Towards biomimetic vibrissal tactile sensing for robot exploration, navigation, and object recognition in hazardous environments

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Abstract. Arrays of actuated, whisker-like tactile sensors could prove useful for the guidance and control of robots in hazardous environments, particularly where the effectiveness of conventional vision sensors is compromised. This paper summarises recent research on biomimetic vibrissal sensing arrays for mobile robots, focusing on the design of the SCRATCHbot whiskered robot platform, and on progress towards algorithms for tactile object detection and recognition, and for robot navigation using vibrissal signals.

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 mainly focused on the facial vibrissae, or *whiskers*. In rodents (such as the rat shown in figure 1) there are two arrays of long facial whiskers surrounding the snout, that endow these animals with the capacity for short-range, but high-speed tactile object detection and recognition. Rodents can also use their vibrissae to navigate and locomote on difficult terrain in the absence of light. A similar sensory capacity in mobile robots could lead to increased versatility and performance in hazardous environments, such as smoke- or dust-filled buildings, or where covert operation in darkness is required. Borrowing inspiration from marine mammals, similar systems might also find applications in aquatic environments particularly in muddy or turgid water.

Bristol Robotics Laboratory, in partnership with the Active Touch Laboratory in Sheffield, have been working on the development of artificial vibrissal systems for robots since 2003. Our latest mobile robot platform, *SCRATCHbot* (see figure 2), has bilateral arrays of 3x3 artificial vibrissae with multiple degrees of freedom of control in the head and whisker-positioning systems, that allow us to orient the vibrissae towards nearby objects or surfaces, and obtain good information sampling rates by rapid forward and backward movement of the vibrissal shafts ("whisking"). We are also developing a modular, actuated artificial vibrissal sensor that can be assembled into different multi-whisker configurations.

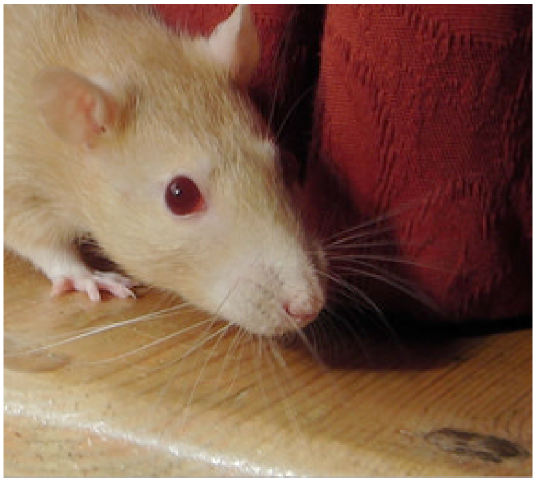

Figure 1. The vibrissal system of the rat consists of bilateral arrays of 30+ actuated whiskers.

Current work is directed towards testing the utility of vibrissal sensing for tactile-guided exploration and mapping of indoor environments. A longer-term goal is to show that these systems could be useful for the guidance of robot locomotion and control in less-constrained and higher-risk settings. In the remainder of this paper we briefly describe the current status of three main strands of work: (i) the design and function of the SCRATCHbot whiskered robot, (ii) the development of pattern recognition systems for vibrissal signals, and (iii) initial progress towards a biomimetic tactile spatial navigation system.

SCRATCHbot (Spatial Cognition and Representation through Active TouCH robot)

The specification for our current whiskered robot platform was developed through experiments and observations of laboratory rats [1, 2, 3] aimed at understanding how these animals control the movements of their whiskers, and at discovering what sorts of behavioural tasks vibrissal information may be useful for.

Two specific co-ordinated motor actions were identified as pre-requisites for effective active vibrissal sensing: (i) the generation of bouts of rapid whisker movement that can be mediated by environmental contact [2], and (ii) the ability to quickly and accurately reposition the head so as to orient the whisker array towards objects of interest. To support these behaviours (as well as others) the robot platform (see figure 2) was built from 3 main components: a head, on to which the whisker arrays would be mounted; a body, to carry the computing resources, locomotion and power supply; and a neck, to allow the head to be moved independently from the body. Each of these components are described in more detail next.

