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SCRATCHbot: Active tactile sensing in a whiskered mobile robot

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Abstract. The rodent vibrissal (whisker) system is one of the most widely investigated model sensory systems in neuroscience owing to its discrete organisation from the sensory apparatus (the whisker shaft) all the way to the sensory cortex, its ease of manipulation, and its presence in common laboratory animals. Neurobiology shows us that the brain nuclei and circuits that process vibrissal touch signals, and that control the positioning and movement of the whiskers, form a neural architecture that is a good model of how the mammalian brain, in general, coordinates sensing with action. In this paper we describe SCRATCHbot, a biomimetic robot based on the rat whisker system, and show how this robot is providing insight into the operation of neural systems underlying vibrissal control, and is helping us to understand the active sensing strategies that animals employ in order to boost the quality and quantity of information provided by their sensory organs.

1 Introduction

In order to cope with nocturnal or poorly-lit environments mammals have evolved a range of non-visual sensory capacities many of which have not been successfully replicated in robots. One such capacity is the tactile hair (vibrissal) sensory system [1] [2]. Tactile hairs are found in all mammals, except for man, and are highly developed in many rodent species (such as rats and mice) and in a variety of aquatic mammals such as seal, walruses, and manatees. Research interest has centred on the facial vibrissae, or whiskers, and our own research has focused on the vibrissae of murid rodents such as rats and mice.

Our approach to this system begins with neuroethology, wherein we study vibrissal neural systems holistically, including the observation of natural behaviour as well as comparative and evolutionary data, and leading to computational models. We then expose these models to the complexities of real-world operation, and the demands of functional robotics, revealing shortcomings that do not manifest in simulation. This engineering process feeds back, raising questions that are not raised (or addressed) by current biological data, and guiding us in the design of future biological experiments. Along the way, we hope to show that whiskers can be a useful robotic sensory system.

Below, we briefly review the ethology of rat whisking behaviour, including results from behavioural experiments conducted in our own laboratory. We then go on to describe our current whiskered robotic platform, SCRATCHbot (the robot name is derived from the acronym Spatial Cognition and Representation through Active TouCH). In this paper we focus on the active sensing and whisker control aspects of the SCRATCHbot platform in comparison to the whisking behaviour of rodents. Some of our recent work on tactile sensing and discrimination using artificial whiskers is described in a companion paper [3], and therefore is not discussed in any detail here. Our work builds on, and was inspired by, a large number of previous research efforts in robotic tactile sensing systems that we have recently reviewed in [1]. SCRATCHbot also replaces and improves on our own earlier whiskered robot, Whiskerbot [6], which was simpler in both mechanical and control terms.

2 Neuroethology of the rat whisking behaviour

The whiskers of murid rodents are of two types. The ‘macrovibrissae’ form two regular grids of longer whiskers (approximately 30 per side) emerging from the ‘mystacial pads’ on either side of the snout and can be moved back and forth in a behaviour known as ‘whisking’. The ’microvibrissae’ are shorter, non-actuated whiskers, that are distributed over the front and underside of the snout in a less regular pattern. Rats generally whisk their macrovibrissae when they are exploring an environment or attempting most forms of tactile discrimination. In neurobiological investigations of this system studies of neural responses to ‘passive’ whisker deflection are therefore beginning to give way to studies of more natural ‘active’ deflection where moving whiskers encounter objects in the world. These studies show that whisker motion plays a key role in signal formation within the brain, hence one of our main goals in developing SCRATCHbot is to get better insight into the effects of this *active sensing* control on the signals processed by the vibrissal system.

Macrovibrissal movements are driven by a complex musculature. This includes intrinsic muscles within the pad, that allow for some individual control of whisker motion, and extrinsic muscles that move all of the whiskers in the pad together or that alter the relative positions of the whiskers by changing the shape of the pad. The principal, and first-described, component of whisker motion is the anterior-posterior (AP) movement of all macrovibrissae together. A smaller synchronised up-down component to this motion has been identified (that is, a typical whisk is reminiscent of a ‘rowing’ action), as has a torsional rotation of the shaft during the whisk cycle. Furthermore, the whisker columns move at somewhat difference speeds during the AP sweeps with the net effect that the angular separation, or spread, between the whiskers varies significantly within each whisk cycle. Finally, the whiskers do not always move in concert on the two sides of the face, and the mystacial pad moves substantially during whisking.

