Active Touch with a Biomimetic 3D-printed Whiskered Robot

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Abstract. We propose a new design of active tactile whiskered robot: the actuated TacWhisker array, analogous to motile tactile vibrissae such as the rodent macrovibrissae. The design is particularly simple, being completely 3D-printed, only having one motor to actuate all 10 whiskers, and utilizing optical tactile sensing to transduce whisker deflections into bending moments. This robot is used to investigate active touch on a simple localization task where the robot seeks to move the whisker array to centre on a stimulus while perceiving its location. Active localization with a threshold-crossing decision rule was found to rapidly improve the perceptual errors with successive whisks. Curiously, although the sensing is dominated by the whisker motion, this does not appreciably affect performance on this simple task. Overall, the robot promises to give a simple embodiment of whisker-based active touch to give insight into the mechanisms underlying perception in the mammalian brain.

Keywords: tactile sensing, active touch, biomimetics, whiskers

1 Introduction

Tactile whiskers (vibrissae) are a striking facial feature of almost all mammals except for humans [1]. Rodent whiskers have evolved into a primary sense organ for navigating, exploring and interacting with their surroundings. Whisker motion is controlled by the animal to direct its attention onto objects and other salient aspects of the environment [2]. In many behaviours, such as locomotion, these movements are based around a periodic protraction and retraction of the whiskers known as whisking [3]. Both the head/body movements and whisker motion are controlled to aid sensing in a process known as active touch, whereby sensing, perception and action are tightly coupled in a feedback loop. The mechanisms underlying active touch are of great interest to neuroscientists in giving a window to understand perception and action in the mammalian brain. A complementary approach to investigating active touch is to embody putative mechanisms in whiskered robots [4], so that one may test and formulate new biological theories based on how they perform in biomimetic systems.

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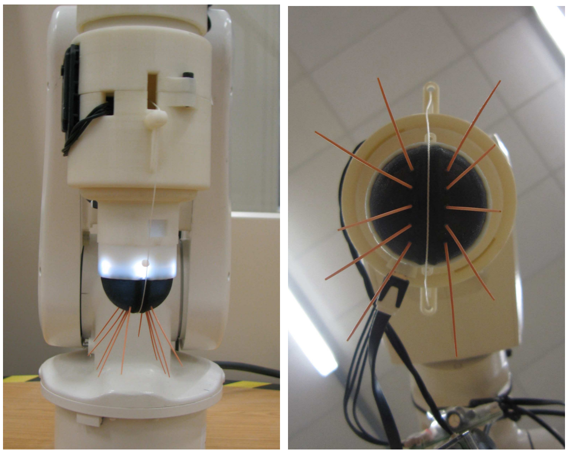

Fig. 1. Side (left image) and front (right image) views of the actuated TacWhisker array. The sensor is modular with actuation, body and whiskered tip components.

In this paper we make two contributions to the biomimetics of active touch with robotic whiskers. First, we propose a new design of active tactile whiskered robot: the actuated TacWhisker array (Fig. 1), analogous to motile tactile vibrissae such as the rodent macrovibrissae. The design is particularly simple compared to state-of-the-art whiskered robots such as SHREWbot [5], being completely 3D-printed, only having one motor to actuate all whiskers (here arranged in 2 rows of 5 whiskers), and utilizing optical tactile sensing to transduce whisker deflections. Second, we investigate active touch with the actuated TacWhisker array on a simple localization task where the robot seeks to move the whisker array to centre on a rod stimulus while perceiving its location. We find that active localization is superior to passive localization, in having lower perceptual errors for a decision time, consistent with past work on active touch [6]. Curiously, although the sensing is dominated by the whisker motion, this does not affect performance on this simple task, as comparable localization is attained with and without self-motion compensation.