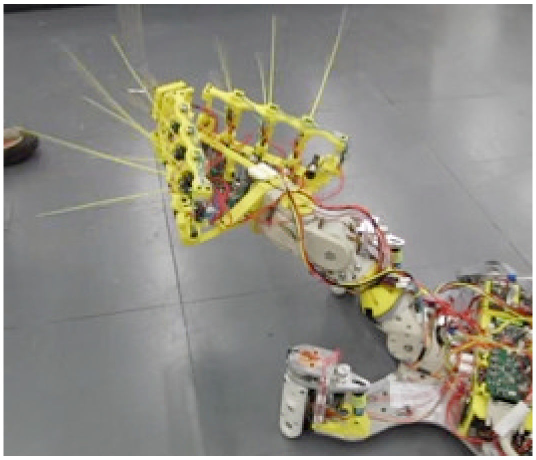

Figure 2. The SCRATCHbot robot platform has two 3x3 array of actuated whiskers on a 3-DOF head. Control uses biomimetic algorithms based on reverse-engineering of rat neural systems for vibrissal sensory processing and actuation.

Head

The head was designed to carry six independent columns of three whiskers, each driven in a single axis (anterior-posterior) by a small dc motor and gearbox. The whisker columns are arranged into two arrays of three columns, each array projecting from opposing sides of the head chassis, and coupled for a second axis of rotation (array tilt). A third, non-actuated, array of nine short whiskers is mounted between the bi-lateral active arrays. The non-actuated array is analogous to the shorter, but high density, *microvibrissal* array found on the chin and lips of the rat, and the actuated bilateral arrays to the longer *macrovibrissae* which emerge from the cheeks (mystacial pads) of the animal. The macrovibrissae on the platform were built from ABS plastic using a rapid prototyping machine. The cross-sections of the whiskers are tapered toward the tip and their lengths (160 - 220mm) are approximately four times larger than the macrovibrissae of a typical adult rat. To measure deflections of the whisker shaft caused by contact with the environment a small magnet is bonded to the base of each whisker and a tri-axis Hall effect sensor IC used to sample the displacements of the magnet in two axes. To maintain the pose of each whisker, and to return it to its resting angle after deflection, the whisker base is mounted into a small plug of polyurethane rubber. The non-actuated whiskers (microvibrissae) have the same transduction technology and polymer return mechanism, however, the whisker shafts are shorter (approximately 80mm) and mounted into a single casting of polyurethane.

Each of the bilateral arrays of macrovibrissae have an associated microcontroller to sample all nine whiskers and to control the rotation of the three columns and the tilt angle of the array (using separate software PID position controllers for each of these). The sensory information from each array is passed to the main computing resources of the platform, located on the body, via serial buses through which are returned the desired angles of each of the controlled axes. Another microcontroller marshals the sensory information from the microvibrissal array and a third bridges output from a three-axis accelerometer, mounted on the tip of the snout, to the platform-wide CAN bus.

Neck

The neck component was designed and built by an external robotics sub-contractor [4] to enable the head to be moved with three degrees of freedom—elevation, pitch and yaw. Each axis is actuated by a brush-less dc motor and harmonic drive gearbox, and is controlled using a micro-controller based PID position controller coupled to the platform CAN bus. Desired angles for each axis are broadcast to the CAN bus at regular intervals from the central computing resources of the platform.

Body

The main chassis of the platform is a single sheet of aluminium onto which the motor drive units and neck are mounted. Each of the three motor drive units are independently controlled and can steer through +/-90 degrees from straight ahead. The desired speed and direction of each motor drive unit are broadcast onto the platform wide CAN bus at regular intervals, and the power supply for the platform can be either from Lithium Polymer batteries or 240VAC mains. The central computing resources consist of a PC-104+ reconfigurable computing platform, composed of a Single Board Computer (SBC) and a closely coupled array of FPGAs for hardware accelerated processing.

