An Artificial Whisker Sensor for Robotics

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Abstract

In this paper, we present a first series of experiments with prototype artificial whiskers that have been developed in our laboratory. These experiments have been inspired by neuroscience research on real rats. In spite of the enormous potential of whiskers, they have to date not been systematically investigated and exploited by roboticists. Although the transduction mechanism is simple and straightforward, and the whiskers are currently used in a passive way only, the dynamics of the sensory signals resulting from the interaction with various textured surfaces is complex and has a rich information content. The experiments provide the foundation for future work including active sensing, whisker arrays, and cross-modal integration.

1 Introduction

Whiskers are widespread in the animal kingdom because they play an essential role in sensing. Rats, for instance, have a highly sensitive whisker system that can be exploited to deliver a wide range of information about the environment such as texture, distance, shape, and orientation. Furthermore, there is a potential overlap with other sensory modalities, for example vision, which yields precise spatial information. It is important for adaptive behavior that the two modalities (whiskers, vision) are based on different physical processes, i.e., mechanical contact and electromagnetic waves. If one modality fails, e.g., if there is no light or too much noise, the other modality can, at least partially, compensate. In spite of the enormous potential of whiskers, they have been to date almost completely neglected by the robotics community: For the better part, the research has investigated sensors based mostly on binary touch devices, called whiskers, whisker probes [10], tactile whiskers [11], wind sensors, which are able to detect wind direction [2], or active antennae used for distance measurements [6]. However, natural whisker systems - according to our hypothesis - yield much richer information. Just recently (see [4]), the rat whisker system has been considered to be a suitable model for designing robust robotic active sensing and exploratory devices.

The rodent somatosensory system is characterized by a prominent representation of their mystacial vibrissae (called whiskers). Though rats and mice strongly rely on visual and olfactory cues, their somatosensory system is an important and accurate sensory modality. Rats are able to distinguish sandpaper surfaces purely on the basis of cues from their whiskers [3]. It is even suggested that the accuracy of rat whiskers is comparable to that of primates finger tips [1]. Whiskers are active sensors which can be swept across surfaces or objects at a dominant frequency of approximately eight Hertz. Peripheral and central vibrissal units encode a variety of hair deflection parameters, including amplitude, velocity, duration, frequency, and angular direction [5].

In this paper, we present a prototype of a realistic artificial whisker sensor, which returns signals with properties, that can potentially be processed in a way similar to the rat somatosensory system. The artificial whisker system consists of a whisker-shaped material probe, which was chosen among a small set of a few *ready-at-hand* artificial and natural materials like plastic, human hair, and real rat whiskers. In section 2, the electric, mechanic and material properties of the artificial whisker system we developed are exposed. The experimental device built to perform simple and passive object palpation is described in section 3. In section 4, we present the methods used to analyze the preliminary data collected with our setup. The analytical results are presented and discussed in the two subsequent sections 5 and 6. The future work and the conclusion are presented in section 7.

2 Mechano-electro Transduction

The core element of our sensor is a standard off-the-shelf *electret* microphone capsule, which is a par-

