Whisking with Robots

From Rat Vibrissae to Biomimetic Technology for Active Touch

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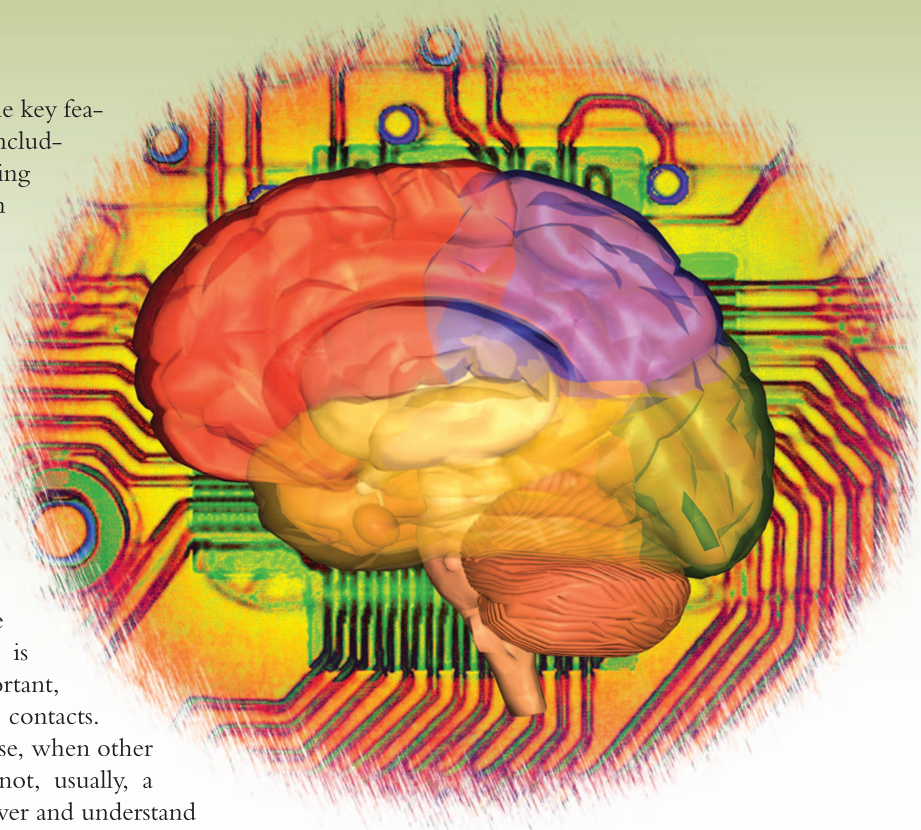

This article summarizes some of the key features of the rat vibrissal system, including the actively controlled sweeping movements of the vibrissae known as *whisking*, and reviews the past and ongoing research aimed at replicating some of this functionality in biomimetic robots.

Cognitive robotics draws inspiration from biology and neurosciences to devise robots that are capable of demonstrating adaptive behavior that is similar to that seen in animals, including humans. An important area in which robotics currently fails to match the capabilities of many mammals is tactile perception. Although touch sensors are widely employed in robotics, their role is largely to support the simple, albeit important, function of detecting unexpected physical contacts. In other words, they are a last line of defense, when other smarter sensor systems have failed, and not, usually, a principal modality through which to discover and understand the world. This situation stands in interesting contrast to the use of tactile sensing in much of the animal kingdom. Be it the human fingertip or the sensitive tactile hairs or antennae found on many animals, in nature, touch is used not only as an alerting stimulus but also to solve complex perceptual tasks—to determine the shape, texture, and position of encountered objects; to decide whether something is moving and, if so, how fast and in what direction; to distinguish soft from hard or living from nonliving. On the basis of our own experience, we may be inclined to think of the skin and, in particular, its most sensitive regions on the fingertips and lips, as the supreme organs of tactile sensation. However, in the natural world, many mammals do a large part of their tactile sensing at a slight distance using long hairs known as *whiskers* or *vibrissae* to explore their surroundings. These vibrissal sensors work rather like an old-fashioned record stylus—the bumps and troughs of a contacted surface are translated into movements of the vibrissal shaft, and these, in turn, are detected by hundreds of pressure-sensitive receptors inside a specialized hair follicle. One of the benefits of this arrangement is that, unlike a fingertip, the

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delicate sensory transducers (the receptors) are kept away from the contacted surface where they might otherwise sustain damage due to the repeated, direct physical contact needed for touch sensing. This is an attribute that could usefully translate into artificial tactile systems where wear and tear of the sensing apparatus is a significant problem.

As illustrated in Figure 1, animals that specialize in the use of vibrissal sensing include rodents (such as rats and mice), seals and walruses, and some of the smallest living mammals, the shrews. In some of these species, particularly those that are nocturnal or live underground, the facial vibrissae or whiskers are a more important sense organ than the eyes. It has been demonstrated that rats can discriminate texture using their whiskers with similar accuracy to the human fingertip [1]; seals can use their whiskers to detect and follow the hydrodynamic trails left by fish [2]; and the whiskers of the pygmy shrew allow these animals to detect, recognize, track, and catch prey insects with lightening speed [3]. It is the prospect of putting these kinds of sophisticated tactile-sensing capabilities onto robots that has enthralled a small but growing band of robotics researchers. In this article, we look at the origins and growth of research into artificial vibrissal systems, examine its current status, and consider some of the prospects and challenges that lie ahead.