2 Background

Over the last decade, a succession of biomimetic tactile whiskered robots have been developed in collaboration between Sheffield Robotics and Bristol Robotics Laboratory [4]. The initial Whiskerbot mobile robot had an array of 6 glass-fibre moulded whiskers mounted on strain gauges to measure 2D deflections of the whisker shaft [7]. This was followed with the SCRATCHbot mobile platform, having 18 actuated 3D-printed whiskers with Hall effect sensors to measure deflections while actively whisking [8]. These single-actuated whiskers were modularized as part of the BIOTACT project, leading to another mobile whiskered platform called SHREWbot [5] and a robot arm-mounted whisker array [9].

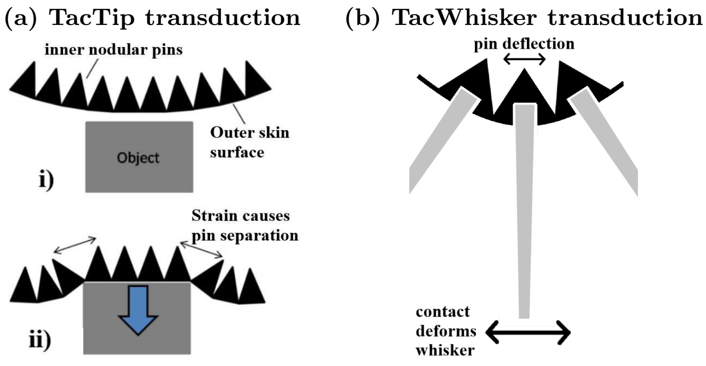

Fig. 2. Common transduction principle of the TacTip and TacWhisker. (a) For the TacTip, surface strain causes separation between the inner nodular pins. (b) For the TacWhisker, whisker shaft deflection causes pin movement. In both cases, the pin movement is tracked by an internally mounted camera.

This paper investigates a novel vibrissal tactile sensor based on modifying a 3D-printed biomimetic tactile fingertip called the TacTip (Fig. 2). The TacTip is based on the layered structure of human glabrous skin [10, 11], with an outer biomimetic epidermis made from a rubber-like material over an inner biomimetic dermis made from polymer gel, which interdigitate in a mesh of inner nodular pins. Local strain on the sensor surface is transduced into pin movements that are imaged with an internal camera (Fig 3). The principle underlying the TacWhisker array is that this transduction mechanism can also be applied to tactile whiskers by attaching the whiskers into sockets protruding into the internal pins; moreover, this design combines with a simple actuation mechanism that actively protracts and retracts the whiskers akin to rodent whisking (Fig. 4). For the actuated TacWhisker array, there are two main contributions to the whisker sense: local shear of the sensor surface from the actuation mechanism; and rotational deflection of the pins when whiskers impinge on an object from the bending moment of the whisker at its base. Both contributions are apparent in the transduced whisker data (Figs 5,6).

3 Methods

3.1 Actuated TacWhisker robot

We call the whiskered version of the TacTip a *TacWhisker* array, emphasising it is based on tactile whiskers rather than tactile (finger)tips. The design comprises several modular components, described below.

TacWhisker housing: The underlying design of TacWhisker array modifies the standard TacTip tip to house whiskers (Figs 3). There is no modification of