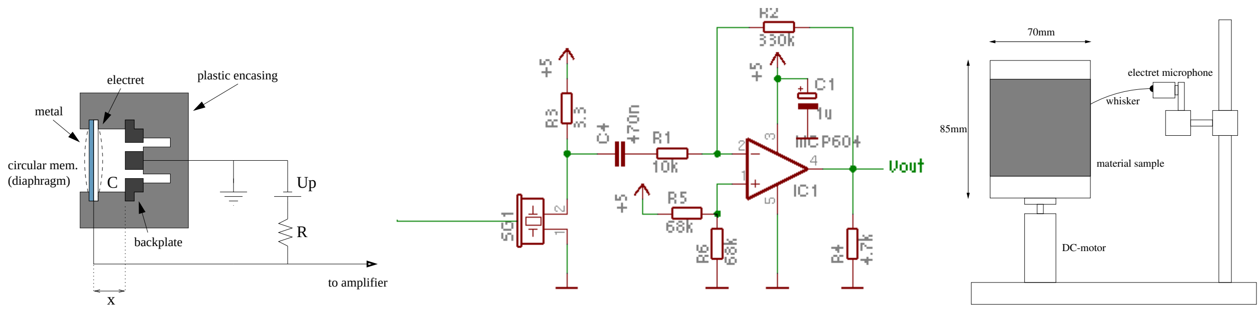

Figure 1: *Basic schematic of an electret microphone and a microphone preamplifier circuit. The necessary bias circuitry for the electret microphone is shown on the left. The deflection of the circular membrane, in response to a change of pressure, is measured by the change of capacitance. The related change of voltage is fed into a standard microphone preamplifier circuit (middle). Right: Experimental device used to perform the experiments described and analyzed in this paper.*

ticular type of electrostatic sound sensor. In order to build the actual *whisker sensor*, we glue a small piece of a whisker-shaped (straight or curved thin and circular) rod of whatever material we wish to employ on the diaphragm of the microphone with a relatively hard glue (vanilla *cyanoacrilic super-glue*). Upon contact with an object, the whisker-shaped rod transmits the resulting contact force to the plate capacitor, where a small, but detectable change of its plate distance is induced. In the following sections we will refer to our sensing device as *whisker sensor*. A schematic drawing of the device is shown in figure 1 left.

3 Experimental Device

The experimental setup consists of a plastic cylinder on which different types of material samples can be attached. It is possible to have samples with smoothly or roughly textured surfaces (e.g., plastic, paper or sandpaper). The cylinder is placed on a $12V$ DC-motor, whose turning speed is controlled by means of a microcontroller unit, connected via a serial cable to a host computer. The distance between the plastic cylinder and the base of the whisker sensor can be adjusted - see figure 1 right. Since the whisker is made of flexible material, the closer the base to the cylinder, the bigger the curvature of the whisker. When the whisker touches an object, a contact force appears between the whisker and the object. By means of the whisker, the contact force between the whisker and the surface of the object is propagated to the diaphragm of the microphone. The reaction torque induced on the membrane not only depends on the distance, but also on the mechanical properties of the whisker itself, and on the material characteristics of the glue used to fix the cylinder to the diaphragm. The voltage at the output of the capsule has an amplitude ranging from $1mV$ to $100mV$. It is this voltage which provides the actual signal from which the sensory information can be acquired.

4 Analysis Methods

The analysis of the time series data collected for this paper have been performed in the frequency domain. There is at least one basic motivation why we decided to focus on Fourier analysis and not on analysis in the time domain. In principle, with this sort of analysis we seek to identify the frequency content of the sensory signal, i.e., a characterization in terms of combination of sinusoids. We are interested in basic oscillations, or fundamental modes, that are the result of the interaction of sensing device and environment.

The discrete Fourier transform (DFT) of N data points of a sequence of samples x_k is defined as $X_n = A_n + iB_n = \sum_{k=0}^{N-1} x_k e^{-2\pi ikn/N}$, and transforms the time series into a series of coefficients X_n at its Fourier frequencies. The squared magnitude of these coefficients, given by $\|X_n\|^2 = A_n^2 + B_n^2$, measures how strongly the oscillation at the Fourier frequency $f_n = nF_s/N$ is represented in the data (in order to extract dominant frequencies, for instance), where n ranges over integer values, F_s is the sampling frequency, and N the number of data samples. In terms of f_n and F_s, X_n can be rewritten as $X(f_n) = \sum_{k=0}^{N-1} x_k e^{-2\pi ikf_n/F_s}$. An alternative view is, that the magnitude plot of the spectrum gives the distribution of power among the various frequency components making up the signal, while the phase plot of the spectrum gives the starting phases of the same frequency components. In speech processing phase contributions are largely ignored. We will do the same in what follows.