Research on artificial whisker systems began in the mid-1980s, continued intermittently through to the turn of the century, and has begun to gather pace in the last decade. Recent progress has been spurred by our increased understanding of natural vibrissal systems and advances in engineering materials, transduction, actuation, and microelectronics. The field has also benefited from increased interest from funding bodies such as the Framework Programmes in Europe and the National Science Foundation in the United States. Although the body of published work accumulated to date is relatively small (less than 50 journal articles and conference papers), it provides a useful platform on which future progress can build. The vibrissal-sensing devices investigated hitherto have been inspired by the whiskers of mammals such as the cat, mouse, rat, and seal or by the antennae of crustaceans and insects; however, the rat has been the most popular model because the vibrissal system of this animal is the most widely researched. In the following sections, we summarize what is known about the biology of rat vibrissal sensing, focusing on whisker physical morphology and early sensory processing, whisker movement control, and neural signal processing and sensorimotor integration. We then review attempts, thus far, to replicate some of this functionality in robotic sensory systems.

The Rat's Whiskers

In rats, the long facial whiskers or macrovibrissae form a two-dimensional (2-D) grid of five rows on each side of the snout, each row containing between five and nine whiskers up to 5 cm long and increasing in length from front to back [see Figure 1(a)]. Each whisker is curved and tapers from a diameter of less than 1 mm at the base to a vanishingly narrow tip. Studies of the physical properties of the whisker shaft and its mounting in the whisker follicle suggest that parameters such as length, thickness, curvature, taper, elasticity, resonance, and damping will be among the critical determinants of the signals generated when a whisker contacts a surface (see, e.g., [4] and [5]). Within the specialized hair follicle that transduces bending of the vibrissal shaft into neural signals, there are several populations of

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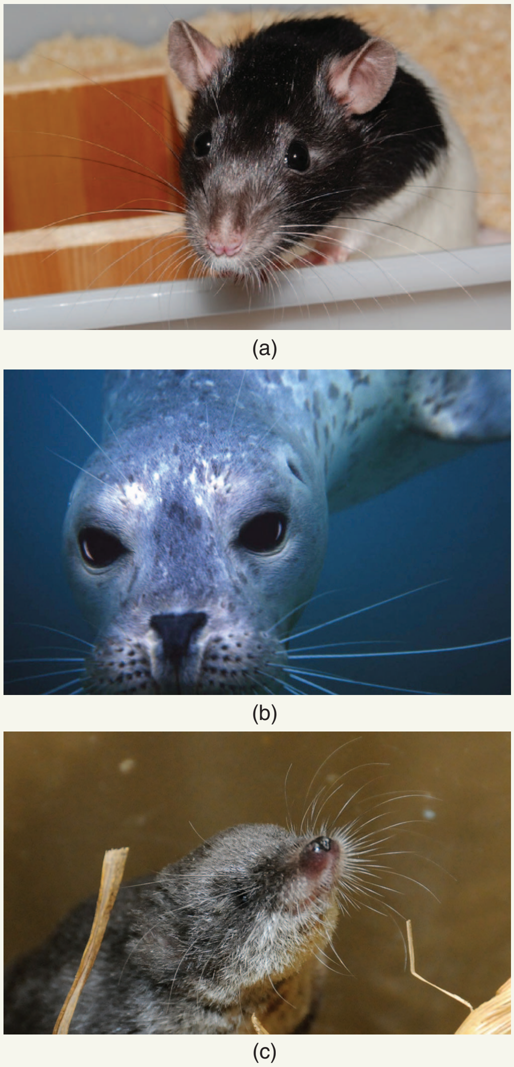


Figure 1. *Mammalian vibrissal specialists. Three species that have evolved sophisticated tactile sensory systems based on the facial vibrissae. (a) Common rat, (b) harbor seal (with permission from M. McEvoy), and (c) water shrew (with permission from S. Prescott).*

Each whisker is curved and tapers from a diameter of less than 1 mm at the base to a vanishingly narrow tip.

mechanoreceptors that respond with high sensitivity to movement or deflection of the whisker. Signals from many such receptors are brought together in each of the primary afferent neurons of the brainstem trigeminal nerve from where they are relayed to rest of the brain. Electrophysiological recording made within these primary afferent cells (of which there are roughly 200 for each whisker) suggest that their activity encodes information about the direction, velocity, and duration of whisker displacements and torques [6] that is sufficient to allow animals to precisely localize contacted objects in a three-dimensional (3-D) space [7], [8].

