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Active Antenna
-- Basic Considerations on the Working Principle --

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Abstract

This paper addresses a new active sensor system (Active Antenna) motivated by insect's antenna. The antenna can be characterized by its "flexibility" and "active motions". Based on these observations on insect's antenna, we discuss an active sensor system composing of only four components, an insensitive flexible antenna, a position sensor, a torque sensor, and an actuator. We first consider the conditions which enable us to localize any contact point between the insensitive flexible antenna and environment by applying an active motion to the antenna. We show that the use of a straight antenna always makes it possible to localize the contact point irrespective of friction at the point of contact. We also show that the contact point sensing by the use of a circular shaped antenna is weakly influenced by the friction at the point of contact.

Key words: Active sensing, Active Antenna, Tactile sensing, Contact-point-sensing

1. Introduction

Plural eyes which are the vision system for insects, may work effectively in either detecting the rough shape of object or confirming the existence of object. However, it is well known that they can neither recognize the precise shape of object nor measure the distance up to the object. On the other hand, insects have two advanced antennae that can compensate for the limitation of the sensing capability by their vision system. Furthermore, insects seem to use their antennae skillfully so that they may avoid hitting with objects particularly close to them. An interesting observation is that insects are always moving their flexible antennae actively as shown in Fig.1, while crawling, running, and even staying still. The antenna can be characterized by its *flexibility* and *active motions*. Active motions might be useful for extending the sensing volume in 3D space, and the flexibility of the antenna would contribute to reducing the impulsive force appeared when the antenna contacts an object unexpectedly. While the antenna possesses these inherent advantages, we do not focus on these advantages in this paper. Instead our main goal is to discuss a new active sensing system, in which both *flexibility* and *active motions* essentially contribute to localizing contact point between the antenna and environment.

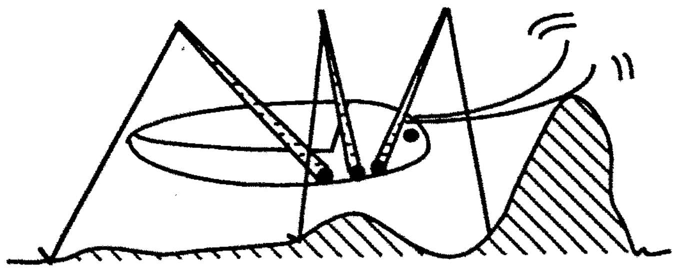


Fig.1 An example of object perception by insect

Here, we briefly review conventional works dealing with flexible beams (or wires) to detect contacts between beams and environment. 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 of electrode and whisker whose end is fixed at the base. This sensor unit has been arranged in array around each foot of legged robot Titan III so that it can monitor the separation between each foot and the ground to allow deceleration of the foot before contact. This sensor is also conveniently used to confirm which part of a foot is in contact with the ground. Similarly shaped whisker has been considered for legs of the Ohio State University active suspension vehicle [6]. Russell has developed a sensor array [7] by mounting whisker sensors on a mobile robot, and succeeded in reconstructing the shape of convex object followed by the whisker. In his work, it is assumed that the whisker tip is always in contact with environment, and that when the whisker contacts environment except the whisker tip, it is assigned to a failure mode. The major difference between previous works [1]-[7] and ours is that the *Active Antenna* enables us to localize a contact point between beam and environment, while previous works do not. On the other hand, Tsujimura and Yabuta have addressed an object shape detection system using a force/torque sensor and an insensitive flexible probe [8]. This approach is based on the original idea that a force/torque information makes it possible to estimate a contact location as well as a contact force, which was first pointed out by Salisbury [9] and later extended more general and mathematical forms by Brock and Chiu [10], Tsujimura and Yabuta [11], and Bicchi [12]. These approaches [8]-[12] can be categorized into passive sensing without utilizing any active motion.

Assuming 2D planar sensing motion, we have introduce a new active sensing system [13], [14] composing of only four components, an insensitive flexible beam, a torque sensor, a position sensor, and an actuator. This simple sensing system enables us to localize a contact point between the beam and environment, when an additional angular displacement is imparted to the beam after the insensitive beam contacts environment. It has been shown that the active motion is essential for this sensing system and a contact point is never localized without such an active motion. In this paper, we discuss the contact point sensing for a curved antenna under the condition that the beam deformation is small enough to keep linear approximation for the force-deflection relationship at the contact point. We show that the utilization of a straight antenna always guarantees the sensing of the contact point between the antenna and environment irrespective of friction at the point of contact, while a curved one is weakly influenced by the friction. We also show a couple of simulation results to explain the effect of friction at the point of contact especially for a curved antenna.