Nonetheless, AP motion of all whiskers together describes a large proportion of overall whisker motion [5].

Whisking motor patterns vary substantially with behavioural circumstance, but discernable 'bouts' of more-or-less periodic whisking at 6-10Hz interspersed by periods of inactivity, are typical. Whisk frequency tends to be relatively constant within a bout but other kinematic parameters can vary substantially. The strongest observed external influence is whisker-environment contact. For instance, a unilateral unexpected whisker-environment contact generally leads to suppression of protraction ipsilaterally (i.e. on the side the contact was made) and to increased protraction amplitude contralaterally [4] [5] (see figure 1 left). We have hypothesised that this is the outcome of a control policy we term 'Minimal Impingement, Maximal Contact' (MIMC), which tends to maximise the count of whisker-environment contacts, whilst keeping the depth of those contacts within a managed range to maintain signal quality. A further observation [5] that spread between whisker columns is reduced during environmental contact is consistent with this policy, with rearward, non-contacting, whiskers brought forward to meet an ipsilateral obstruction. In addition to these asymmetries, a temporary loss of bilateral synchrony in whisker movements is often observed following a unilateral contact [4], whilst repeated contacts with the environment can lead to longer periods of desychronization (unpublished results from our laboratory).

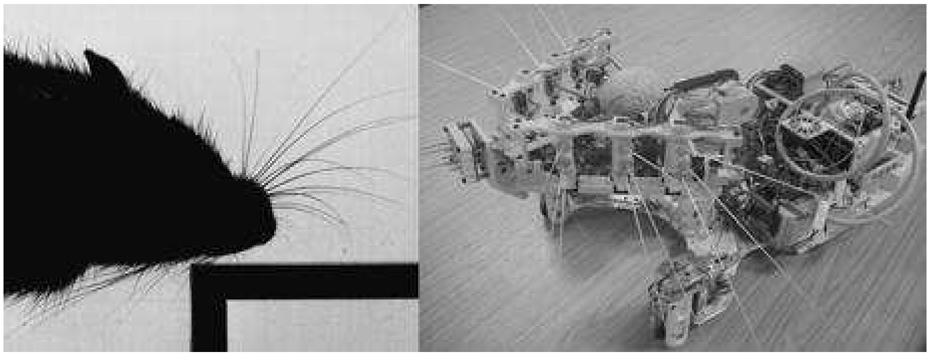

Fig. 1. Natural and artificial vibrissal systems. *Left.* Frame from a high-speed video sequence recorded in our laboratory, showing an exploring rat with whiskers at the maximum protraction phase of the whisk cycle, but with the whiskers ipsilateral to an object of interest held back towards the cheek, whilst the contralateral whisker field pushes forward towards the surface. Electromyograph recordings from the whisking muscles confirm that the contralateral whiskers are driven significantly harder than the ipsilateral ones [4]. *Right.* The SCRATCHbot robot platform has two 3x3 arrays of actuated whiskers and a single central array of non-actuated microvibrissae. Control uses biomimetic algorithms based on reverse-engineering of rat neural systems for vibrissal sensory processing and actuation in order to generate life-like active sensing behaviours.

Psychophysical and behavioural experiments (see [8] for review) show that, using only the data gathered by their macrovibrissae, rats can locate objects accurately in space, perform fine textural discriminations, and judge gap widths, and that both macro- and micro- vibrissae are required for effective prey capture. However, a reasonable hypothesis is that macrovibrissae are primarily used for locating objects, and then microvibrissae are brought to bear for close investigation. As a consequence of these findings, and from inspecting many in-house video recordings of rats exploring environments, we consider the 'orient' behaviour, in which a rat positions its head so that the front of its snout is brought to bear on its apparent focus of attention, to be a key component of active sensing. Indeed, orienting should perhaps be considered as the primary active sensing strategy employed by the animal, with repetitive whisker motion (whisking) adding a second component that allows better exploration of space, increased frequency of contact, and more precise control over the nature of those contacts. If we allow that the body must also be moved if the rat is to orient its snout to locations a little distance away, then we could consider that locomotion of a rat in a novel environment may be largely the consequence of a stream of orients to one location after another. That is, the rat shifts its focus of attention and the head, whiskers, and body follow. Thus, we might consider orienting to constitute the foundation of exploratory behaviour in general, and therefore to be a prerequisite for effective active sensing in any whiskered entity, animal or robot.