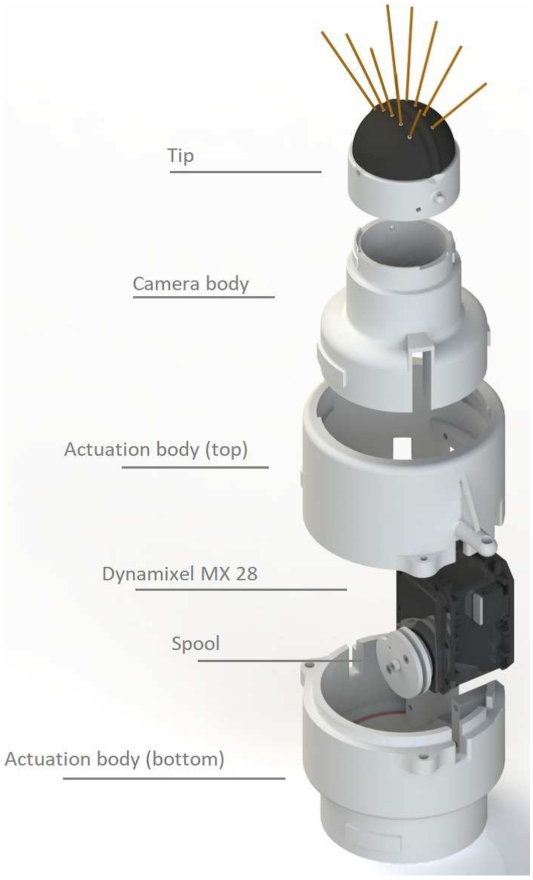

Fig. 3. Actuated TacWhisker array. The 3D-printed tip with mounted whiskers attaches to the base housing the camera, which attaches to the actuation module comprising the motor and housing. A tendon runs from the spool, through guides and across a groove in the compliant tip.

(a) Active protraction **(b) Passive retraction**

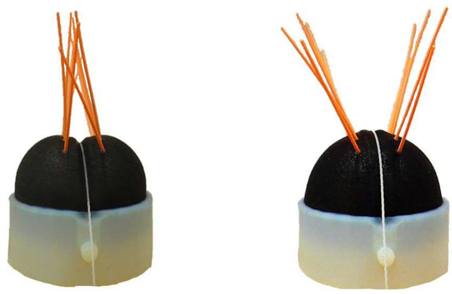

Fig. 4. Whisking motion. (a) The motor pulls on the tendon to actively protract (bring together) the two rows of whiskers. (b) Reversing the motor releases the tendon to passively retract (pull apart) the whiskers by elastic reformation of the tip.

the 3D-printed TacTip base (Fig. 3), which contains the USB camera (Lifecam, Microsoft) and an LED ring to illuminate the pin markers (see [10] for details). The tip is based on recent versions of the TacTip [10] that use multi-material 3D-printing. The compliant surface and inner pins printed in a rubber-like material (Tango Black+ 27) and the pin tips and mount in hard plastic (Vero White); this outer surface is filled with a soft clear silicone gel (Techsil RTV27905) held in place with a clear acrylic lens cap.

TacWhisker tip: For housing whiskers that can be actuated, the tip is modified to: (i) reduce the number of pins to 10 (from 127) sited near the top of the tip; (ii) arrange the pins in 2 rows of 5 in a bilaterally symmetric pattern; (iii) enlarge and extrude the solid markers through the compliant surface (2.2 mm dia.×3.5 mm depth pins, increased from 1.2 mm×2 mm); and (iv) include a hole (1 mm dia.×3 mm depth) functioning as a socket for the whiskers. These design choices were chosen to give good pin movement upon deflection of the whiskers, and to site the whiskers appropriately for contacting objects.

The whiskers (Fig. 4) are modified versions of BIOTACT vibrissae [5] that are 3D printed using nanocure-25. The main change is to reduce the whisker size for the smaller scale of the TacTip (40 mm dia.) compared with the BIOTACT conical housing (100 mm dia.). Accordingly, we chose whiskers 40 mm long with a 0.98 mm dia. base tapering to 0.6 mm dia. at the tip, similar in scale to real rat whiskers. For simplicity, all whiskers had the same dimensions, but it would be straightforward to introduce size variations like those of rodent macrovibrissae.

Actuation body: The actuated TacWhisker array is designed to be modular and re-use parts of the static TacWhisker array. Apart from the modified whiskered tip, the TacWhisker base housing the camera and LED lighting is the same as the conventional TacTip. The underside of the base has a bayonet fitting, which is used to connect to an actuation module for driving the tendon (Fig. 3). This actuation body houses a Dynamixel MX 28 servomotor and spool for the tendon, with outer guides to ensure the tendon runs smoothly from the spool, outside the actuation and body modules, and over the TacWhisker tip.