Processing architecture

The processing architecture implemented on the robot takes inspiration from the neural pathways identified in the rat whisker sensory system [1, 2, 5]. 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 [5, 6]. A BRAHMS process within this architecture acts as the interface to the hardware of the robot through which sensory information is made available and motor commands are sent. Function calls from the platform API within this process communicate with the FPGA bridge and thus act as the real-time regulator to the software BRAHMS system. 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 3 is a block diagram of the components that make up the current processing architecture. The arrows indicate control loops within our model whisker sensory system [5] which correspond to current understanding of the real sensory system [1, 2]. The blue arrow indicates the control of whisking whilst the green arrow shows the control loop for the 'orient to point of contact' behaviour described in the next section. The orange arrow highlights one of the directions for future work, namely, cortical modelling and the development of tactile spatial mapping.

Orient to point of contact

Through observation of rat behaviour [1, 3] the tendency of rats to direct their snout and micro-vibrissal array toward unexpected macrovibrissal contacts was chosen as a behaviour that was suitable for investigation by physical modelling. 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 [7]. A model SC was designed, implemented in software, and integrated into the BRAHMS processing framework for demonstration on the SCRATCHbot platform. This model 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 robot's 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* that are thought to implement a form of centralised switch [8].

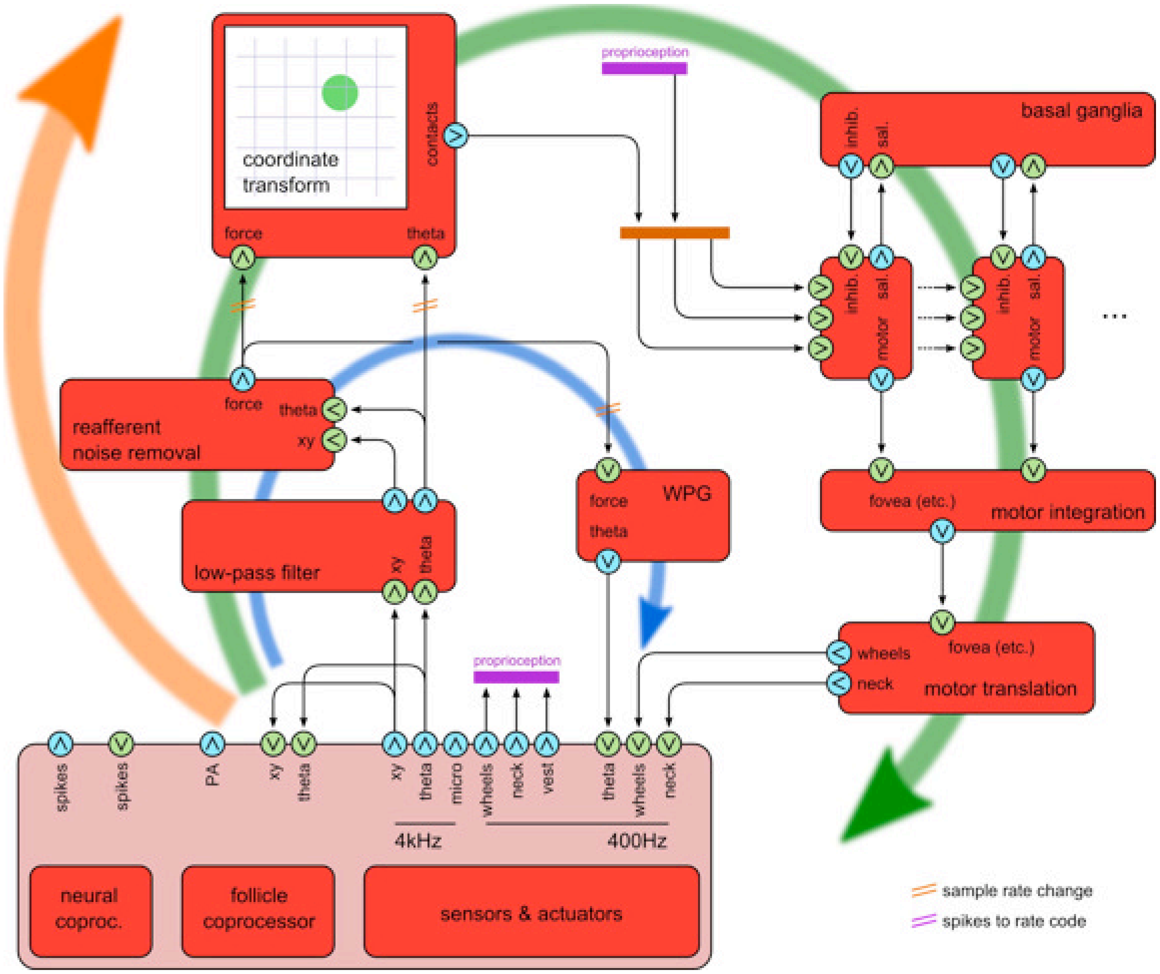