After orienting, the animal will often keep its snout near to an attended object for a few whisks in order to investigate it more closely using the sensory equipment around the snout. This activity can be complex, and is thus less easy to describe, but we often see an investigative behaviour we refer to as 'dabbing', whereby the microvibrissae are lightly touched or brushed against the object in synchrony with macrovibrissal protractions. The result is that tactile information is obtained at high spatial density towards the centre of the dab, through the microvibrissal array, whilst, within the same narrow time window, surrounding surfaces are sampled in a sparser fashion by the macrovibrissae.

3 Towards a robot model of vibrissal active sensing

Based on the experimental data reviewed above, we have identified a number of specific co-ordinated motor actions as pre-requisites for effective active vibrissal sensing. Next we briefly describe the robot hardware and software architecture that we have developed to support this active sensing control.

3.1 Hardware

The SCRATCHbot platform (see figure 1 right) is built from 3 main components: a head, on to which the whisker arrays are mounted; a neck, that allows the head to be moved in 3d and independently from the body; and a body that carries the computing resources, locomotion systems, and power supply.

The head is designed to carry six independent columns of three 'macrovibrissae', with each column driven in a single axis (anterior-posterior) by a small dc motor and gearbox. These columns are arranged into two arrays of three, projecting from opposing sides of the head chassis, and coupled for a second axis of rotation (array tilt). A third, non-actuated, 'microvibrissal' array of nine short whiskers is mounted between the bi-lateral active arrays. The cross-sections of the macrovibrissae are tapered toward the tip and their lengths (160 - 220mm) are approximately four times larger than the long whiskers of a typical adult rat. To measure deflections of the whisker shaft caused by environmental contact a small magnet is bonded to the base of each whisker and a Hall effect sensor used to sample the displacements of the magnet in two directions. To maintain the pose of each whisker, and to return it to its resting angle after deflection, the whisker base is mounted into a polyurethane rubber plug. The non-actuated whiskers (microvibrissae) have the same transduction technology and polymer return mechanism but are shorter (80mm) and mounted into a single polyurethane casting. Dedicated microcontrollers are used to sample the different whisker arrays and to control the rotation of the whisker columns. The neck component enables the head to be moved with three degrees of freedom: elevation, pitch and yaw, each axis actuated by a brush-less dc motor and harmonic drive gearbox, and controlled using a PID micro-controller. The robot chassis is a single sheet of aluminium onto which three independently-controlled motor drive units and the neck are mounted. The central computing resources consist of a PC-104+ reconfigurable computing platform, composed of a single board Computer and a closely coupled array of FPGAs for hardware accelerated processing.

3.2 Processing architecture

The control architecture implemented on the robot takes inspiration from the neural pathways identified in the rat whisker sensory system [1] [2]. Neural structures such as the trigeminal sensory complex, superior colliculus and basal ganglia are modelled and developed in software, at various levels of modelling abstraction, and integrated into a unified system for testing using the BRain And Head Modelling System (BRAHMS) execution framework [7]. To allow independent development of robot hardware and software neural models, a platform simulator has been written which can be inserted into the BRAHMS system in place of the robot interface. Figure 2 is a block diagram of the components that make up the current processing architecture. At the bottom left is the interface to the hardware consisting of the sensors (x, y, θ) and actuators (whiskers, wheels, neck). The remainder of the architecture can be described as an inner loop (blue arrow) mediating whisking pattern modulation, and a middle loop (green arrow) mediating the orient to point of contact behaviour described below. Higher loops (orange arrow) model cortical and hippocampal systems, for such competences as object discrimination and spatial mapping, are the subject of current work in our laboratory.