The actuation module moves the whiskers back and forth in a whisking motion (Fig. 4). A tendon runs through a groove between these rows and two guides in the tip mount. Forwards whisker motion (protraction) results from tensioning the tendon to compress the surface at the midline (Fig. 4a); backwards whisker motion (retraction) results from releasing the tendon to elastically reform the surface (Fig. 4b). The compliant surface and whisker mounts are shaped so that the whisker tips can meet under modest surface compression. The actuated TacWhisker array can thus rhythmically protract and retract its whiskers together and apart in a motion akin to rodent whisking.

Robotic platform: For testing, the static or actuated TacWhisker array is mounted as an end-effector on a 6-DOF robotic arm (IRB 120, ABB; Fig. 1).

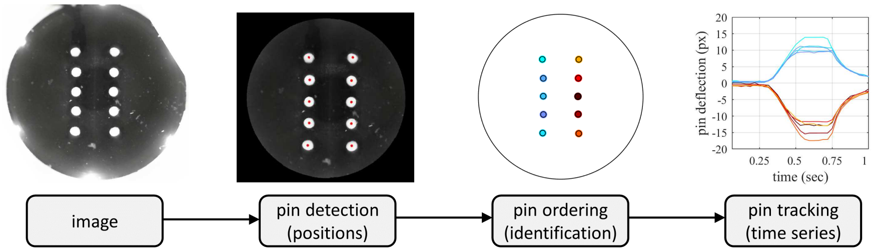

Fig. 5. Data processing pipeline. The internal camera captures an image of the pins attached to the shafts of the whiskers. The pins are detected and tracked from frame-to-frame (here coloured by their row) to produce a real-time output.

The arm is mounted on a table that also contains mounting stations for the stimuli. A custom 3D-printed mount is bolted to the rotating (wrist) section of the arm to which either sensor can be attached via a common bayonet fitting on the TacWhisker base and actuation module.

A modular software infrastructure is used in which MATLAB is the primary interface for running tests and analysing data. The ABB arm is controlled via an IronPython and RAPID interface, and data gathered from the USB camera within the TacWhisker sensor with Python OpenCV. Similarly, a Python interface controls the dynamixel motor of the actuated TacWhisker array. Communication between software modules is via TCP/IP ports and sockets.

3.2 Sensing, perception and active touch

Sensing: Following recent studies with the TacTip [10, 12], the sensor output is treated a time series of pin deflections extracted from the camera images. The transformation of the camera image to marker positions requires that the pin markers be detected, which is done via standard 'blob detection' methods in Python OpenCV. Overall, the data processing is a pipeline: camera image to pin detection to pin identification (nearest neighbour tracking) to give an ordered time series of pin deflections measured in pixels (Fig. 5).

The resulting tactile whisker data comprises a multi-dimensional time series of pin (x, y) deflections, measured in pixels on the camera image. For visualization, the time series plots of the x- and y-deflections are labelled by colouring the tactile dimension by its pin location (Fig. 5, right plots).

Perception: Tactile perception is the process of inferring the properties of a stimulus from data collected by contacting that stimulus. Here we use a likelihood model that transforms tactile data D into a likelihood probability $P(D \,|\, H_i)$ for a set of perceptual hypotheses $\{H_1, ..., H_N\}$, which could be the labels (*e.g.* location in mm) for training data used to construct the model. The perceptual decision is then the hypothesis H_j with $j = \arg\max_i P(D \,|\, H_i)$ that has the maximum likelihood for some sensed tactile data D.