Figure 3. Block diagram of the current processing architecture of the SCRATCHbot platform. Each red block indicates a separate BRAHMS process, with inputs as green circles and outputs as blue. The coloured arrows indicate the two control loops that have been built to date—whisking control (blue) and orient to contact (green); the orange arrow indicates planned future developments.

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 self-motion (i.e. 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 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 in remote or hostile environments. Clearly, the SCRATCHbot platform itself would be inappropriate for such applications, however, our novel vibrissal sensor technology could be applied to future, more robust, land- or submarine-based vehicles.

Vibrissal pattern recognition for tactile object discrimination

Vibrissal object recognition must begin with low-level tactile feature discrimination. When an object contacts a whisker, that particular contact may carry information about a number of object properties such as its speed and direction of movement, distance from the base of the shaft, as well as the object's surface orientation and texture. Discriminating these lower level features is key to building up higher-level perceptions of objects and environments.

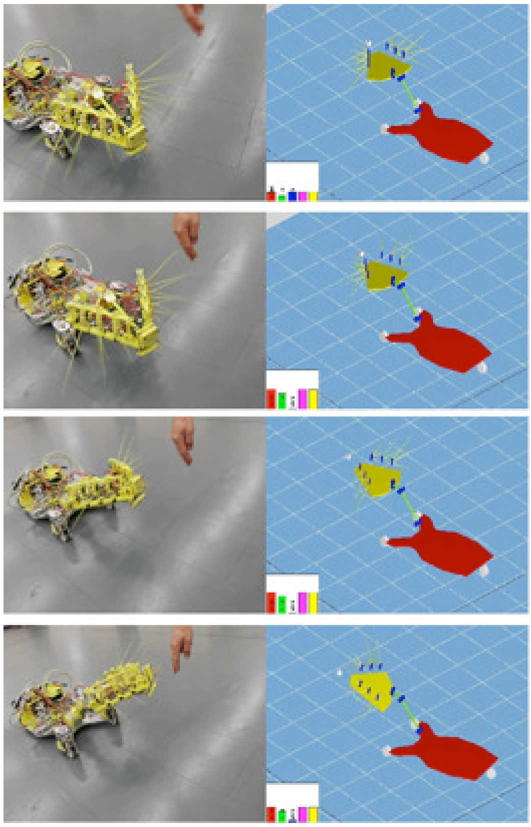

Figure 4. A sequence of video frames from an experimental run of the SCRATCHbot platform demonstrating an autonomous orient toward a point of contact made by the active macrovibrissal array. The animations to the right of the video frames were constructed using odometry collected during the live run. The coloured bars in the lower left corner of the animation indicate the current level of inhibition projecting to each of the robot behaviours currently competing for control of the motors. In this example, the upper whisker of the rear column makes contact with an unexpected obstacle. The orient response competes for, and wins, control of the motor plant. A series of motor commands are then issued which brings the tip of the robot snout (the microvibrissal array) to the point of contact.