2. Brief review of Active Antenna

2.1 *Passively-Sensible* and *Actively-Sensible*

Before addressing the precise description of Active Antenna, we recall important concepts, *Passively-Sensible* and *Actively-Sensible* [15] with the following definition 1.

[Definition 1] Assume the output of sensor S_i α_i (i=1,...,n). If a sensing event ϕ can be realized using α_i and without utilizing any active sensing motion, we say that sensing event ϕ is *Passively-Sensible* for S_i (i=1,..., n). If a sensing event ϕ can be realized by an active sensing motion with α_i, we say that sensing event ϕ is *Actively-Sensible* for S_i (i=1,...,n).

In this work, we mainly focus on contact-point-sensing between a beam and an object. Our goal is to design an active sensor system making this sensing event *Actively-Sensible* with insensitive flexible beam and fewer number of sensors installed.

2.2 Hardware model of *Active Antenna*

Insect's antenna may have several sensing organs not only at the base joint but also along the antenna itself [16]. While we leave the precise observations and analyses to biologists, we try to incorporate the *flexibility* of antenna and *active motions* into our sensing system. For example, a hardware model based on this idea is shown in Fig.2, where the system is simply composed of an insensitive flexible antenna, a torque sensor, a joint angular sensor, and an actuator. In a later section, we show that this simple system still enables us to make the contact-point-sensing *Actively-Sensible* with a proper active motion. We would note that the actuator is not limited to a rotational type. A linear type actuator will also work, if we combine a linear position sensor and a force sensor instead of both joint angular sensor and a torque sensor.

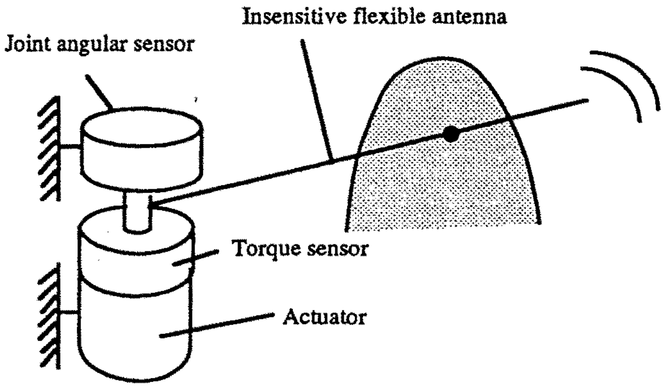


Fig.2 Hardware model of *Active Antenna*

2.3 Necessity of Active Motions

In this section, we explain why active motions are essential for localizing a contact point utilizing a flexible antenna. Let us now consider an antenna element contacting an object as shown in Fig.3, where (a) and (b) are rigid and flexible antennae, respectively. When an antenna contacts an object, more or less a contact force will appear between the antenna and the object. As a result, the actuator receives an reaction torque generated by such a contact force. This torque τ is given by

$$\tau = f_n s_x \tag{1}$$

where f_n and s_x are the force component normal to the antenna and the distance from the antenna fixed end to the contact point. Note that when the antenna is rigid, we can not introduce any other equation except eq.(1). Equation (1) includes two unknown parameters, i.e., f_n and s_x. Even when we can detect τ, we can not decompose it into f_n and s_x, if the antenna is rigid. Thus, we can not determine the contact distance s_x.