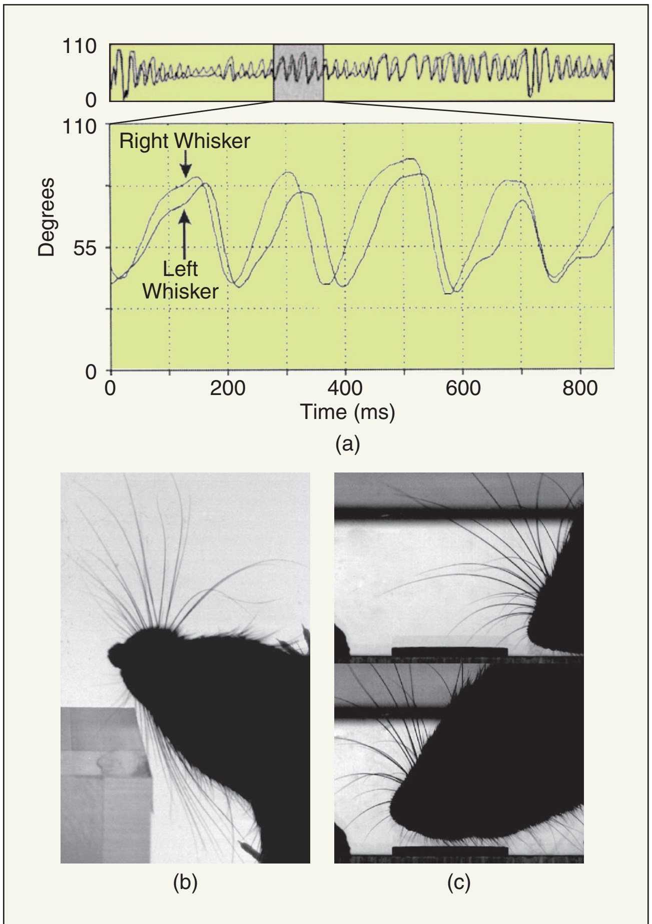


__Figure 2.__ Whisking control in the rat. (a) Left- and right-whisking movements (mean whisker position) for a head-restrained rat whisking in air (with permission from Society for Neuroscience and P. Gao [33]). (b) Asymmetry arising due to unilateral contact with a perspex block (the left whisker field is much less protracted than the right whisker field). (c) Use of macro- and microvibrissae (reproduced from [32]).

Whisking Movements and Active Touch

One of the most striking characteristics of the rat whisker system is that the macrovibrissae are not passive sensors waiting to be deflected by an encounter with an object. Rather, the whiskers are often actively swept back and forth at high speeds (5–25 times/s) in a behavior known as *whisking* with the forward movement of each whisker partially determined by its own intrinsic muscle. Since whisking requires energy, it presumably has some important benefits to the animal. These are likely to include the capacities to 1) sample across a large area of space around the head, 2) direct the whiskers toward interesting nearby targets, and 3) control the velocity and duration of contacts with surfaces. In other words, rats may whisk for the same reason that people repeatedly adjust the position of their fingertips when exploring objects with their hands—because, we get better sensory information when we can control how and where our sensors interact with the world.

When a rat whisks in air (i.e., without contacting any surfaces and without moving its head), the whiskers on the two sides of the head move largely synchronously and symmetrically (i.e., at similar amplitudes) [see Figure 2(a)]. However, there is increasing evidence that rat whisker movements are actively controlled—depending on the animal's motivation, head and body movement, and recent sensory experience—in a manner likely to boost the amount of useful and goal-related sensory information that is obtained [9]. This control often leads to measurable left–right differences in the amplitude and timing of whisker movements. For instance, when the rat turns its head, the whiskers often move asymmetrically so as to direct exploration in the direction of the turn [10]. Likewise, when the whiskers on one side of the head encounter an object, the whiskers on the contacting side rapidly cease protracting (moving forward) and subsequently move with smaller amplitudes so that contacts are made with a light touch [11]. Following such a contact, whisker movements are also adjusted on the contralateral (noncontacting) side of the face; here, the whiskers can be seen to move with a larger amplitude than before, as if reaching round in search of the contacted object [see Figure 2(b)]. There is also evidence that the rat may be able to modify the relative speed of movement of the whiskers within each left and right field. For instance, drawing the whiskers closer together to explore a located object or spreading them apart so as to maximize the area of free space sampled in each sweep [9]. Reconstruction of whisker movements in 3-D space has allowed more accurate characterization of whisker trajectories and has demonstrated, for instance, that, although movement is primarily parallel to the anterior–posterior plane of the head, there is some movement in the axis perpendicular to this plane, as well as torsional rotation of the whisker shaft/follicle during whisker protraction [12]. The extent to which these additional degrees of freedom of control are functionally important for vibrissal sensing remains to be established.