In previous work with mobile robot platforms [9, 10] we have demonstrated that actively-controlled vibrissal sensors can discriminate different texture types (e.g. grades of sandpaper). However, more rigorous investigation of tactile pattern recognition calls for precise control of the whisker-object interaction. To this end we have built a 2-DOF robotic positioning system (see figure 5) that allows us to present objects to a SCRATCHbot vibrissal array in a very accurate and repeatable manner. In initial experiments, using this setup, we have presented a straight-sided object to a single vibrissal sensor at a range of radii, speeds, and orientations. These investigations have demonstrated that deflection signals from the Hall effect sensor at the whisker base are sufficiently transparent to be used as inputs to a classifier without any pre-processing. For instance, after presenting 900 unique deflections a template-based nearest-neighbour classifier is capable of 90% accuracy in distinguishing radial distance to contact, and the speed and orientation of the object, for contacts that are at least 5mm in from the whisker tip.

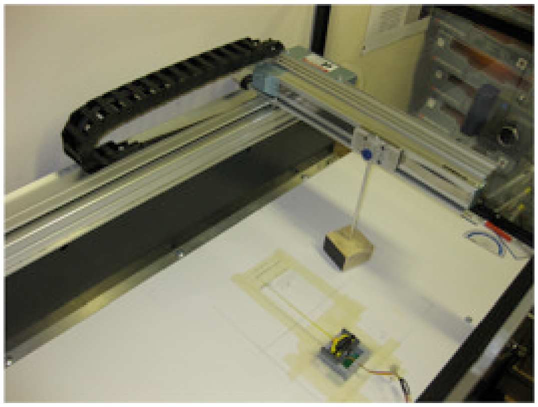

Figure 5. 2-DOF positioning robot for precise exploration of whisker-object interactions. The robot arm is capable of moving up to 1000mm/s, has a range of 650x300mm, and is repeatable to ± 0.02mm.

Our current work is aimed toward the development of feature-based classifiers. Inspection of the signals produced from object contacts reveals features of the signal that consistently predict object properties. For example, the magnitude of deflection predicts object distance and deflection duration reliably predicts object speed. Picking certain features in the data as input to a classifier reduces the complexity of the feature space, allowing the development of more robust and versatile classifiers.

Texture is a key surface property for tactile object recognition and one that rats are able to discriminate, using their vibrissae, with accuracy similar to that of the human fingertip [1, 2]. We have previously shown that vibrissal texture discrimination is dependent on both surface properties, such as location and orientation [9], and on how the whisker interacts with the surface [10]. Using the feature-based classifiers described above we hope to develop a system for simultaneous extraction of multiple object features, including texture, and ultimately object shape, that will be effective for a wide range of contact situations. As these 'shapelet' classifiers are developed they will be transferred from the XY positioning table to be evaluated and tuned for operation on SCRATCHbot and other multi-whisker vibrissal sensing systems.

Tactile robot navigation and mapping

We are currently constructing a biologically inspired Bayesian-filtering navigation module for SCRATCHbot.

In general, Bayesian filtering computes

$$P(x(t) \mid z(1:t)) = P(z(t) \mid x(t)) \sum_{x(t-1)} P(x(t) \mid x(t-1)) P(x(t-1) \mid z(1:t-1))$$

at discrete steps, where *x(t)* is the pose, and *z(t)* are its sensor measurements (which may include odometry). Exact computation of this filter is an intractable problem and approximation techniques may be constructed in several ways. For instance, sensor models may use raw data or extracted/reduced features, the state model may use assumed parametric form (such as Faussians) or brute-force grid histograms, filter-based navigation may be passive or may include active control of information-gathering explorations. Vibrissal sensors present their own particular challenges in making each of these choices. In developing the navigation model we have also drawn on the rat neurobiology literature by seeking to build a high-level approximation to a further set of rat brain structures—the *hippocampal* system.