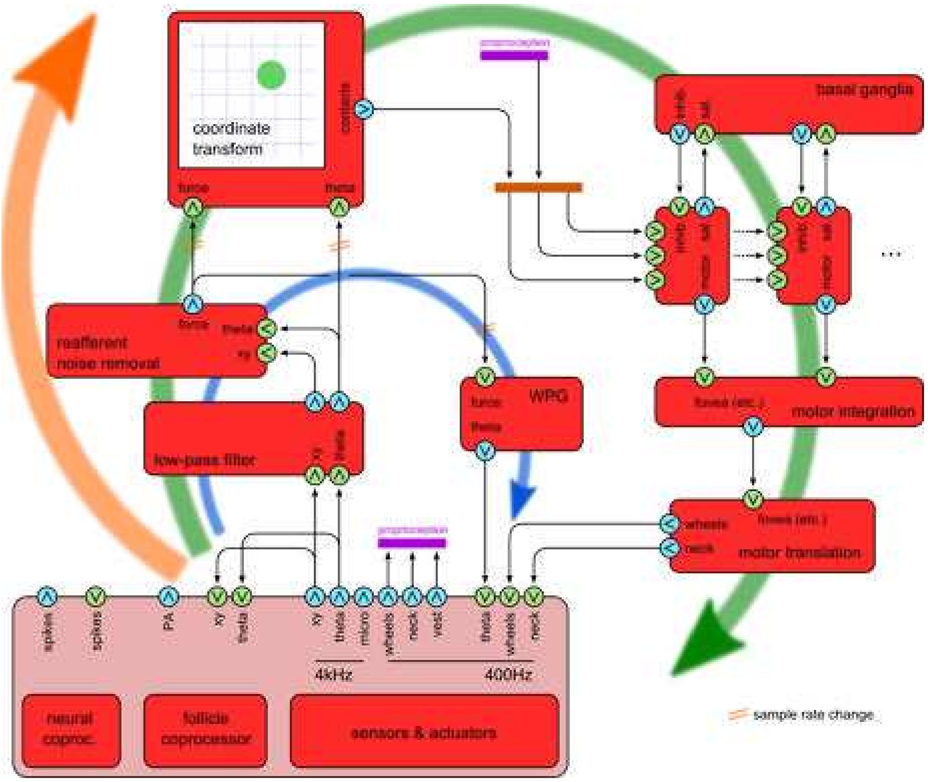

Fig. 2. Overview of control architecture of SCRATCHbot. Arrows indicate control loops within our model whisker sensory system that correspond to current understanding of the real sensory system. See text for details.

4 Active sensing behaviour

In this section we describe some of the active sensing control strategies that we have so far implemented and tested on the robot platform. For details of recent and ongoing work on tactile sensory processing please see [11] [3].

4.1 Feedback modulated whisking pattern generation

The Whisking Pattern Generator (WPG) in SCRATCHbot is a model of the central pattern generator present, though not yet located, in the rat brain and whose activity underlies the rhythmic whisker motions observed in the behaving animal. Typical rat whisking, as described above, can be broadly described as modulated periodic oscillations. The simplest possible model is a single oscillator generating the angular position of each separate whisker through a gain. In such a model, the whiskers would be constrained to move synchronously (all whiskers in phase), symmetrically (whisking on the two sides having the same profile), and periodically (each whisking cycle is identical). However, as previously noted, although bilaterally synchonized and symmetric movements are sometimes observed in the animal, this simple model is inadequate to describe rat whisking generated under natural circumstance of exploration and object contact. Therefore, in our robotic models, we gradually relax these constraints by testing more complex MPG models in order to investigate the impact of different modulation strategies. For instance, in our original whisking robot (Whiskerbot) we used a single WPG to generate a base whisking signal and derived movement patterns for each whisker using this signal. This WPG model was used to test the likely consequences of a Minimal Impingement (MI) control strategy on the whisker deflection signals processed in the brain. As noted previously, our own behavioural observations in animals had indicated that whiskers rapidly cease to protract following contact with an object during exploration. We hypothesized that this result implied a control strategy that sought to minimize the extent to which whiskers were allowed to bend against surfaces. To implement MI in our robot control architecture the total activity across all whisker deflection cells on one side of the face was fed back to suppress activity in the ipsilateral WPG relay. This has the desired effect that protraction ceased rapidly after contact. With MI enabled, the signals were also cleaner and more closely matched those observed in the animal [6].