Intuitively, the power spectral density (PSD) describes how the energy of a time series is distributed with frequency. Different algorithms are used for the estimation of the PSD. In our case, we make use of a popular nonparametric scheme developed by [12].

5 Results of First Experiments

In order to better understand the mechanical properties of the whisker sensor we developed, various experiments have been performed. Note that the results exposed and analyzed in this and the subsequent sections are only of preliminary nature. For a complete and thorough understanding of this sensing device, many parameters will have to be taken into account. These include length and mechanical properties of the whisker (elasticity, stiffness, moment of inertia), material characteristics of the glue, location where the whisker is glued on the diaphragm, amplifier gain, speed with which the contact point or contact points between whisker and object move relative to each other, radius of curvature of the whisker, and so forth. Furthermore, note that the experiments described do not involve any form of active sensing. The sensor is used in a purely passive way. In other words, it is stimulated externally, by the relative motion of whisker and texture of the material sample fixed on the plastic cylinder. In the context of this paper, three issues are taken into consideration (emphasized in italic).

Issue 1: *Dependency on material properties.* The goal of the initial set of experiments was to get a feel for the extent to which the material properties of the whisker are responsible for the characteristics of the sensory signal. Four different whiskers have been built and tested, one made of a small hair-shaped piece of polyvinyl (plastic) of length $L = 38mm$ (sometimes referred to as *broom fiber*), a human hair ($L = 37mm$), and two types of rat whisker - a long and peripheral one (*caudal*), with $L = 51mm$, and a short one (*rostral*), attached near the nose, with $L = 35mm$. Note that the length of the whisker was measured from the base where the whisker is attached to the diaphragm - see figure 1 left. In order to be able to compare the resulting plots, the time series were normalized to have zero mean. The distance d to the moving surface (again measured from the base to the contact point on the surface), the speed V of the turning cylinder, and the roughness r of the material sample (in this case, sandpaper) were kept constant. Figure 2 top displays the PSD of the time series of the different whiskers over a $= 1\,sec$ time interval.

Issue 2: *Caudal natural rat whiskers for categorization.* Since in the context of our research endeavor we are highly interested in category learning and the role played by the different material properties of the

