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# Biomimetic whiskers for shape recognition

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**Abstract**

Rodents demonstrate an outstanding capability of tactile perception with their whiskers. Mechanoreceptors surrounding the whisker shaft in their follicle structure measure deflection of the whisker. We designed biomimetic whiskers following the basic design of the follicle. In experiments with the artificial whiskers, we have explored tactile perception based on active whisking where the deflection angle or velocity provides the localization information which is the basis of shape recognition. Measuring contact distances at varying protraction angles allows discrimination of round objects with a varying curvature, or objects with different lateral shapes, such as square and round objects. We show the capabilities and limitations of a single whisker for shape recognition as well as the usefulness of multiple whiskers. In addition, measuring both vertical and horizontal deflection of a single whisker allows detection of the vertical shape for objects with a smooth surface. 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 provide a clue on how autonomous robots could improve their sensory capabilities with mechanical probes.


*Keywords:* Biomimetic whisker; Biorobotics; Tactile sensors; Shape recognition; Active perception

## 1. Introduction

Recognizing shapes of objects with only a mechanical probe is a challenging problem. There have been several methods to use mechanical probes or antenna to recognize objects in the robotics field. The engineering approaches evaluate deflection with vision, torque sensors, strain gages, or potentiometers [13, 25,27,21]. The angle sweeped by an actuator was observed at the base of a mechanical probe and the contact distance was determined from the torque or force measurement. Russell [21] designed a tactile sensor array, each sensor consisting of a potentiometer and a long inflexible beam, and the potentiometer sensor at the whisker root measured the rotational angle proportional to the contact force applied to the antenna tip. The tactile system thus obtained the surface profile of an object. Alternatively, a flexible beam can be used as a probe. Such an antenna probe system, including a piano wire, a sweeping actuator and strain gages, has been tested for object detection [27]. To obtain localization information of an object, the contact point on objects can be determined by observing the fundamental resonant frequency of the vibration at the contact moment [26]. A combination of distance information based on force/moment sensors and a variety of force directions by an active antenna was used to extract the shape information of an object [25]. Kaneko et al. [14] presented a geometrical analysis for the relation between a probe and the 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 [14].

Recently a biomimetic whisker system, consisting of a capacitor microphone and a real rat whisker has been studied [18,8,7], and it was shown that it can be a useful tool to discriminate textures of target objects. Later Bovet and Pfeifer [4] proposed a robot control architecture which learns cross-modal correlations between visual, tactile or motor modalities. Seth et al. [22] developed artificial whiskers to provide signals proportional to the bending magnitude. Their

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Fig. 1. Mouse whiskers (photo: Wolfram Schenck).

whiskers consist of polyamid strips with 20 resistive areas embedded regularly along the longitudinal length, and the resistance of each whisker changes depending on the amount of bend. As a result, the whiskers can measure bending in only one direction. Our earlier work reported that a biomimetic whisker with steel shaft and magnetic sensors can measure the vibration of the whisker beam as well as the deflection angle [16]. We have explored tactile perception based on active whisking, and found the deflection amplitude or velocity provides localization information of a target object. Here, we will show that based on this localization approach, a collection of contact distances at varying protraction angles can provide shape information.

Real rodents demonstrate an outstanding capability of shape recognition and texture discrimination with their whiskers [6,5,3]. Rodents have tactile whisker arrays in the face as shown in Fig. 1 and they can process spatial information with laterally oriented vibrissae through active whisking. Our work on shape recognition is motivated by their whisking function and sensory abilities. 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 [17,20,24,23,10]. 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) [16]. Here, we will use low-frequency signals for shape recognition.

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. Based on the localization approach, we describe several possibilities to detect the shape of a target object with a single whisker or multiple whiskers. We start with a theoretical analysis of deflection amplitude for our artificial whisker. Then we present the experimental results with single and multiple whiskers to discriminate various shapes of objects.

## 2. Method

We mounted two arrays of whiskers on a Koala platform (K-team) — see Fig. 2(a). For active whisking, each array is mounted on a plate which can be rotated around a vertical axis by a DC motor. Both rotation angle and sweeping speed can be controlled, and its maximum rotation angle is about 120°. Whisker sensors can be mounted in arbitrary position and orientation on the plate. All whiskers on the plate share the same angular movement. Since the whiskers are moved by the same DC motor, their protraction and retraction movements are synchronous. The sensor signals are amplified and transmitted into the on-board computer (PC104+) mounted on the robot, via a multi-channel data acquisition board (PCM-9112+).

In each individual whisker, the whisker shaft is a steel beam with diameter 0.5 mm and is clamped at the aluminium base. Here we use artificial whiskers based on hall-effect sensors. The hall-effect magnetic sensors can measure the difference of magnetic flux at two sensors on opposite sides caused by the movement of the whisker to which a permanent magnet is attached. Directional sensitivity was achieved by using two pairs of sensors arranged orthogonally to each other. To test shape recognition, we can build several types of objects consisting of circular or square discs (10 mm height for each disc) — see Fig. 2(b).

### 2.1. Theoretical estimation of deflection

We will first provide the theoretical model of deflection of our artificial whiskers and show how the deflection signal during active whisking is influenced by the shape of target objects. 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 $3EI\theta/\tau$ [15,14]. $E$ is the Young's modulus of elasticity and $I$ is the cross-sectional area momentum of inertia. Thus, the distance estimation with torque measurement depends on the material and thickness of the whisker shaft. In fact, rodents have slowly adapting and rapidly adapting mechanoreceptors around the whisker shaft in the follicle, and there has been physiological evidence that the deflection amplitude and velocity signals are coded at ganglion cells [23,24]. In this paper, we will focus on measuring the deflection amplitude and velocity, and investigate how they can serve to extract shape information. The artificial whiskers that we designed do not measure torque but record the deflection angle which is proportional to the contact force or torque at a given distance. The term *deflection angle* will be synonymously used with *bending angle*, which corresponds to the transverse movement at the sensor position.

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, which is given as:

$$EI\tan\theta = \frac{\tau}{2d}x^2 - \tau x + \frac{1}{3}\tau d \quad (1)$$