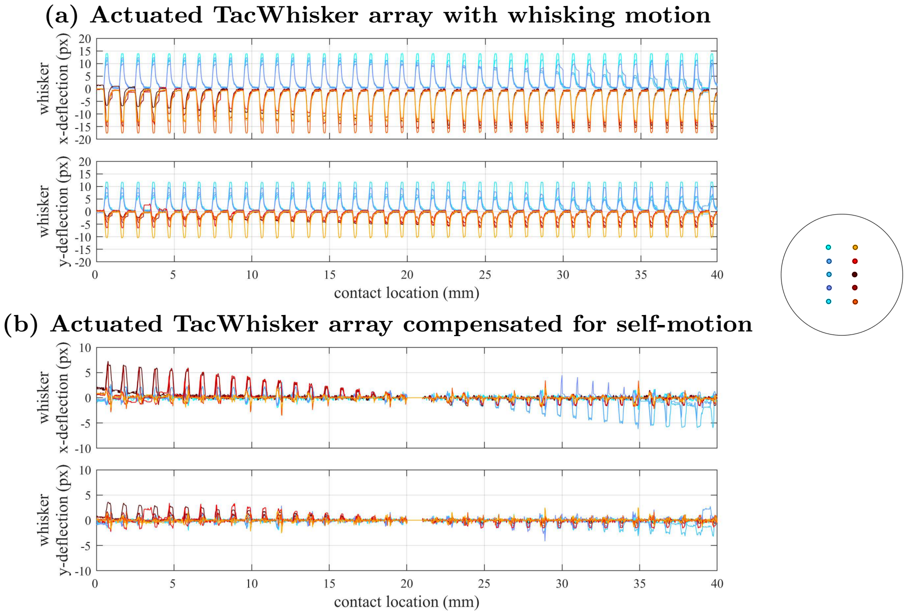

Fig. 6. Whisking data over a (40 mm) range of locations from the actuated TacWhisker array. The plot colour denotes the identity of the whiskers (right image). Both the raw whisker data (a) and self-motion compensated (b) data are shown.

Following recent studies with the TacTip, here we use a histogram likelihood model [6, 13], which bins the sensor data into intervals and counts bin frequency to form sampling distributions that are multiplied over sensor dimension and time. While simple, this model is effective for the TacTip and other sensors [6, 12], bears analogy with neural processing [6] and is fairly robust and efficient. That said, the likelihood model is not the focus of this study, and so any model that works reasonably well would have been sufficient.

Active touch: In active perception, we assume that perceptual decisions are sequential over multiple tactile contacts $D(1), \cdots, D(T)$, with actions being made between contacts to improve the perception. As perception is over multiple contacts, we combine the likelihood model of each contact into a probability using Bayes rule applied recursively after the tth contact

$$P(H_i \,|\, D(t)) = \frac{P(D(t) \,|\, H_i)\, P(H_i \,|\, D(t-1))}{\sum_j P(D(t) \,|\, H_j)\, P(H_j \,|\, D(t-1))},$$

beginning from flat priors $P(H_i \,|\, D(0)) = P(H_i) = 1/N$. Here we use a very simple active perception policy, in which actions are taken to move the tactile sensor directly onto the object x_{fix}, which we assume to be in the centre of the training data range $x_{N/2}$. Thus, if the perceptual hypotheses are positions $H_i = x_i$, then

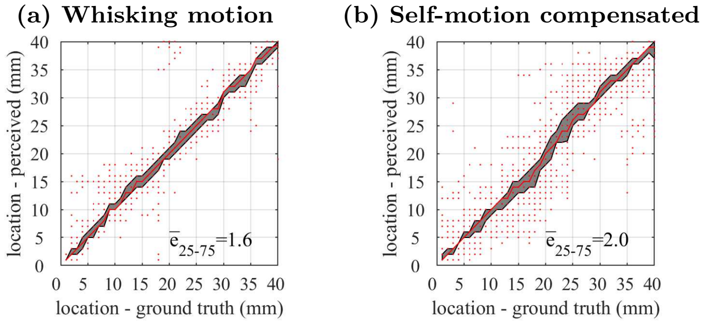

Fig. 7. Accuracy of location perception. Monte Carlo 10-fold cross validation (10000 samples), plotting the perceived against ground truth locations (red markers). Variability of location perception is shown between 25th and 75th percentiles (gray region).

the actions are translations $\Delta x(t) = x_{\rm fix} - x_j(t)$ where $j = \arg\max_i P(D(t) \,|\, x_i)$. Following past work on biomimetic active perception [6], the decision is made when the probability crosses a decision threshold $P(H_i \,|\, D(t)) > \theta$ that can be set to give a particular decision time $\bar{T}$ averaged over many decisions.