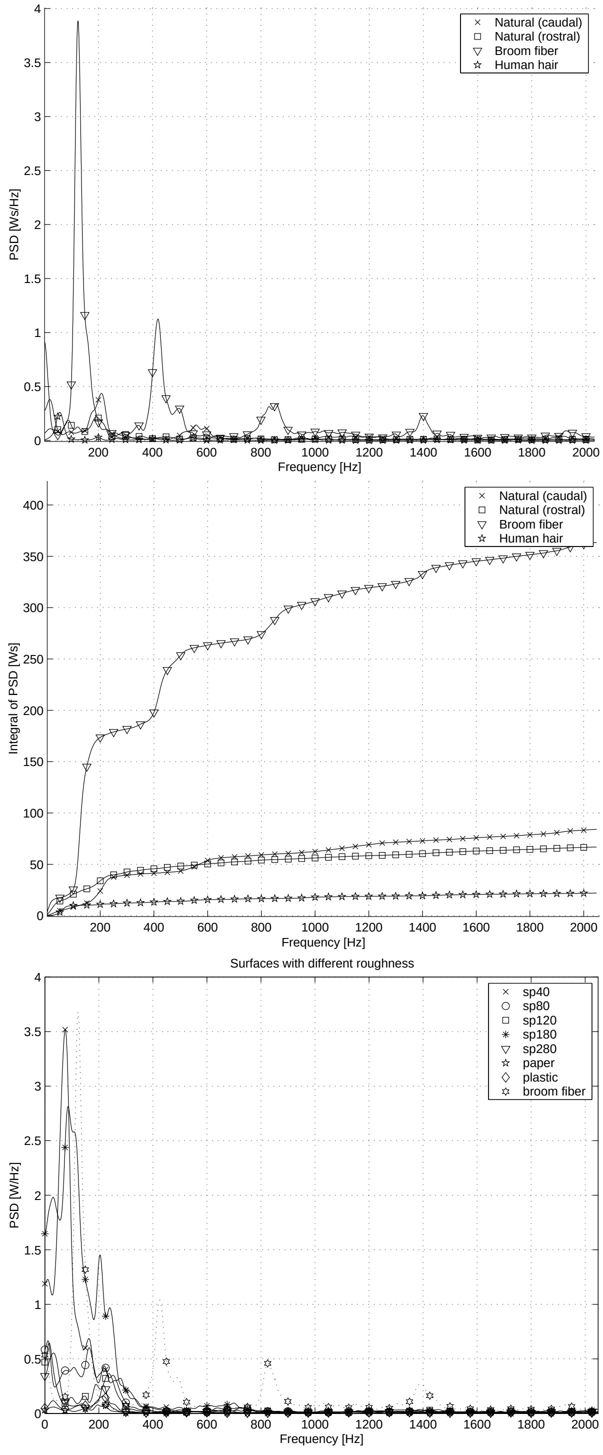

Figure 2: *Top: Power spectral density (PSD) of four different types of whiskers (natural-caudal, natural-rostral, broom fiber, human hair). Center: Cumulated sum of the top plot. Bottom: PSD of the raw data generated through the interaction of whisker and textured surface. The dotted curve corresponds to the PSD of the time series obtained using the polyvinyl whisker.*

natural rat whiskers, we performed a basic experiment related to the categorization of samples of different materials making use of natural caudal (long) whiskers. The experiment was inspired by work done by [3] and [1] on real rats, which seem to use their large, caudal, external whiskers to actively palpate and explore objects. As in the previous setup, the distance d to the object, and the speed V of the whisker relative to it are kept constant. Subject to variation in this case was the roughness r of the textured surface. We chose sandpaper of various roughness ($r = 80, 120, 180, 280$), paper ($r < 400$), and a rectangular patch of an overhead slide (r unknown). The results (PSDs) are displayed in figure 2 bottom. In order to be able to compare the plots of the natural whisker with the one obtained with the polyvinyl whisker, the PSD of the latter (obtained from a typical experiment) was added to the graph (dotted line in figure 2 bottom).

Issue 3: *Caudal whiskers for distance measurement.* The last experimental result described, concerns *contact point localization*, i.e., distance measurement. In this case we employed natural caudal whiskers ($L = 51mm$). The sensors were positioned at nine different distances from the cylinder, and the rotational speed of the cylinder was kept constant. The PSDs of the signal were estimated by means of Welch's method. The distance vs. frequency plots (*DF-plots*) in figure 3 are generated by means of a linear interpolation of the nine different PSDs computed. Similar *DF-plots* were produced by using a whisker made of polyvinyl (plastic), and one made of human hair. The brightness of the pixels indicates the magnitude of the Fourier coefficient at a certain frequency.

6 Discussion

Using the results presented in the previous section, we can make a few points. The following discussion is held qualitative on purpose.

First, we consider the material properties of the whisker. Stiffness S (measured by the product of Young's elasticity modulus and the moment of inertia of the whisker) seems to play a major role. A look at the plot in figure 2 top shows that for the polyvinyl whisker (*broom fiber*), the ratio of the amplitude of the $1st$ peak and the amplitude of the $2nd$ peak and the one of the $2nd$ and the $3rd$ peak are bigger than the same ratios for the other three whiskers. Stated differently, the *jumps* in the cumulated PSD are "bigger" and more "abrupt" in the case of the *broom-fiber* - see figure 2 center. This is probably due to the higher stiffness (lower flexibility) of the plastic whisker compared to the other three types of whisker. The energy of the stiffer whisker is mostly contained in a few modes, four or five, in the case depicted in figure 2 top (curve with triangles pointing downwards).