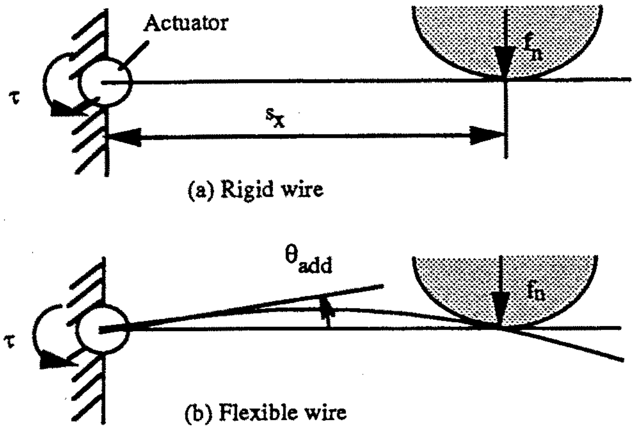


Fig.3 A straight antenna contacting an object

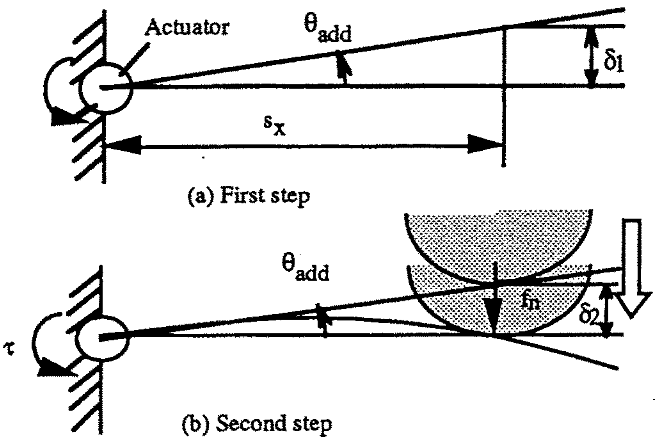


Fig.4 Decomposition into two steps

Let us now consider a flexible antenna as shown in Fig.3(b). For such a flexible antenna, we can impart an additional angular displacement θ_{add} to the antenna even after it contacts an object. For simplifying our explanations, let us assume no contact force $f_n=0$ (or no torque $\tau=0$) before imparting θ_{add}. It can be understood that the final state can be generated by combining two steps. In the first step (Fig.4(a)), the antenna is rotated in a free space with the angular displacement of θ_{add}. The displacement at the contact point is given by

$$\delta_1 = s_x\theta_{add} \tag{2}$$

In the second step (Fig.4(b)), the object is pressed to the antenna and moved until it comes to the original position. During this motion, the contact force increases according to both s_x and θ_{add}, and at the end of this phase the contact force satisfies the following relationship.

$$\delta_2 = \frac{f_n s_x^3}{3EI} \tag{3}$$

where E and I are the Young's modulus and the second moment of cross sectional area of the antenna, respectively. From the geometrical relationship between δ_1 and δ_2, the following relationship exists.

$$\delta_1 = \delta_2 \tag{4}$$

From eq.(1) through (4), we obtain eq.(5).

$$s_x = 3EI\frac{\theta_{add}}{\tau} \tag{5}$$

Equation (5) is quite simple but tells us an important relationship, namely, the distance s_x is in proportion to the angular displacement θ_{add} and in inverse proportion to the joint torque τ. It should be noted from eq.(5) that without any active motion, the contact length can never be obtained. To obtain a more compact form, we introduce the following relationship between τ and θ_{add},

$$\theta_{add}=C_\theta\tau \tag{6}$$

where C_θ is the compliance for rotating motion. Note that C_θ is a function of s_x and varies depending upon contact point. Substituting (6) into (5), we obtain

$$s_x=kC_\theta \tag{7}$$

where k=3EI. Equation (7) implies that the distance s_x is simply in proportion to the compliance of the beam being in contact with the object. In other words, compliance changes linearly according to the contact length. Equation (7) is the simplest relationship expressing the nature of the active antenna. Hereafter, the model as shown in Fig.4 is termed as *primitive model*. We would once again note that eq.(5) (or eq.(7)) can not be derived without both antenna's *flexibility* and an *active motion*. In other words, an active motion for a flexible antenna contributes to decomposing the torque τ into f_n and s_x, respectively. These discussions prove that contact-point-sensing is *Actively-Sensible* for both a torque sensor and an angular sensor by utilizing the sensor system explained in this section. We call the sensing system *Active Antenna*.

