Biomimetic Whisker Experiments for Tactile Perception

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Abstract—Rodents use their whiskers (vibrissae) for tactile perception. Our artificial whiskers follow the basic design of the follicle of rodent vibrissae. In experiments with the artificial whiskers, we have explored tactile perception based on active whisking, and found the deflection amplitude or velocity provides the localization information of a target object. Based on this localization approach, a collection of contact distances at varying protraction angles can discriminate round objects with a varying curvature, or objects with different lateral shapes, such as cubes or cylinders to some extent. In addition, the whisker slip of a single whisker can detect the vertical shape for a smooth surface of objects. Two or more whiskers stacked vertically can recognize the vertical shape by observing the difference of their deflection amplitudes or the time shift of deflection velocity peak. The results may provide a hint of how rodents recognize various shapes using their whiskers.

I. INTRODUCTION

Recognizing the shape of objects only with a mechanical probe is a challenging problem. There have been several approaches to use mechanical probes or antenna to recognize objects. Russell [12] designed a tactile whisker array to obtain surface profile of an object, and a potentiometer with an inflexible beam was mounted to monitor whisker deflection which depends on the force applied to the whisker tip. With a flexible beam, the contact point on objects can be determined by observing the fundamental resonant frequency of the vibration at the contact moment [17]. The whisker probe system consisting of a piano wire, a sweeping actuator and strain gages has also been tested for object detection [14]. A combination of distance information based on force/moment sensors and a variety of force directions by an active antenna has been used to extract the shape information of an object [16]. Kaneko et al. [6] studied a geometrical analysis for the relation between a probe and a curved shape of objects. They developed an active antenna system to determine the contact location as well as detect the slip of the antenna depending on the force direction. Their active antenna system consists of a flexible beam, actuators to move the beam, a torque sensor and angular position sensors to measure the rotational angle of the beam [6]. Most of research related to the active antenna system has focused on estimating contact location for shape information, and torque sensors or strain gages have been used for the purpose.

Real rodents demonstrate an outstanding capability of shape recognition and texture discrimination [2], [1]. Our work for shape recognition is motivated by their whisking function and sensory abilities. A biomimetic whisker system and its properties have been studied by Lungarella et al. [11] and Fend et al. [3]. Their artificial whisker is based on a capacitor microphone with a real rat whisker directly attached to the sensitive surface. In the biological whisker system, the whisker shaft is embedded in a follicle structure. Mechanoreceptors surrounding the shaft measure deflection in all directions, some of them with tonic, others with phasic response [10], [15], [13], [4]. Our artificial whisker system imitates this design in a very simplified way. In all our designs, the whisker is surrounded by sensors, and whisker deflection either affects these sensors without contact (magnetic sensors affected by magnets on the whisker shaft) or with contact (piezoelectric sensors).

Previously we reported that the artificial whiskers can detect the deflection angle and the deflection direction for both low frequencies (including static deflection) and high frequencies (texture-related signals) [8]. Here, we will use low-frequency signals for shape recognition. There have been engineering approaches to evaluate deflection with vision, torque sensors, strain gages or potentiometer [5], [16], [14], [12]. The angle swept by an actuator was observed at the base of whisker and contact distance was determined from the torque or force measurement. Their style of deflection evaluation is far from the biological model. Our artificial whisker system measures the deflection level through a pair of sensors located near the whisker base.

In this paper, we suggest a novel method to recognize the shape of target objects, based on deflection angles. The deflection amplitude or velocity signal directly provides the localization information, the distance and angular position of an object. The shape information can be extracted from these two signals for each whisker. We start with a theoretical analysis of deflection amplitude for our artificial whisker. Then we provide the experimental results with multiple whiskers to discriminate various shapes of objects.

II. THEORETICAL DEFLECTION

For active whisking, we mounted two arrays of whiskers on a Koala platform (K-team) – see Figure 1, where a DC motor rotates a plate on which an array of whiskers is mounted. Whisker sensors can be mounted in arbitrary position and orientation on the plate. Its rotation angle and sweeping speed
can be controlled by a robot and the whiskers on the plate share the same angular movement. Its maximum rotation angle is about 120 degrees. Since the whiskers are moved by the same DC motor, their protraction and retraction movements are synchronous.