Another point concerns the sensitivity of the whisker sensor, which is defined as the ratio of change of output voltage δV to deflection of the tip δx, i.e., $\delta V/\delta x$. We performed some preliminary experiments with a stiff metal (aluminum) wire, but we gave up as soon as we noticed that even very small deflections of the tip of the whisker induced strong and long lasting oscillations with a low decay constant. These oscillations lead to saturation of the preamplifier, although its gain was set to the minimum allowed value. A whisker made of plastic is still relatively stiff, but its stiffness is less than the one of a metal wire. So compared to rat whiskers and whiskers made of human hairs, the polyvinyl whisker exposed to the same amount of tip deflection delivers an output with a bigger amplitude. This is also reflected in the amount of energy E transferred to the sensor, which is directly related to the amplitude of the sensed signal. Figure 2 center shows exactly this point. The total energy flowing into the system in the case of the polyvinyl whisker is around five times bigger than for the natural whisker and around 17 times bigger than for a whisker made of human hair. We did not analyze this any further, but we hypothesize, that this is again due to the stiffness of the material involved. If the distance from base to object is kept constant, $S_{humanhair} < S_{natural} < S_{polyvinyl}$, and $E < E_{natural} < E_{polyvinyl}$.

Statements going into the same direction, emphasizing the role played by the material and the mechanical properties of hair-shaped structures can be found in [7] for instance, where the intrinsic mechanical parameters of a certain wind-receptor of crickets are analyzed. The shape of this particular wind-receptor hair seems to be a biological trait which determines the amount of sensory stimulation transmitted, and thus the content of the sensory information available to the central nervous system. We put ourselves in the same line, but we think that apart from the right mechanical and material properties of the whiskers, an appropriate embodied sensory-motor coordinated interaction with the object to be explored, is necessary in order to generate "good" sensory data (see [8]).

Our hypothesis is, that passive sensing is not enough to provide truly useful sensory signals. In other words, other mechanisms have to be taken into account. From our previous work on categorization we are led to believe that apart from active sensing, i.e., sensory-motor coordinated interaction, additional whiskers (whisker array) are necessary preconditions for the generation of "good" and easy cat-