Movements of the rat's macrovibrissae are closely coordinated with those of the head and body, allowing the animal to locate interesting stimuli through whisker contact and investigate them further using both their macrovibrissae and an array of shorter, more densely packed, nonactuated microvibrissae on the chin and lips. Typically, the animal will encounter an object or surface of interest with the macrovibrissae then, within one or two whisk cycles, orient its head so that the microvibrissal field can be brushed against the area of greatest interest. For instance, in the upper frame of Figure 2(c), the rat encounters an interesting object (a coin) with its macrovibrissae, and in the next whisk cycle [Figure 2(c), lower frame] and in subsequent cycles, it investigates the coin by brushing against it with the microvibrissae on its lower lip and chin. Thus, the microvibrissae may act as a foveal region for vibrissal touch [13]. The macro- and microvibrissae together thus appear to function as an integrated active touch system for detecting and investigating environmental structure at multiple spatial scales—from the relatively large-scale properties of distance, shape, and extent, down to fine-grained properties of surface roughness and pattern.

Neural Processing of Vibrissal Signals for Tactile Perception and Control

As previously noted, whisker deflections are transduced into neural signals in the primary afferent cells of the trigeminal nerve. From here, the sensory signals ascend to processing stations in the brainstem, midbrain, cerebellum, and forebrain (the thalamus and sensory cortex) [see Figure 3(a)], before being relayed to further brain areas involved in memory and spatial mapping (such as the hippocampus) and decision making. A useful feature of the system, which makes it easier to study, is the one-to-one mapping from whiskers to barrel fields in the sensory cortex. Many of the vibrissal-sensitive neurons within the brainstem, thalamus, and sensory cortex are found in cellular aggregates formed during development, which have a somatotopic one-to-one mapping with the whiskers. In the primary somatosensory region of rat cortex, these aggregates are known as *barrels*, and, thus, this part of the cortex is often referred to as the barrel cortex. The existence of these highly ordered and easily identifiable neuronal pathways from individual whiskers through to their cortical representations has made the vibrissal system an attractive model system for many neurobiological studies. Indeed, research on vibrissal-processing pathways and cortical microcircuits that extract perceptual information from whisker signals is a highly active area in which new data are published on a weekly basis (see [14] for a recent review).

Since whisker movement and positioning is actively controlled, the neural centers involved in processing vibrissal sensory signals are also strongly interfaced with those involved in positioning the head and generating and controlling the rhythmic whisking movement. In fact, the neural architecture for the processing of vibrissal sensory signals and control of whisker movement can be thought of as a series of layers or nested sensorimotor loops, connecting sensing to actuation at all levels of the brain from the brainstem through to the cortex [15], [16] [see Figure 3(b)]. This architecture is probably typical of the organization of sensorimotor control systems in mammals. Good progress has been made in understanding signal representation in these circuits (see, e.g., [6], [14]–[17]); however, the functional roles of the various loops and the nature of their interactions have yet to be adequately characterized. More generally, the nested-loop architecture illustrated in Figure 3(b) appears to be typical of the way that sensorimotor systems are organized in the vertebrate brain [18]; thus, studying layered control in the context of the vibrissal system should provide wider insights into brain function.

The whiskers are often actively swept back and forth at high speeds in a behavior known as whisking.

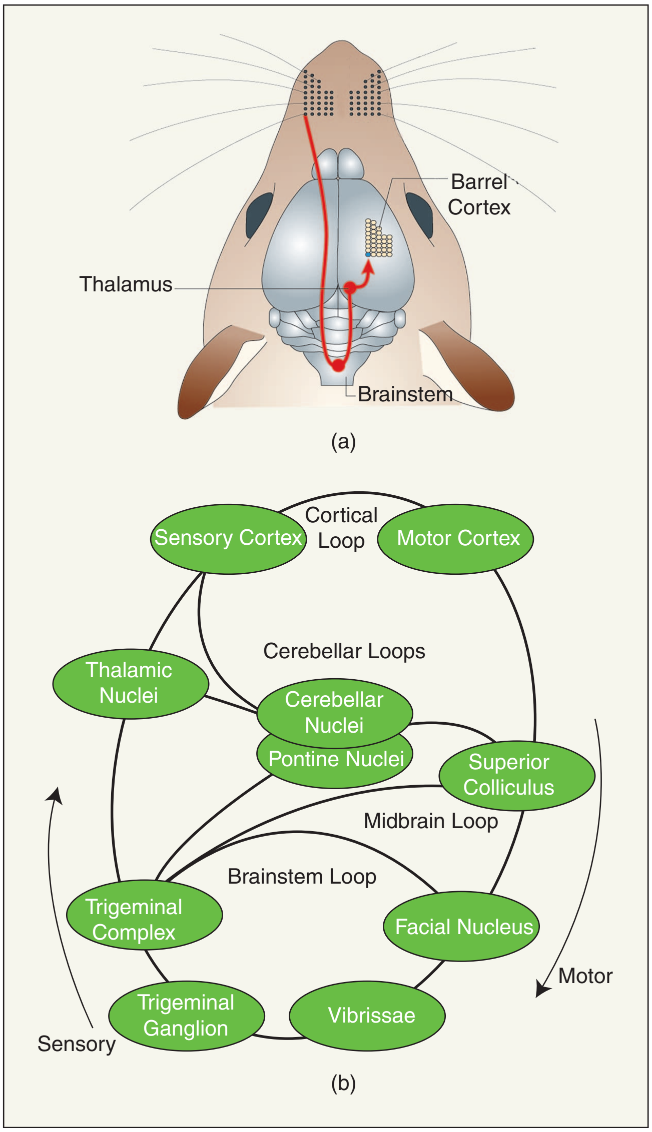


Figure 3. *The neural substrates of vibrissal sensory processing and control. (a) Illustration of the vibrissal sensory-processing pathway from the vibrissae to the sensory cortex via the brainstem and thalamus (with permission from McMillan Publishers and M. Diamond [17]). (b) A set of nested loops in the brainstem, midbrain, and forebrain of the rat connects sensory-processing centers with brain structures involved in controlling movement of the whiskers and head (adapted from [16]).*

Whisker deflections are transduced into neural signals in the primary afferent cells of the trigeminal nerve.