In an active antenna system, if the torque \( \tau \) and the angular displacement \( \theta \) at the antenna base are given, the distance can be easily estimated by the equation \( 3EI\theta/\tau \) \cite{7, 6} (\( E \) is the Young’s modulus of elasticity and \( I \) is the cross-sectional area momentum of inertia). However, it is unlikely that rodent whiskers include high-precision torque sensor in their follicle structure. The above distance estimation with the torque measurement depends on the material and thickness of the whisker shaft. Rodents have slowly adapting and rapidly adapting mechanoreceptors around the whisker shaft in the follicle. There has been a physiological evidence that the deflection amplitude and velocity signals are coded at ganglion cells \cite{13}, \cite{15}. In this paper, we will focus on measuring the deflection angle with the sensors at the side, which is proportional to the contact force or torque. The term deflection angle will be equivalently used with bending angle, which corresponds to the transverse movement at the sensor position. The sensor signals at the side are amplified and transmitted into the on-board computer (PC104+) mounted on the robot, via a multi-channel data acquisition board (PCM-9112+).

For a given torque \( \tau \) in a contact phase of active whisking, we can derive the bending displacement or slope of the whisker from the Bernoulli-Euler equation \cite{9}, which is given as:

\[
EI \tan \theta = \frac{\tau}{2d^2} \frac{d}{2} - \frac{\tau x}{2} + \frac{1}{3} \tau d \tag{1}
\]

where \( \tan \theta \) is the slope at a position \( x \) (\( 0 \leq x \leq d \)) along the whisker bar, \( \theta \) is measured with an axis connecting from the whisker base to the contact point, and \( d \) is the distance of an object from the whisker base at the onset of contact. The magnetic sensors in the artificial whisker measure the deflection of the whisker 14 mm away from the whisker base.

In our artificial whisker system displayed in Figure 2, the whisker base (clamped position) is 45 mm away from the rotational axis of the DC motor, and the position of the whisker base moves by the rotation of DC motor. Here, the term contact distance is defined as the distance from the center of rotation to the contact position, and deflection distance as the distance from the whisker base to the contact position. We also define \( \vec{c} \) for a position vector on the whisker base with a rotational angle \( \theta_0 \), and \( \vec{p} \) for a position vector on the contact point \( (\vec{p}) \) will be the distance from the center of rotation to the contact point, simply denoted as \( p \) in the text). For the vectors, the motor axis will be the reference point. Then \( \vec{d} = (|\vec{c}| \cos \theta_0, |\vec{c}| \sin \theta_0) \), and \( d = |\vec{p} - \vec{c}| \) represents deflection distance.

By applying the sensor position \( x = h = 14 \text{mm} \) and the clamped position \( x = 0 \) to the equation (1), we can cancel out \( \tau \) and obtain the following equation:

\[
\tan(\theta_1 + \alpha) = \left( \frac{3h^2}{2d^2} - \frac{3h}{d} + 1 \right) \cdot \tan(\theta_0 + \alpha) \tag{2}
\]

where \( \alpha \) is the angle of a vector pointing to the whisker base from the contact position, \( h \) is the distance 14 mm between sensor position and clamped position, and \( \lambda = \theta_0 - \theta_1 \) is deflection angle or bending angle that the sensors measure, which is distinguished from the protraction angle \( \theta_0 \). As a result, the magnitude of deflection angle is inversely propor-
Fig. 3. Theoretical deflection amplitudes depending on contact distance (with the assumption that the whisker bar is long enough to be bent with the corresponding distance)

...tional to the contact distance\(^1\) as shown in Figure 3, and smaller distances increase the deflection angle more rapidly in proportion to the protraction angle.

III. EXPERIMENTS

Shape information of an object is divided into two parts, lateral and vertical shape information with respect to the whisking direction. We will show active whisking results over several types of shapes.

A. Lateral shape

In the first experiment, we observed static deflection signals for varying protraction angles and contact distances by placing

\[ |p| = d \cos(\alpha) + |\theta| \cos(\theta_0) \]

where \( |\theta| \) is fixed to 45 mm.

\(^1\)The contact distance \(|p|\) can be calculated as \(|p| = d \cos(\alpha) + |\theta| \cos(\theta_0)\) where \(|\theta|\) is fixed to 45 mm.

Fig. 4. Deflection amplitude depending on distance in the experiments (data for large protraction angles are not available because the tested whisker shaft has a limited length of 240 mm (steel beam with 0.5 mm diameter) and the protraction angle in the graph is the angle after the onset of contact)

In the first experiment, we observed static deflection signals for varying protraction angles and contact distances by placing the cube at various positions in the sweeping area. The curve in Figure 4 shows that the deflection amplitude depends on distance and protraction angles, which is similar to the theoretical estimation shown in Figure 3.