Many navigation algorithms [see 11] assume that distances to a fixed set of identifiable, distinct landmarks are always available, as would be the case for range-finding beams and certain visual feature-detection systems. Whiskers differ in providing only very local and ambiguous information. In particular, the *shapelet* reports discussed above will contain information about the position, orientation and texture of walls and other objects within the whisker field and about textures on the floor. Office environments typically contain very few distinctive whisker features that would uniquely identify a location, rather, they yield many repeated shapelets such as edges, corners and floor textures. Hence, prior information about previous locations visited and path-integration mechanisms may be more important for tactile navigation than for wayfinding based on other modalities.

Common heuristics underlying probablistic reasoning systems for navigation [11] typically assume that the distribution of pose beliefs is either Gaussian (leading to the *Kalman filter* and its relatives) or represented by a set of samples (leading to *particle filters*). Our biologically-inspired model [12] assumes that perception is unitary, i.e. that we perceive a single state of the world rather than a "Bayesian blur" of probabilities. This constraint suggests the following algorithm, illustrated in figure 6, which may be though of as a Particle filter with a single particle or as an extended Kalman filter with all posterior uncertainty moved into the transition noise.

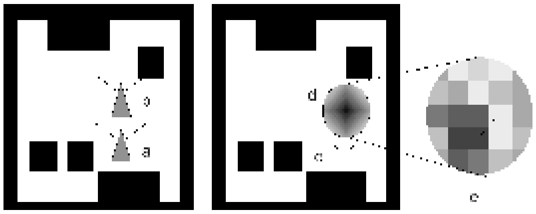

Figure 6. Using a biologically-inspired Bayesian approach to solve the problem of tactile navigation and mapping (see text for full explanation).

In the example shown in the figure, the model robot has moved from *a* to *b* and has detected a shapelet with its right whisker, triggering an update. Assume that the robot's initial position is known exactly as shown by *c*. All odometry since the previous observation is summed, and a corresponding Gaussian error term is computed that is dependent on the length of the summed path. As the shapelet reports are highly nonlinear functions of location, we then switch from the Gaussian parametrisation to a quantised, grid-based method. We consider a trust region, *d*, centred around the middle of the prior, having a radius of two standard deviations (see magnified inset on right). This region is then quantised into a 2D grid, and likelihoods found for the data in each grid position. Fusing these likelihoods with the Gaussian prior gives an approximate posterior, *e*, whose weighted mean location is taken as the next unitary state estimate (shown by the cross is the magnified grid).

Unitary tracking encounters a well known problem. If tracking is ever lost, then it becomes impossible to relocalise without some additional mechanism. A standard solution [13] is to monitor the difference between the sensors and their predicted values, and switch temporarily to purely likelihood-driven sampling if this difference is large for a prolonged period. In our recent theoretical model [12] we postulated a role for the *subiculum-septum* hippocampal pathway in performing such a function. The rat hippocampus is known to be capable of replaying and generating short sequences of states [14]. A possible function of these replays may relate to recovery when lost. If the robot remembers a recent time at which it was not lost, and remembers the sequence of observations since (in non-hippocampal working memory), then this sequence can be replayed and an alternative unitary sequence tested for the possibility that it could provide a better current localisation. This could be repeated multiple times, thus providing a form of biologically-inspired backtracking. Forward generation of possible future trajectories should also be possible, and could prove valuable in hazardous environments where it would allow the robot to simulate and evaluate the risks of moving to different locations before actually doing so.

Conclusion

Current work has brought us to the point where we can begin to evaluate the practicality of active vibrissal sensing for robot tactile object detection/recognition and navigation in indoor environments. We believe that our vibrissal sensors also have great promise for use in riskier environments, particularly in situations where vision can provide only degraded or ambiguous input. In future research we hope to combine vibrissal sensing with artificial sensing in modalities such as vision, audition and olfaction, and with a locomotion system that will allow the robot to negotiation rough terrain. This will bring us closer to the possibility of building autonomous robots with similar capabilities to one of the most successful and versatile animals on the planet—the common rat.

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