4 Results

4.1 TacWhisker data on a rod localization experiment

The localization capabilities of the actuated TacWhisker array are assessed with an experiment where a (6 mm dia.) rod stimulus is sensed across a (40 mm) range of horizontal locations in the whisker field, motivated by similar experiments in rats examining the neural encoding of location [14]. The sensor oriented with its whiskers pointing vertically downwards with the rod oriented along the rows of the whiskers (y-direction in Fig. 5), and rod positions sampled every 1 mm moving from left to right (examples in Figs 8a,b and 8c,d). The TacWhisker whisks onto and off the rod by protracting then retracting its whiskers.

In all experiments, good quality data were obtained from the TacWhisker array, as is evident in the smoothly varying sensor readings with signal apparently dominating over noise (Fig. 8).

The unprocessed sensor data is dominated by the whisking motion, visible as the large periodic signals in both the x- and y-deflection data (Fig. 8a). Overall, there are two main contributions to the sensor signals: (i) local shear of the sensor surface from the actuation mechanism, resulting in large periodic signals; and (ii) rotational deflection of the pins when whiskers impinge on an object, resulting in smaller perturbations of the whisking signal.

To compensate for the whisking self-motion, a reference signal is subtracted from the sensor data to leave the perturbations due to object contact (Fig. 8b). Whisking data from the centre of the range ($x_i = 20$ mm) is used for this reference, as the rod lies between the two whisker rows when they are fully protracted.

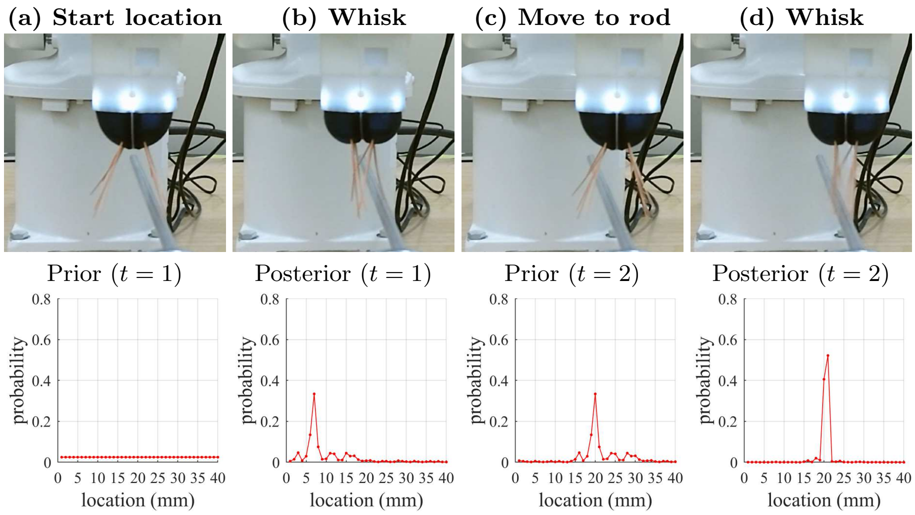

Fig. 8. Example of active touch. The TacWhisker array begins to the left of the rod (a), then whisks onto it (b); from an initial estimate of the rod location, the sensor then moves right to centre on the rod (c) and whisks again (d). The according probability distributions over location at each step are shown below.