To check the relationship between the contact distance and deflection angle during the whisking period, we collected 16 whisker sweeps of temporal sensor signals with 200 Hz sampling rate for each distance (100 mm to 240 mm with 20 mm step) and then the average peak of deflection amplitude and velocity were calculated. The motor control circuit for the DC motor can adjust the sweeping frequency and protraction/retraction angle of the whisker. The protraction angle after the onset of contact and the retraction angle after the offset of contact was set to about 28 degrees, 30 degrees, respectively. It was assumed that the whisker does not pass by the object in the sweeping period.

To see the influence of contact distance, we tested varying distances of a square object and the object is placed with a large skewed angle such that the whisker has one fixed contact position. The sensor signals were pre-processed by a low-pass filter. We can easily see different deflection amplitudes depending on contact distance – see Figure 5. The deflection

Fig. 5. Deflection signal for a cube
axis from the rotational axis to the contact position, which is denoted as whisker. We adjusted the angle of a square object relative to the horizontal plane, which contact a square object in sequence. To disambiguate the two situations, we define a point contact depending on the surface shape along the whisking direction. Large protraction angles often provide prominent differences of deflection over a varying size of round objects. Large protraction angles often provide prominent differences of deflection over a varying size of round objects.

Localization information, the contact distance and angular position of a target object is obtained by assuming that the contact point is fixed. However, the contact point can vary depending on the surface shape along the whisking direction. To disambiguate the two situations, we define a point contact as the situation in which the contact position is fixed during the whisking period. A surface contact is defined as the situation in which the contact point varies.

For an edged-surface object, the deflection signal depends on how the edged surface is placed in the sweeping area of the whisker. We adjusted the angle of a square object relative to the axis from the rotational axis to the contact position, which is denoted as $\beta$ – see Figure 2. We used two whiskers in the same horizontal plane, which contact a square object in sequence. In the experimental setting, the first whisker touches two-edge points depending on $\beta$, but the second whisker, which has a delayed touch, always experiences a point contact in the motor movement. The second whisker has almost constant deflection amplitude with varying $\beta$’s, because it has a point contact with the first edge point. Figure 6 shows examples of the effect of varying $\beta$’s, where each curve is averaged over five whisking cycles. For $\beta$’s smaller than 28°, the first whisker touches two-edge points and the contact distance for the second edge point increases as $\beta$ increases. Thus, small $\beta$’s have high deflection amplitudes for the first whisker. For large $\beta$’s, for instance, $\beta = 28^\circ$ or greater, the whisker experiences a point contact, because it touches only the first edge point. The graph of deflection signals over the two whiskers can determine angular conformation of the square object for a given contact distance. We can estimate the contact distance by comparing the onset times of contact of a pair of whiskers. Short contact distances lead to larger time-shift for the onset of contact between a pair of whiskers than long distances, if the whiskers are aligned in parallel or positioned within some angle. We can also observe the deflection amplitude for the advanced touch at the onset time of the delayed whisker touch. Arrows in Figure 6 indicate the moment and a larger contact distance produces smaller deflection amplitude of the first whisker at the onset time of contact of the second whisker.

For the next experiment, we observed the deflection signal of a single whisker in a sweeping mode for round objects. Unlike edged-surface objects, round objects always have surface contact, and also the curvature of objects determines the level of deflection angles as shown in Figure 7. A larger curvature of objects have a shorter contact distance for each given protraction angle, and thus they will have higher deflection amplitudes in time course. We tested varying sizes of round objects. Figure 8 shows examples of how the curvature of round objects influences deflection signals for a given contact distance. A large size of round objects produces large amplitudes and also they experience more variation of contact distances along the surface. Large protraction angles often provide prominent differences of deflection over a varying size of round objects.

Generally we can discriminate point contact and surface contact by observing deflection amplitude or velocity signal. If a higher level of deflection is observed than expected with point contact, then we can say it is a surface contact. However, it is not an easy task to discriminate a curved surface and an edged surface including more than one point contact, based on the deflection amplitude alone, if the size and distance of objects are unknown. Theoretically their curves of deflection magnitude in Figure 5(a) is inversely proportional to the contact distance, as predicted in the theoretical estimation. The deflection velocity, which is calculated as a derivative of deflection amplitude, is another cue to determine the contact distance.

Localization information, the contact distance and angular position of a target object is obtained by assuming that the contact point is fixed. However, the contact point can vary depending on the surface shape along the whisking direction. To disambiguate the two situations, we define a point contact as the situation in which the contact position is fixed during the whisking period. A surface contact is defined as the situation in which the contact point varies.

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![Fig. 7. Deflection angles with a varying curvature of round objects](image-url)
angle in time course are different (an edged surface will produce a more sudden change of deflection as well as high deflection velocity at the transition of edge touch), but noisy signals and the presence of natural frequencies in the deflection signal make it a hard problem in our system. Possibly a sequence of different robot positions or a collection of tactile signals at different view angles can yield better discrimination.