Predictable variation in whisker spread (the angular separation between the whiskers) was noted previously as a characteristic of animals that are exploring surfaces [5]. To investigate the possible causes of this variability we extended the modulation options of SCRATCHbot's WPG by implementing a separate relay for each column (rather than having just one for each side of the head). Whisker-environment contact excites all of these relays, whilst suppressing only those relays driving the whiskers that contacted the environment. The result is that, in addition to the per-side MIMC elicited in Whiskerbot, more rearward whiskers move more rapidly than they would otherwise, and are thus brought forward to meet a contacted obstacle. The net result is a reduction in inter-column spread following contact as seen in the animal. Another way of putting this, is that, by implementing MIMC at the per-column level, 'control' of whisker spread appears as an automatic consequence of this general active sensing strategy - the whiskers are brought forward to meet the environment wherever possible, whilst being restrained from bending too far against it. In experiments with SCRATCHbot platform (see Figure 3) we have been able to demonstrate that per-column MIMC is effective in cleaning up contacts on multiple whiskers and in generating more contacts than would otherwise have occurred.

Bilaterally asynchronous whisker movements are sometimes observed in animals, particularly following, or during, interactions with surfaces. Ongoing ethological experiments in our laboratory are seeking to quantify these effects, meanwhile we have developed a model of whisking control for SCRATCHbot based on separate left and right WPGs in which we can investigate hypotheses about the nature of the coupling between the pattern generators for the two sides of the snout.

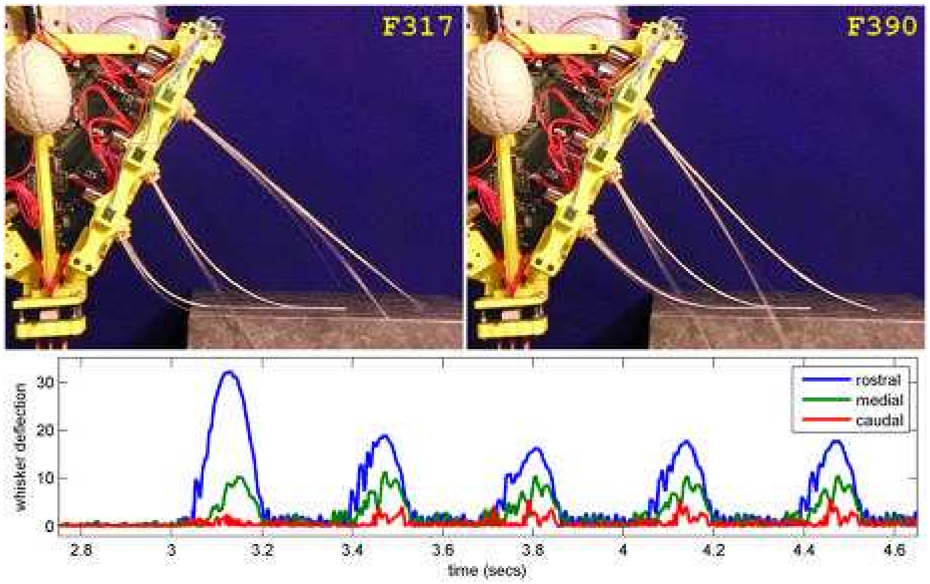

Fig. 3. Investigating the impact of per-column MIMC on whisking patterns. For this experiment we fixed the robot head in a position facing a stationary 'wall'. The first whisk against the wall is unmodulated (left upper panel), and shows that the more rostral column whiskers are heavily deflected, whilst the most caudal column whiskers do not touch the wall at all. On the second whisk, the MIMC modulation has taken effect (right upper panel), the rostral whiskers are less protracted and thus are deflected less heavily, and the caudal whiskers are brought forward (i.e. whisker 'spread' is reduced) and generate contacts with the wall. The effect of this modulation on the contact signals collected can be seen in the lower panel – across the three columns, there is a tendency towards normalisation of contact depth.

4.2 Orienting to point of contact

The tendency of rats to direct their snout and micro-vibrissal array toward unexpected macrovibrissal contacts was chosen as a second behaviour suitable for investigation by physical modelling. For this purpose our control system implements the hypothesis that a region of the mammalian brain known as the superior colliculus (SC) is used by the rat to control orienting to tactile stimuli [9]. A model SC was designed, implemented in software, and integrated into the BRAHMS processing framework for demonstration on SCRATCHbot.