3. General Discussions on Active Antenna

In section 2, we explained the basic idea of active antenna for a straight antenna. In this section, we give more general discussions for an antenna having curved shape as shown in

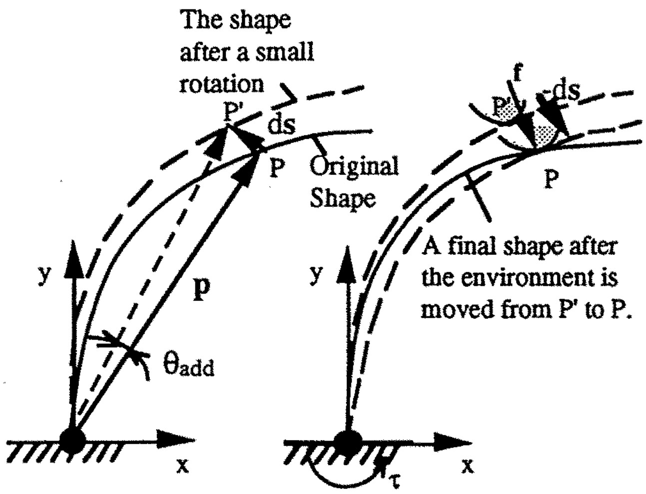
Fig.5. In order to simplify our discussions, we set the following assumptions.

Mian assumptions:
(1) The deformation of the antenna is small enough to ensure that we can apply linear approximation.
(2) The antenna's motion is limited to 2D.
(3) The stiffness of environment is sufficiently large compared with that of antenna.
(4) The contact length s_x is a single-valued function of the position vector **p**.

Assumption (4) means that s_x is uniquely determined by $s_x=\|\mathbf{p}\|$. Now, let us assume that the antenna is actively rotated with θ_{add} after it makes contact with an object. By recalling the approach taken in section 2, we again decompose the problem into two steps as shown in Fig.5. In Step1, a small rotation is imparted to the antenna in a free space. In this step, the contact point moves from point P to P' and this displacement vector ds is given by

$$ds = (\delta x, \delta y)^t = s_x \theta_{add} \mathbf{u} \tag{8}$$

where **u** denotes the unit vector directing from P to P'.



(a) A small rotation of antenna (Step 1)

(b) Environment is moved from P' to P. (Step 2)

Fig.5 An antenna model with curved shape

In Step 2, the object is pressed at P' and moved till it comes to the original contact point P, which is equivalent to imparting the displacement vector -ds to the object. However, we would note that this is not equivalent to giving the displacement vector -ds to the antenna itself. Because for an appropriate angular displacement imparted to the antenna, a slip may be induced between the antenna and the object when the contact force is away from the frictional cone. Here, we start by formulating several basic equations dominating contact physics.

There always exists the following relationship between the contact force **f** and the joint torque τ.

$$\tau = \mathbf{p} \times \mathbf{f} \tag{9}$$

where "×" is a linear operator which makes $v \times w = ad - bc$ under $v=(a, b)^t$ and $w=(c, d)^t$. By substituting $\mathbf{a}=-(p_y, -p_x)^t$ for $\mathbf{p}\times$, we can rewrite eq.(9) into

$$\tau = -\mathbf{a}^t \mathbf{f} \tag{10}$$

where p_x and p_y are components of the vector **p**, respectively. Since stiffness matrix K (or compliance matrix C) is determined when the contact point is designated, we can obtain the contact force by utilizing the following relationship.

$$\mathbf{f} = K dx \tag{11}$$

where dx is a displacement vector whose starting point exists on the shape after a small rotation and its arrow end coincides with point P. If no slip is guaranteed between the antenna and the object, which may happen for a very small angular displacement, dx is equal to -ds. Then, eq.(10) results in

$$\tau = \mathbf{a}^t K ds. \tag{12}$$

Substituting eq.(8) for ds, we can finally obtain in the following form.

$$C_\theta = \frac{1}{s_x \mathbf{a}^t K \mathbf{u}} \tag{13}$$

If C_θ is a single valued-function for the contact length, the contact length s_x can be uniquely determined through the measurement of the rotational compliance C_θ. In other words, the contact point sensing is *Actively-Sensible* for a joint angular sensor and a joint torque sensor.

Since it can be considered that the antenna generally makes slip over the object under a relatively large angular displacement imparted to the antenna, the above mentioned discussions can not be applied when a slip is induced. When a slip happens between the antenna and the object, the relationship of dx=-ds can no more be ensured, which means that the contact force changes according to the friction at the point of contact as well as the angular displacement θ_{add}. This implies that the rotational compliance is the function of the contact distance as well as the friction at the point of contact. Thus, it is not ensured that the contact point sensing becomes *Actively-Sensible* for a joint torque sensor and a joint angular sensor, when a slip is allowed. Now, let us consider the following interesting question: Does a slip occur between the antenna and the object? If this is the case, under what condition, a slip occur?