B. Vertical shape

Kaneko et al. [6] studied a geometrical analysis on the relationship between varying force directions and the corresponding slip. In their experiments, the force direction of the beam was iteratively changed to a normal direction of the surface with the help of slip information. However, there was no process to translate the whisker slip into the shape of objects directly and they needed a set of contact positions to build a contour of an object. In our active whisker system, we use two channels of sensor signals, horizontal and vertical channels together, to evaluate the slip of whisker. The deflection of both channels can directly estimate the surface slope of target objects. Figure 9 shows the deflection signals of two types of cones for 3-5 sweeps of a whisker, and a protraction period of deflection signals shows the surface slope of a cone. To see the effect of the protraction angle after the onset of contact, we measured the two channel sensor signals over several protraction angles ($4^\circ - 16^\circ$). Regardless of the range of protraction angles, the slope information can be obtained from the X-Y plot. In the retraction period, they have a different course of whisker movement, depending on the curvature of the object, the protraction angle, surface friction and whisker bending on the surface. Presumably the shape of X-Y plot may also reveal the curvature of a conical object.

We built another type of conically-shaped objects consisting of circular disks with different diameters (each disc has 10 mm height), which has a discrete stepping level. In this case, the whisker slip of each whisker is not observed. Thus, we stacked two biomimetic whiskers vertically. The onset time of deflection can determine the angular position of an object as well as the vertical shape. For example, a conically shaped object produces a time-shift of deflection signal for the upper whisker and the lower whisker. In addition, the time-shift can also be observed in the deflection velocity. Especially the velocity signal shows high peaks close at the moment the whisker touches an object and at the moment that the whisker detaches from an object.
Figure 10 shows the time course of deflection signals for a conically-shaped object. In Figure 10(a), the upper whisker has a relatively small amplitude, since its contact duration with the object is short. We can first estimate the distance information by the magnitude of deflection amplitude or deflection velocity. Then we calculate the difference between the peak amplitude in the upper whisker signal and that in the lower. The sign of the difference will determine which part, the upper or the lower, is contacted first. The difference magnitude between the two amplitudes at a given contact distance will provide the information of the size difference between the upper and the lower. We can also estimate the vertical shape by a time shift in deflection velocity signals – see Figure 10(b). However, fast sweeping produces a small time shift, which may result in a precision problem when estimating the relative size difference. It seems that the difference between the deflection amplitudes can be a more prominent cue to recognize the vertical shape.

As an alternative sensor technology, an array of piezoelectric sensors directly produces the deflection velocity instead of the deflection amplitude. A stack of piezo-type whiskers can also provide the time-shift depending on the vertical shape of an object. Thus, the temporal whisker signal with a given sweeping speed can determine the shape of an object. Figure 11(b) shows the original sensor signals and their low-pass filter signals of vertically stacked whiskers. Piezoelectric sensors directly produce the velocity signal, while magnetic sensor signals needed to calculate a derivative of deflection amplitude to obtain the velocity. The original sensor signals always include ripples corresponding to the fundamental natural frequency. The natural frequency signal is dominantly interfering with the velocity signal, even though high peaks related to the touch
of an object are observed. This interference is removed by low-pass filters as shown in Figure 11(b). Thus, we also find the time-shift in the piezoelectric velocity signal. The positive peak corresponds to the moment that the whisker starts to touch the object and the negative peak to the moment that the whisker detaches from the object. The velocity signal can be a dominant feature to detect the vertical shape of an object, as the deflection amplitude with magnetic sensors. The velocity signal can be obtained from both sensor technologies, magnetic sensors and piezoelectric sensors.

IV. CONCLUSION

Deflection amplitude or deflection velocity signals provides the localization information of a target object, that is, contact distance and angular position of an object. Also they show the potential of detecting the lateral shape and the vertical shape of objects. For the lateral shape recognition, we found the level of deflection amplitude changes relying on whether a sweep of whiskers experiences point contact or surface contact along the surface of a target object. The result is caused by the dependency of deflection on the contact distance. The deflection signal helps discriminating round objects with a varying curvature or objects with different lateral shapes, for example, round and square objects.

A single whisker with two channels arranged orthogonally each other can recognize the slope of the vertical shape. Alternatively, the vertical shape can be estimated by two whiskers or more stacked vertically. For instance, a conically shaped object will produce a time-shift in whisker signals for the upper whisker and the lower whisker. The time-shift for contact can be measured by observing the deflection velocity. An alternative is to use the time course of deflection amplitudes. The difference of deflection amplitudes also provides the vertical shape information.

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