Overall, although there are still many unknowns concerning the biology of the vibrissal system, it is currently one of the most studied mammalian senses. The very considerable volume of the past and ongoing research in this field therefore makes it practicable to consider building whisking artifacts that strongly mimic many of the functional and processing characteristics of the biological model. Progress in vibrissal robotics offers the prospect not only of devising novel tactile-sensing devices but also making a real contribution to the understanding the brain by providing physical systems in which models of complete neural sensorimotor loops can be instantiated and evaluated.

Whisking Robots

As described previously, the rat's vibrissal system demonstrates exquisite sensitivity to patterns of whisker deflection, the capacity to drive sophisticated behaviors (such as identification, tracking, and capture of agile prey), and is evidently an active-sensing system in which movement and positioning of the whiskers play a critical role in determining the signals that are processed via its neural pathways. Clearly, an artificial vibrissal system designed to operate in this way would be very different from the passive binary collision-detectors that provide the tactile sensing competence of many contemporary robots.

Beginning with Russell [19], a variety of robotic vibrissal systems have been developed that claim direct inspiration from the rat; a selection of the most recent of these are illustrated in Figure 4. The various designs that have been investigated (as well as others not illustrated) differ from each other in a number of important ways.

First, the mechanical properties of the vibrissal shaft vary considerably, with solutions ranging from steel wires [19]–[21] through specially molded composites that follow the general shape (curvature and taper) of rat whiskers while scaled to a larger size [22], to actual rat vibrissae [23]. Based on recent analyses of the relevant physical properties of real whiskers (as mentioned earlier), it seems likely that the most effective