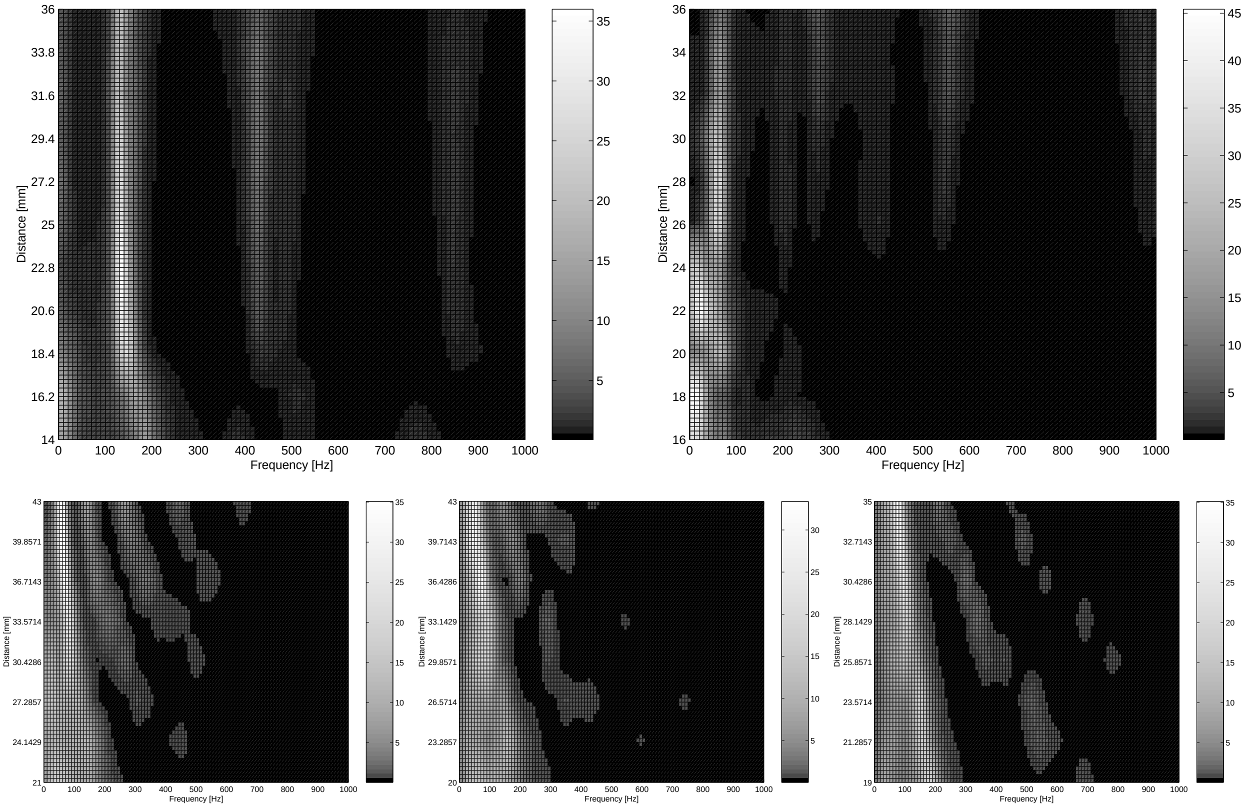

Figure 3: *Top: Distance vs. frequency plot for two different whisker sensors. On the left: Polyvynil (highest stiffness in our case, $L = 37mm$). On the right: Human hair (lowest stiffness in our experiments, $L = 38mm$). Bottom: Typical* DF-plots *for the same whisker sensor, but result of the interaction with surfaces of different roughness. The whisker is caudal, with $L = 51mm$. From left to right: Sandpaper with a granularity of 80 units, sandpaper of granularity of 180, and plastic (piece of an overhead slide).*

egorizable sensory data (see [8], but also [9] for an overview on the issue).

In the graph of figure 2 bottom we added the plot of the PSD corresponding to a whisker made of a polyvinyl fiber (dotted line). The purpose is to show the mechanical filtering effect of whiskers and its dependency on different materials. The sensor built with the natural whisker cuts off at around $350\,Hz$ (independently of the roughness of the surface), whereas the whisker made of polyvinyl has a bandwidth which is at least four times as large, and which has frequency peaks up to $1400\,Hz$.

The whisker can be modeled as an insensitive flexible beam with one clamped end (the base) and one free end (the contact point). When the whisker makes contact with an object close to the base, the beam has a higher stiffness (is more rigid) compared to the case when the contact point is close to the tip. This characteristic is largely independent of the material used. It is intuitive, that the closer the contact point to the base, the lower the compliance of the beam, i.e., it yields less elasticity to an applied force. This leads to a higher torque on the diaphragm, and to a higher amplitude and power of the sensed signal - see figure 3 top left, for instance. The higher power of the signal is represented by the higher brightness of the pixels. In the *DF-plot*, the power is coded in terms of shades of gray. White corresponds to a very high value, whereas black corresponds to a very low value. Furthermore, since the eigenfrequency of a beam structure is proportional to its stiffness and inversely proportional to its length, a contact closer to the base increases the eigenfrequency of the structure. This can be seen in figure 3 bottom right, where the first peak shifts towards lower frequencies, if the distance increases. The plot on the top left of figure 3 belongs to a more stiff whisker (*broom fiber*), whereas the one on the right to a less stiff one (*human hair*). Apparently the stiffness of the *broom fiber* does not change very much with distance from the surface, and this is the reason why the first peak does not shift. What changes is the intensity of the signal. The torque transmitted to the base is higher, if the distance to the textured surface is smaller. In any case, it seems to be possible to use this whisking device to detect the contact location, i.e., as a distance sensor.

