tracing type whisker sensor

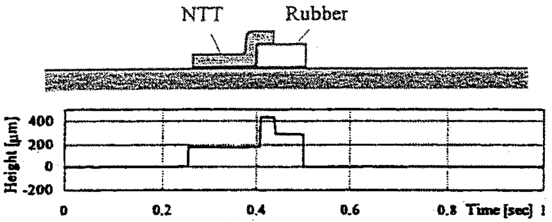


(d) Measured by an electric dial gauge



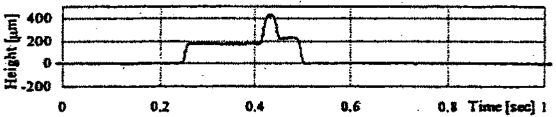
(e) Measured by a laser sensor

Fig. 6: Experimental results

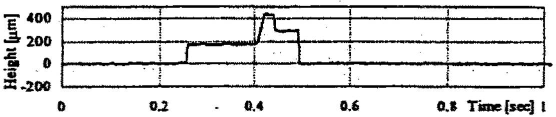


(a) Input shape

(b) Measured by the tracing type whisker sensor



(c) Measured by an electric dial gauge



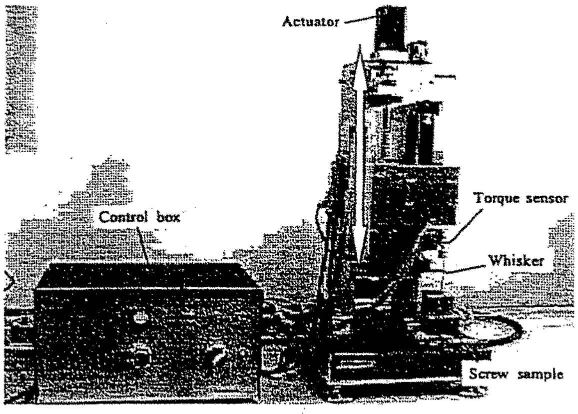
(d) Measured by a laser sensor

Fig. 7: Experimental results

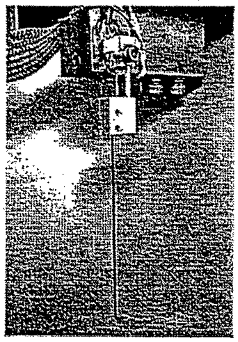
tion. It should be noted that the laser distance sensor does not provide with an accurate height for a semi-transparent tape, while it can estimate a pretty accurate height for paper. This is because a part of light reflects on the top surface and the remaining on the bottom surface, when a semi-transparent tape is used as a surface. As a result, the laser sensor provides with an intermediate height between two surfaces. Fig.7 shows another experimental result where the irregular surface is made by a non-transparent tape and rubber, as shown in the top of Fig.7. The outputs from three sensors provide almost with the same height when the tip traces over the non-transparent tape, while they are different each other when the tip traces over the rubber. We note that the rubber is compliant. Therefore, it deforms while both whisker sensor and the dial gauge trace over the surface, through their direct contact with it. On the other hand, since the laser distance sensor is a non-contact sensor, it can provide the shape without any deformation. For such a compliant material, a tactile sensor generally provides a different shape depending on how much contact force is applied.

Through these experiments, we could confirm that this type of whisker sensor is enough for measuring the effective length of the screw after tapping process, as far as the accuracy is concerned.

5 Application for Shape Detection of Screw

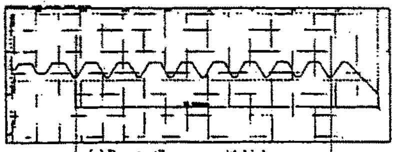


(a) Overview

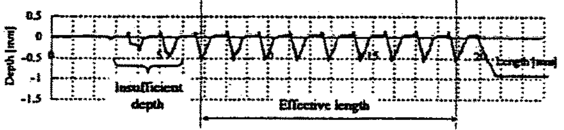


(b) Sensing part

Fig. 8: Experimental system



(a) By a tactile sensor with high accuracy



(b) By our sensor

Fig. 9: Experimental results for screw

Knowing of an excellent sensitivity of the tracing type whisker sensor, we now discuss an application example where a slightly modified sensor is designed for detecting the shape of screw after tapping. Through the measurement of the shape of screw, we can detect the effective length of screw. This sensing procedure is really important, especially in automobile companies, so that we can keep the quality of the product.

For this purpose, we designed and developed an experimental system as shown in Fig.8(a), where it is composed of a whisker anchored at the base with a torque sensor, a motor for moving the whisker sensor, a screw sample, and a control box, respectively. Since a straight–lined whisker can not reach the bottom part of screw, the tip of whisker was bended as shown in Fig.8(b). The change from straight line of whisker is, of course, not desirable, since a friction force produces an error for the detected shape.

One of main purposes of experiment is to observe how the detected shape differs from the original one. Fig.9 shows the experimental results where (a) and (b) are measured by a tactile sensor with high accuracy and by our sensor, respectively. The sensor utilized for comparison has the accuracy of $0.05\mu m$ while it is extremely expensive. It can be seen from Fig.9 that our sensor can classify two local concave points where one can not be included in the effective length and the other can be included. It is important to note that the sensing resolution is about $100\mu m$ for screw shape sensing, while it keeps $5\mu m$ for surface tracing. The reason why the resolution is down for screw is that the whisker tip has the thickness of about $200\mu m$ and it can not touch the bottom of screw tooth. Overall, however, we are hopeful to obtain the effective length of screw by using a modified version.

6 Concluding Remarks

We considered a whisker sensor and showed that a straight-lined whisker can successfully work as a surface reconstructing sensor with one-axis torque sensor alone, while a curved whisker can not. We also showed that the straight-lined whisker can detect a surface irregularities with the sensitivity of less than 5 $[\mu m]$ under a conservative evaluation. We applied a modified version for detecting the effective length of screw. Although the results are not in sufficient level, we believe that this type of whisker sensor can be applied to various fields where the slender sensor tip is especially required.

Finally, the authors would like to express their thanks to Mr. Yoshiharu Bessho and Mr. Tatsuya Shirai for their help for the experiments.

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