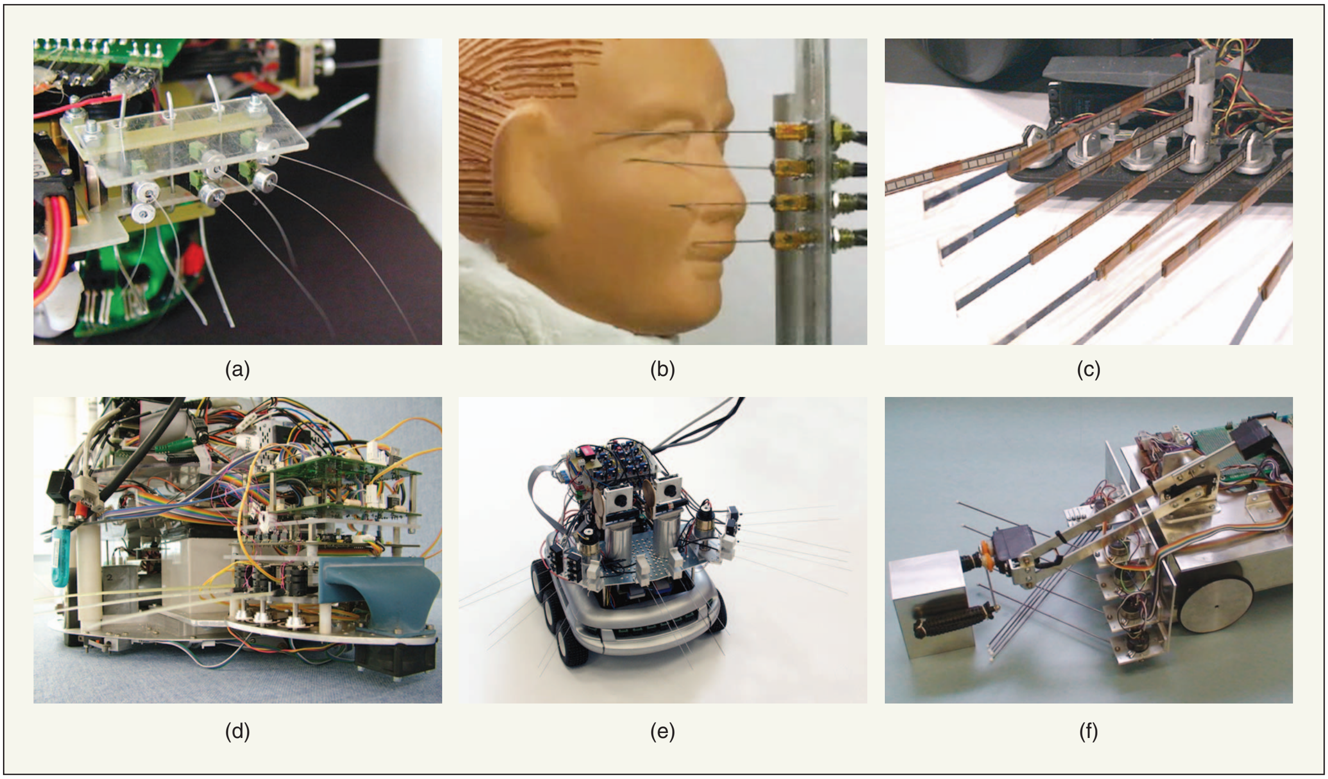


Figure 4. *Whisking robots. (a) aMouse [23] (with permission from R. Pfeifer). Real rat vibrissae were glued to electret microphones. Artificial neural networks and spectral analysis were used to process the resulting signals. (b) Whisking sensobot [27] (with permission from J. Solomon and M. Hartmann). This 4×1 active whisker array was used to extract radial object distance and measure 3-D object shape. (c) Detail from Darwin IX [26] (with permission from Acta Press and A. Seth). Whiskers detected deformation along their length unlike natural vibrissae; however, robot control employed computational neuroscience models. (d) Whiskerbot (UK) [30]. Outputs of these actuated whiskers were transduced by a model of the rat whisker follicle and primary afferent neurons. Behaviors included orienting to vibrissal-detected targets. (e) Whisking koala robot [21] (with permission from Elsevier and D. Kim). Two active arrays of steel whiskers were mounted in Hall-effect sensors and used to demonstrate shape and texture discrimination. (f) Whiskerbot (Australia) [20] (with permission from A. Russell). Rotating rigid steel wire whiskers were used to demonstrate object shape recognition.*

sensors will copy at least some of the morphological characteristics of rat whiskers; however, for sensors specialized for a specific task (e.g., distance detection), it might also be possible to choose shaft designs that are optimized for that single function (and thus differ considerably from the multipurpose solution seen in the rat).

Second, sensor transduction has used a variety of solutions. Transduction within the rat whisker follicle is poorly understood, although there now exists a simulation model of some of its mechanical properties [24]. Existing robot models have therefore sought to simulate the function of the follicle rather than its exact mechanisms. Some early robotic whisker implementations used potentiometers to measure the torque of steel whiskers as they made contact with surfaces [25]. More recent work has used electret microphones [23], resistive arrays [26], strain gauges [22], [27], piezoelectricity [28], and magnetic, Hall-effect sensors [21], [28]. Each of these technologies has advantages and disadvantages. For example, the electret microphone has high sensitivity to amplitude of whisker deflection but lacks the capacity to detect direction (a key property of the rat whisker follicle); strain gauges overcome this problem but are delicate, prone to noise, and difficult to miniaturize; piezoelectric sensors can be of small size but do not deliver a dc signal (thus cannot measure static deflections). Hall-effect sensors currently appear to be a useful option that can generate repeatable 2-D displacement vectors proportional to forces that are applied anywhere along the length of the artificial whisker shaft. They are also robust, lightweight, and reprogrammable (i.e., the sensitivity of the sensors to applied forces can be adjusted after initial fabrication).

Third, many of the artificial whisker systems constructed thus far have not been independently actuated or have been moved in a stereotyped and uniform fashion. Recent data, summarized earlier, has shown a much greater capacity for control of whisker movement in the rat than was first thought likely, including the possibility of differentially controlling individual whiskers. However, to actuate an artificial whisker system with all of the degrees of freedom of the rat vibrissae would be very challenging using existing motor technology, particularly, if a further aim was to match or come close to matching, the number of whiskers, speed of movement, and overall size of the rat model. In practice, most robotic whisker systems have actuated all the whiskers together or have separately actuated just the left and right sides. Drive systems have included miniaturized conventional electric motors and actuators with more musclelike properties such as shape-memory alloys [22] or air-muscles [29]. The ability of whiskered animals to actively modify their whisking patterns according to task and modulate instantaneous whisker movements using incoming sensory signals appears to be a hallmark of vibrissal sensing in the rat, and is therefore an issue toward which current research effort is directed (see the following).

Finally, only two of the artificial vibrissal systems investigated to date have interfaced physical sensors to signal-processing algorithms specifically modeled on biological neural systems. Seth et al. [26] provided artificial whisker input to a high-level brain-inspired model of cortical

Hall-effect sensors appear to be an useful option that can generate repeatable 2-D displacement vectors.

sensory-processing circuits to investigate the integration of input from multiple whiskers for texture discrimination learning. Pearson et al. [30] interfaced an active physical whisker model to an electromechanical model of the whisker follicle and primary afferent neurons [24], and thence to a robot-control architecture containing models of brainstem and midbrain neural-processing systems involved in whisker control and head/body positioning. An important element of the design of this platform was the use of different underlying