7 Future work and Conclusions

We have built an artificial whisker sensor consisting of an electret microphone on which we have glued a small whisker made of different materials. By performing palpation experiments with a rotating cylinder, we have shown that the artificial whisker sensor is producing complex data, which depend on various parameters. Comparing different materials for the whisker, we found out that a real rat whisker attached to our sensory system produces more clear and stable data. We assume that the natural whiskers have good damping properties compared to the artificial materials. Transferring the artificial whisker sensor data into the frequency domain allowed a human observer to distinguish different surfaces explored by the whisker. The same was possible by acoustically listening to the raw whisker sensor data.

There are many possible options for future work on our preliminary artificial whiskers sensor. An important goal would be to perform active whisking as rats do it, and to investigate sensory-motor interactions in the real world. We hypothesize that the active whisking behavior can also facilitate tasks like categorization and object recognition by effectively transforming the sensory space. We are planning to develop a neural processing model able to classify different objects and materials by palpation using the data from our prototype. It will be interesting to find out how well parameters like distance, angle, velocity, etc. can be filtered out using our artificial whisker sensor. Another extension to our current prototype will be an array of artificial whiskers in analogy to rats and mice. Finally, we would like to investigate issues like cross-modal interactions and cross-modal learning between whisker data and visual or auditory data.

8 Acknowledgements

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References

[1] G.E. Carvell and J. Simons. Biometric analyses of vibrissal tactile discrimination in the rat. *Journal of Neuroscience*, 10(8):2638–2648, 1990.

[2] T. Chapman, A. Hayes, and T. Tilden. Reactive maze solving with a biologically-inspired wind sensor. In J. Meyer, A. Berthoz, D. Floreano, H. Roitblat, and S.W. Wilson, editors, *From Animals to Animats 6. Proc. of the 6th Int. Conf. on Simulation and Adaptive Behavior*, pages 81–87. Cambridge, MA: MIT Press. A Bradford Book., 2000.

[3] E. Guic-Robles, C. Valdivesco, and G. Guajardo. Rats can learn a roughness discrimination using only their vibrissal system. *Behavioral Brain Research*, 31:285–289, 1989.

[4] M.J. Hartmann. Active sensing capabilities of the rat whisker system. *Autonomous Robots*, (11):249–254, 2001.

[5] M. Ito. Some quantitative aspects of vibrissa-driven neuronal responses in rat neocortex. *J. of Neurophysiology*, 46:705–715, 1981.

[6] M. Kaneko, K. Kanayama, and T. Tsuji. Active antenna for contact sensing. *IEEE Trans. on Robotics and Automation*, 14(2):278–291, 1998.

[7] T. Kumagai, T. Shimozawa, and Y. Baba. The shape of wind-receptor hairs of cricket and cockroach. *J. Comp. Physiol. A*, 183:187–192, 1998.

[8] M. Lungarella and R. Pfeifer. Robots as cognitive tools: Information theoretic analysis of sensory-motor data. In *Proc. Humanoids 2001. IEEE-RAS Int. Conf. on Humanoid Robots*, pages 245–252, 2001.

[9] R. Pfeifer and C. Scheier. *Understanding Intelligence*. MIT Press, Cambridge, Mass., USA, 1999.

[10] R.A. Russell. Object recognition using articulated whisker probes. In *Proc. 15th Int. Symp. Industr. Robots.*, pages 605–612, 1985.

[11] R.A. Russell. Using tactile whiskers to measure surface contours. In *Proc. IEEE Int. Conf. Robot. Automat.*, pages 1295–1300, 1992.

[12] P.D. Welch. The use of fast fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. *IEEE Trans. Audio Electroacoust.*, AU-15:70–73, 1967.