Instead of giving a general answer for these questions, we examine whether or not a slip occurs when imparting an angular displacement to the particular antenna having the shape of 1/4-circle and homogeneous material. First let us consider the possible region where a contact force appears. While imparting an angular displacement θ_{add} to the antenna, a friction force will appear between the antenna and the object. This friction force always appears so that it may resist a slip, and thus, the friction force f_t will be exerted upon the antenna as shown in Fig.6. Since the object can only push the antenna without pulling, we have such a normal directional force f_n as shown in Fig.6. Thus, the possible region where the contact force appears is limited into the region shown by the oblique lines in Fig.6. A force within the region can be applied for all possible contacts including both non-frictional and frictional contacts. For example, under non-frictional contact, the contact force has the normal directional component f_n alone, and under a large frictional coefficient, a large tangential directional force may appear. Now, let us evaluate the displacement vector due to a contact force within the oblique lines in Fig.6. Since we have $\mathbf{f}_p=K_p d\mathbf{x}_p$, we can evaluate $d\mathbf{x}_p$ through the relationship of $d\mathbf{x}_p=K_p^{-1}\mathbf{f}_p$ or $d\mathbf{x}_p=C_p\mathbf{f}_p$, where the lower subscript "p" denotes the contact point P and the coordinate system is so selected that two axes are directed in normal and tangential directions, respectively. Each component of C_p can be obtained in the following way.

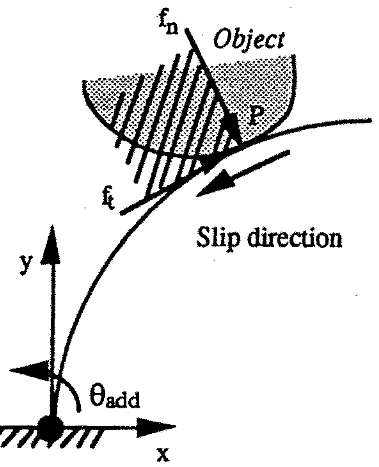


Fig.6 The circular antenna contacting with an object

Let us define the coordinate system as shown in Fig.7. Let D be an arbitrary point over the antenna. The moment at point D can be given by,

$$M=(\mathbf{p}-\mathbf{d})\times\mathbf{f}_p \tag{14}$$

We can compute the total strain energy U stored in the antenna with the following equation.

$$U=\int_0^{q_1}\frac{M^2}{2EI}R\,dq \tag{15}$$

By applying Casteriano's Theorem, we can obtain the following relationship.

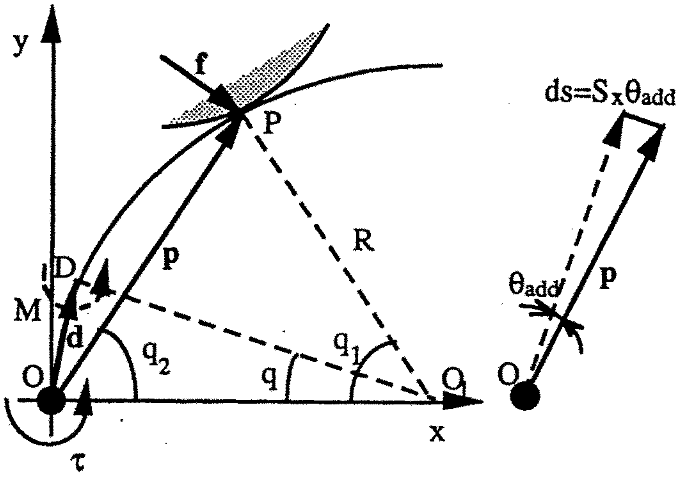


Fig.7 Coordinate system for a circular antenna

$$\delta x'=\frac{\partial U}{\partial F_x}\qquad \delta y'=\frac{\partial U}{\partial F_y} \tag{16}$$

More exactly, eq.(16) can be rewritten in the following form.

$$\delta x'=C_{11}f_x+C_{12}f_y \tag{17}$$
$$\delta y'=C_{21}f_x+C_{22}f_y \tag{18}$$

Both eqs.(17) and (18) can simply be written in the vector form of $d\mathbf{x}=C\mathbf{f}$. Since there exists the relationship with $d\mathbf{x}=Td\mathbf{x}_p$, we have eventually the following relationship,

$$C_p=T^tCT \tag{19}$$

where T is the rotational matrix between $d\mathbf{x}$ and $d\mathbf{x}_p$.