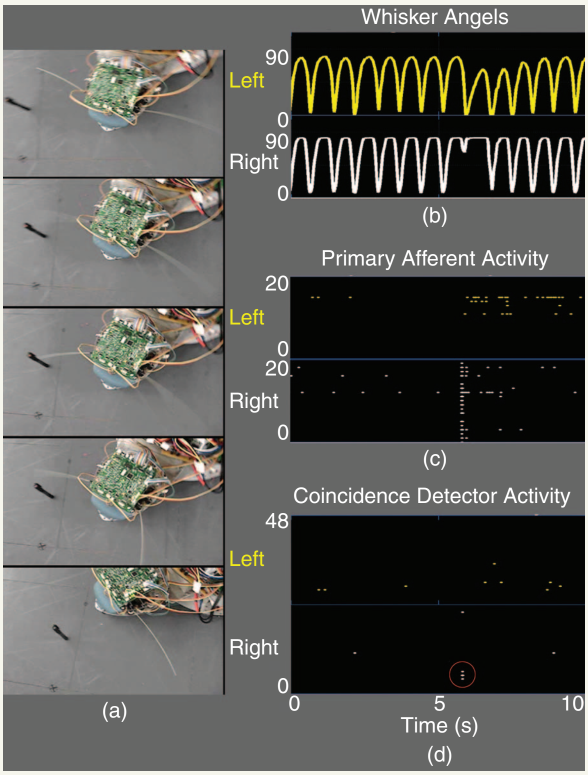
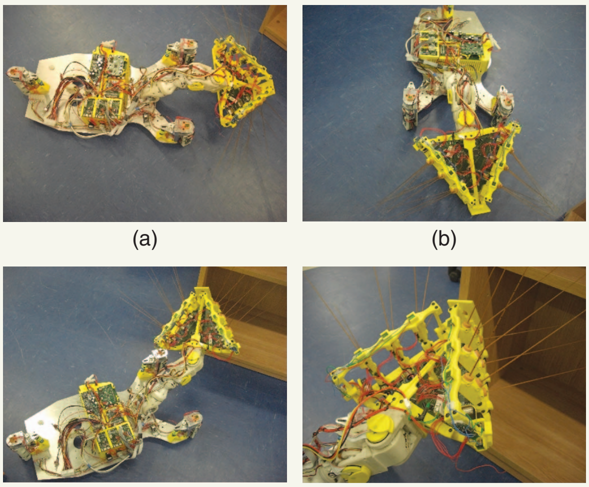


Figure 5. *Example of robot behavior controlled using biomimetic models of the rat vibrissal system. (a) Frames taken from a video recording of the Whiskerbot [30] platform during an experiment in which it whisks while moving across a smooth floor then encounters and orients to an object (an upright pen). (b) Trace of the angular position of the left and right whiskers over 10 s bridging the period of contact with the pen (at around 6 s). (c) Activity in two populations of model primary afferent cells (ten per whisker), activity for the right whisker population shows a sharp peak immediately after contact. (d) Activity in a population of 48 neurons in a model of the midbrain superior colliculus, which perform coincidence detection and triggers orienting.*

Some early robotic whisker implementations used potentiometers to measure the torque of steel whiskers as they made contact with surfaces.

processing hardware (PC, field programmable gate array, and digital signal processing) to implement spiking neurons and rate-coded neural network models of different system components; and the use of the brain and head modeling system (BRAHMS) process-control framework [31] to generate integrated real-time operation. The resulting system was shown to produce similar activity in some of its model neural circuits to that found in rat whisker-processing pathways, while performing ratlike whisker-guided behaviors such as orienting to a stimulus (see Figure 5).

In functional terms, previous work has provided proof of principle that artificial vibrissal systems can compute estimates of distance and shape [7], [21], [25], [27], [29] and can distinguish between textures with different spatial frequencies [28], [32]. These results demonstrate the potential for vibrissal sensors as effective devices for tactile object recognition. However, as Fox et al. [32] have shown, the capacity to perform effective classification in tasks such as texture discrimination is dependent on how whisker movement is controlled in relation to the target surface. Specifically, Fox et al. compared a range of feature-based classification methods on whisker-deflection time series data obtained using an actively controlled model macrovibrissae and a range of differently



(a) (b) (c) (d)

Figure 6. The SCRATCHbot robot. (a)–(d) This new platform has many more degrees of freedom for moving and positioning the whiskers than earlier whisking robots, including a three degree of freedom neck.

textured surfaces (grades of sandpaper). Their general finding was that discrimination was most effective when the whiskers were moved against the to-be-classified surfaces in a controlled and predetermined manner. When whisker-surface contact was not so constrained, classification beyond a simple rough/smooth discrimination became much more difficult. This result highlights the important contribution of active control to vibrissal sensing. Evidence from animal studies (e.g., [1]) suggests that rats do adopt task-specific whisking strategies that appear to assist them in extracting useful information from whisker-surface interactions. This result also demonstrates that effective decoding of surface properties from whisker-deflection signals may, in general, require knowledge of how the whiskers were moving before and during contact.