There is no evidence of proprioception in the whisker musculature, instead, angle cells innervating the follicle are thought to provide the information necessary to transform deflections of moving whiskers into an appropriate head-centred reference frame. Our robotic model therefore integrates whisker deflection information (from the Hall effect sensors) with shaft encoding of whisker column angles in order to map environmental contacts onto a 3-D representation of the space surrounding the robots head. The most salient contact point then primes a request for an appropriate series of orienting motor commands that move the tip of the snout to that position. The request to perform orienting competes with other salient behaviours for control of the motor plant. This competition is resolved using an action selection mechanism modelled on a group of brain structures known as the basal ganglia [10].

A key task for the motor system is to generate control signals for the wheels and neck that achieve the desired snout movement; this takes place in the Motor Translation Layer of our control architecture. Conventional robotic approaches to this problem (e.g. potential-field or sampling-based) can be expensive to solve, and are not generally bioplausible. We use, instead, an algorithm we call 'Snake', which takes a bio-inspired approach, causing free (uncontrolled) nodes of the mechanics adjacent to a controlled node (the snout, in this case) to follow it. Thus, actuators are 'recruited' to contribute to the movement in a distal-first pattern, as has been seen in the animal during fictive orienting, and more massy central nodes tend to be moved less than lightweight peripheral nodes. This algorithm results in motion that appears quite natural to the human observer.

Figure 4 shows video stills from a typical robot experiment demonstrating the orient to contact response. Implementing this task for our whiskered robot provided insight into some additional problems that the rat must also encounter and has overcome through the mechanisms of evolution and neural plasticity. Specifically, it was evident that there is a significant noise component in the whisker deflection signals that is due to self-motion (i.e. caused by the whisking and head movements) and can cause the robot to make orients to ghost objects that are not actually present. This motivated us to look for brain structures that might function to remove this noise, a prime candidate being the cerebellum. Interestingly, the cerebellar-inspired algorithms that we have implemented to successfully remove this re-afferent noise [12] essentially learn the dynamics of each whisker as it is moved. Therefore, if a whisker shaft were to be damaged or replaced, the new dynamics would be acquired and integrated into the control system without the need for manual calibration. This tolerance to damage of individual whiskers and the gradual degradation in performance afforded by an array-based system could provide significant advantages to platforms operating over long periods or in remote environments.

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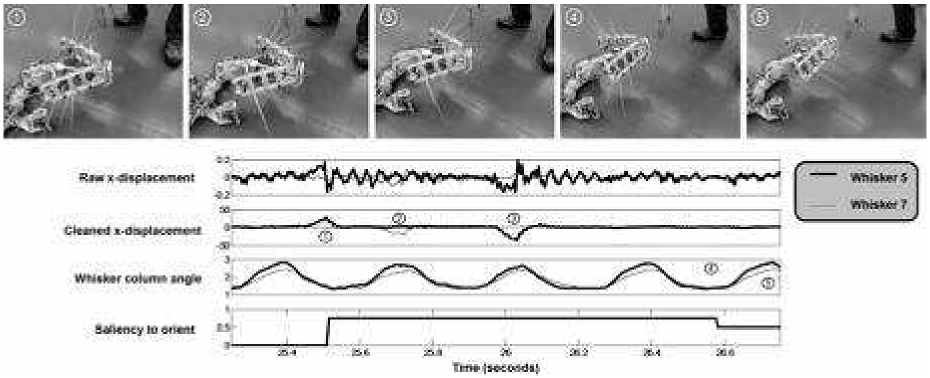

Fig. 4. Frames taken during an orient towards a point of whisker contact, along with plots of data recorded during the run. The upper plot shows the unfiltered x-component output from two whiskers on the left side of the robot (normalised to the maximum calibration range). The second plot has the re-afferent component of these signals removed, greatly improving the signal-to-noise ratio. The third plot displays the current angular position of the rear 2 whisker columns, π radians indicating straight ahead. The lower plot shows the saliency of the emphorient behaviour. Frame 1: contact on whisker 5 during retraction leads to an increase in saliency of *orient*; this action is selected, and the orient begins. Additional contacts during the orient (frames 2 and 3) are ignored. In frame 4 the snout arrives at the initial point of whisker contact, completing the orient, and saliency is reduced. In frame 5 the micro-vibrissae are used for fine inspection of the contacted feature.

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