Now, let us evaluate the displacement vector caused by both f_n and f_t. This vector can be easily computed by utilizing the relationship with $d\mathbf{x}_p=C_p\mathbf{f}_p$. Figure 8 shows the simulation result when f_n and f_t are independently applied to the antenna, where the arrows with dotted line and real line denote the displacement vectors caused by f_t and f_n, respectively. This simulation result suggests that the direction of displacement vector changes only little even when the direction of applied force varies over 90 degrees. On the other hand, the arrow having non-pasted head denotes the vector of -ds, which shows the negative displacement vector at the point P due to a small angular displacement θ_{add}. From Fig.8, it can be seen that -ds never exists within the vector plane spanned by two displacement vectors. This means that a contact force within the region shown in Fig.6 can never generate the displacement vector -ds and, in other words, the displacement vector ds can not be imparted to the antenna without a slip between the antenna and the object. This result should be noted, because a slip is induced even under an extremely small angular displacement θ_{add}.

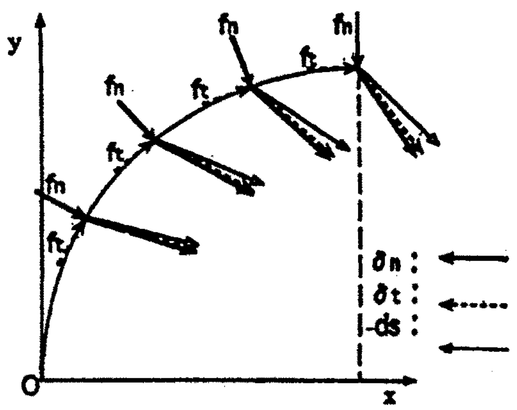


Fig. 8 The relationship between applied force and displacement

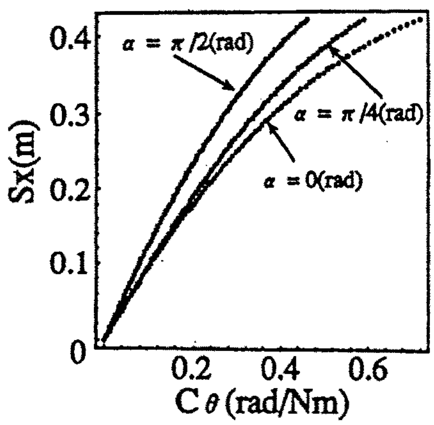


Fig.9 The relationship between s_x and C_θ

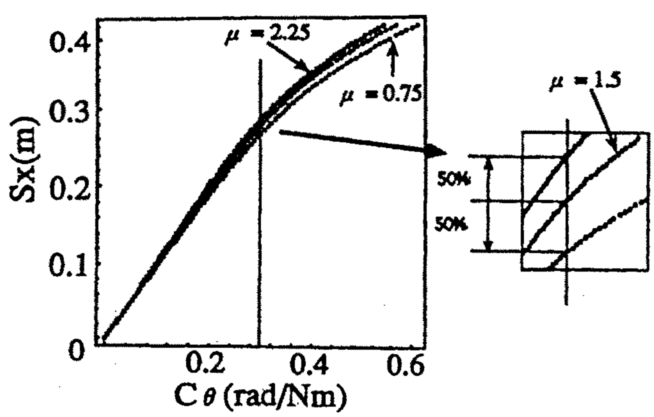


Fig.10 The relationship between s_x and C_θ

Now, knowing of the existence of slip between the antenna and the object, let us now consider the contact force and eventually the relationship between the angular displacement and the measured torque. Here, we assume that the contact force exists on the surface of friction cone during slipping. Since the friction force always appears against the motion of antenna, we can determine the direction of contact force if the friction coefficient between the antenna and the object is given. Assuming that the friction coefficient at the point of contact is known, we can compute the direction of displacement vector due to the contact force by utilizing the relationship with dx=Cf. In the next step, we extend the direction from point P until it intersects the antenna (shown by the dotted line in Fig.7(b)) after imparting a small rotation under the absence of object. The vector from this intersection to point P provides the displacement vector dx. Therefore, we can compute the contact force by f=Kdx and, then, τ by using eq.(11). Even under the same contact point, τ is the function of friction coefficient as well as the angular displacement θ_{add}, while τ is the function of the angular displacement θ_{add} alone in straight antenna. Figure 9 shows the simulation result obtained for various frictional coefficients, where $\alpha=0$ and $\alpha=\pi$ correspond to non-frictional contact ($\mu=0$) and extremely large frictional contact ($\mu=\infty$), respectively. As expected, the rotational compliance varies according to the friction at the point of contact. Considering that the friction coefficient can not be measured exactly, we evaluate the effect of friction change on the sensing accuracy. Figure 10 shows the simulation result when changing the friction coefficient with 50%, where $\mu=2.25$ and $\mu=0.75$ correspond to 50% increase and decrease with respect to $\mu=1.5$, respectively. The important feature in Fig.10 is that the change of contact length s_x is less than 4% even under 50% change of frictional coefficient. This suggests that a rough measurement of friction coefficient will work for the contact point sensing when we use a circular antenna. This feature is really important from the viewpoint of ensuring the frictional robustness for sensing. Because it is highly difficult to measure the frictional parameters accurately in practical fields.

4. Discussions