Next Steps in Vibrissal Active Touch

To conclude this article, we briefly describe how our own laboratories and those of our close collaborators are currently seeking to advance the capabilities of robot vibrissal touch systems, so as to reduce the discrepancies in performance between artificial vibrissal systems and their biological counterparts.

One project currently in progress at the Bristol Robotic Laboratory, in collaboration with the Active Touch Laboratory at the University of Sheffield and funded by the Framework Programme 6 ICEA project, is to develop a successor to the Whiskerbot platform [30] that has a larger vibrissal array and an enhanced capacity for precise control and positioning of the whiskers. The design of this new platform was inspired by the realization that one degree of freedom of whisker control together with the ability to translate or rotate the robot was rarely sufficient to make adequate whisker contact with all of the potentially interesting surfaces in the robot's laboratory environment. Observation of rats' exploratory behavior further convinced us that effective use of a vibrissal array requires that the robot can quickly and rapidly reposition the entire array through movements of the head and body so as to approach and explore salient objects from several angles. To this end, the new robotic platform, Scratchbot, shown in Figure 6, has a three degrees of freedom neck (pitch, yaw, and elevation control) that allows the robot to simulate the rat's ability to rapidly reorient the whiskers, and target them toward specific surfaces from different approach angles, and a body that is supported on three independent motor drive units, allowing near instantaneous movement in any direction. The robot snout supports left and right 3×3 arrays of macrovibrissae, with each vibrissal column actuated using a separate, miniature dc motor, thus allowing control of the angle of arc between the whisker columns. The macrovibrissal shafts are manufactured from a synthetic polymer molded to have taper, curvature, and material properties similar to those of rat whiskers, while scaled to the size of the robot (which is about $4\times$ that of an adult rat). Each whisker is mounted at its base in a Hall-effect sensor that detects deflection in two directions. An array of 24 short, non-actuated whiskers at the snout tip emulates the rat microvibrissae. Scratchbot inherits the hybrid multiprocessor system architecture of its predecessor (Whiskerbot) but will include

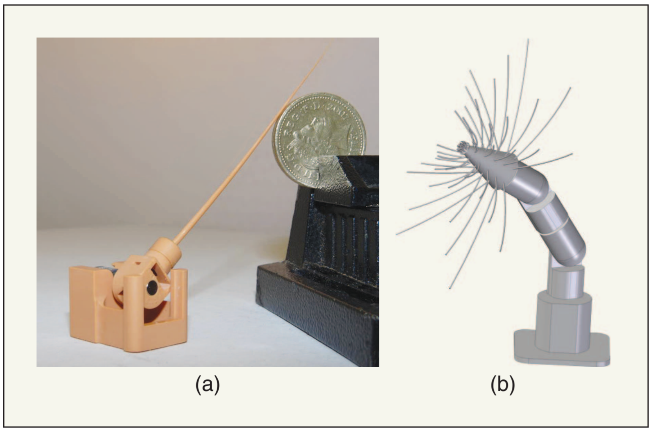


Figure 7. Design for a BIOTACT sensor. The BIOTACT project (http://www.biotact.org) is developing an active vibrissal sensing system based around (a) a modular active whisker unit that can be assembled into different configurations such as (b) the radial array illustrated here.

additional biomimetic components, modeled on the sensory cortex, hippocampus, and basal ganglia [31], for extracting tactile features and constructing tactile maps of the environment to support self-localization and navigation behaviors.

In a further development, we have recently started a four-year research project involving nine partners in seven countries, funded by the European Union Framework Programme 7, to develop novel biomimetic technologies for vibrissal active touch (BIOTACT). This project, which contains interwoven research strands on biomimetic robotics, the neurobiology of the rat and shrew vibrissal systems, and computational neuroscience modeling, seeks to develop a novel, modular vibrissal sensing unit [see Figure 7(a)] that can been assembled into different multiwhisker configurations. One possible configuration of these modular elements could be as the radially symmetric vibrissal array shown in Figure 7(b), which is currently under construction. The prototype whisker module shown in Figure 7(a) contains a miniature geared brushless dc motor that drives the movement of the artificial whisker shaft; whisker deflection is defected by a Hall-effect sensor fitted at the front of the rotor assembly. A miniature flexible PCB, containing all driver and interfacing electronics, will be wrapped around the housing. The completed assembly will fit within a volume of $15 \times 15 \times 20$ mm^3.

An important aim of BIOTACT is to demonstrate the potential of artificial vibrissal sensing for a range of different tasks settings, including industry-relevant problems such as object sorting and mobile robotic applications such as navigation in visually occluded environments, such as smoke- or dust-filled buildings. The project is also seeking to devise biomimetic algorithms for the control of whisker movement and processing of vibrissal signals. For instance, models of the brainstem and midbrain motor loops [see Figure 3(b)] are currently under development, as are models of feature extraction in barrel cortex and of the role the cerebellum in noise cancellation. More generally, the wider goal of this project will be to bring about a step change in the understanding of active vibrissal touch sensing and promote greater use of whiskerlike sensors in intelligent machines.

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Keywords

Control architectures and programming, biologically inspired robots, biomimetics, neurorobotics, force and tactile sensing.

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