Now, let us again consider a straight antenna. The straight antenna can be regarded as the antenna whose curvature is extremely small. Without losing generality, we can assume that the tangential direction of the antenna at the base coincides with y-axis. With this assumption, the unit vector **u** of the straight antenna and the vector **a** are given by $\mathbf{u}=(-1, 0)^t$ and $\mathbf{a}=-(-s_x, 0)^t$, respectively. From the relationship between the contact force and the displacement, we can obtain, $K=\mathrm{diag}(3EI/s_x^3, k_0)$ where k_0 corresponds to the stiffness in the longitudinal direction of the antenna and it is extremely large compared with $3EI/s_x^3$. By substituting these relations for **a**, **u** and K in eq.(13), we can finally obtain $s_x=3EIC_\theta$ which exactly coincides with eq.(7). The big difference between straight and curved antennae is that the tangential component of contact force never contributes to deforming the antenna in the straight one because of its extremely high stiffness in the longitudinal direction, while it also contributes to that in a curved one because of the low stiffness in the tangential direction. In some sense, this is disadvantage for a curved antenna, since the rotational compliance becomes the function of friction at the point of contact. On the other hand, this is a big advantage for a curved antenna. In a straight antenna, a lateral load applied produces a well defined deflection proportion to load, for example. However, the antenna will be able to support a much larger axial load with little deflection because of extremely high stiffness in such a direction. At some poorly defined critical value of axial load the antenna will buckle and collapse. Furthermore, since such an axial load generates no torque around the torque sensor, this situation can not be monitored by the sensors installed. Russell [7] has pointed out that this behavior is not desirable as a tactile sensor and that whisker shape should be carefully designed so that we can avoid this behavior. As he has pointed out, one solution for this is to use an antenna with curved shape, because such antennae can prevent them from supporting large axial loads.

Now, we summarize an important remark:

> [Remark] The use of straight antenna always makes it possible to localize the contact point irrespective of the friction at the point of contact. In other words, the contact point sensing becomes *Actively-Sensible* for a joint angular sensor and a joint torque sensor when utilizing a straight antenna. (Friction robustness for sensing). For the use of curved antenna, the contact point sensing is weakly influenced by the friction at the point of contact.

5. Conclusions

We discussed the working principle of *Active Antenna*. *Active Antenna* is a new active sensing system composing of an insensitive flexible beam, a position sensor, a torque sensor, and an actuator. We explained the basic principle by using a straight antenna and showed that the contact length is simply in proportion to the compliance in *Active Antenna* being in contact with environment. We also discussed the basic behavior of antenna when we utilize a curved antenna with focusing on the antenna with circular shape. We showed that a straight antenna is preferable to a curved one in the sense of sensing robustness for friction. We also showed that the contact point sensing is weakly influenced by the friction at the point of contact when utilizing an antenna with curved shape. We further plan to develop this idea to 3D *Active Antenna*, by adding one actuator and one torque sensor to cover a large area in 3D space. One difficulty to realize such a system may arise from that the antenna at point of contact will slip laterally as well as longitudinally according to both the object's shape and the direction of active motion.

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