This compensation makes a whisker contact more visually apparent, with a clear trend of the right row of whiskers (shown in red) being increasingly deflected as the rod moves to the left of the array, and likewise the left row of whiskers (shown in blue) being increasingly deflected in the negative direction as the rod moves to the right of the array (Fig. 8b).

4.2 Location perception with the actuated TacWhisker array

The accuracy of location perception with the TacWhisker array is quantified with a probabilistic classifier that estimates the maximum likelihood of a location from the sensor data (Sec. 3.2). Examples of TacWhisker data at labelled locations $x_i = 1$-40 mm are used for training data, from which a histogram model of the data is constructed that used to estimate the likelihoods of an instance of test data. Overall, we collected 10 sets over this location range, using 10-fold cross validation to compare the perceived location with the ground truth.

Both the raw whisking data and the self-motion compensated whisking data appear similarly good for perceiving location (Fig. 7a,b): in both cases, the mean estimated location is centred on the true location (red line), with a spread in perceived locations (red markers) of which the central 50% percentiles are within 1-2 mm of the overall 40 mm range (1.6 mm for raw data; 2.0 mm compensated). These results are in accordance with visual inspection of the TacWhisker data (Fig. 6), which covaries with contact location, consistent with the data being well suited for perceiving location.

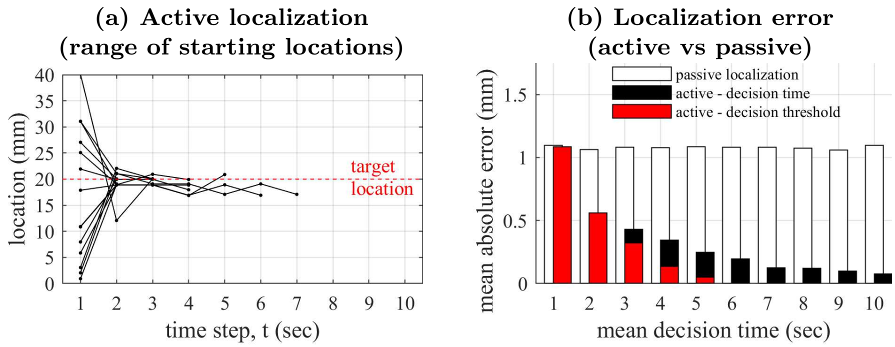

Fig. 9. Comparison of active and passive perception of location. Under active localization, the sensor centres itself on the stimulus while perceiving its location (panel a). Experimentally, active perception has a lower mean error at longer decision times (panel b), with a threshold-crossing stopping rule better than a fixed-time rule.

4.3 Active localization with the actuated TacWhisker array

A simple example of active touch is to localize an object while using intermediate estimates of the object location to move the sensor to a better location on the object for perceiving its location. For a simple object, such as perceiving the location of a rod, a basic active touch strategy is to move the sensor to centre the object within its whisker field. Active touch can then be seen as implementing a control policy (centre the object of interest) while simultaneously perceiving the object, in this case the object's location.

An illustration of active touch for localization in action shows the TacWhisker array beginning off-centre to the left of the rod (Fig. 8a), then whisking (when the right whiskers are deflected in Fig. 8b); from an initial estimate of the rod location, the array then moves to the right to centre (Fig. 8c) and then whisk onto the rod (Fig. 8d). In accordance, before the whisker has contacted the probability of it being at any location is constant (Fig. 8a, prior), after contacting it is a fairly broad distribution peaked to the left of the rod (Fig. 8b, posterior); after moving, the location distribution has the same broad shape shifted to centre on the rod (Fig. 8c, prior), and then after whisking and using Bayes rule to combine the new likelihood distribution with that prior, the posterior distribution becomes more strongly peaked around the rod location (Fig. 8d, posterior).

Repeating the active localization experiment over many trials with a range of starting locations, shows that the robot robustly localizes onto the rod (Fig. 9a). The overall decision time is stochastic, because a probability-threshold crossing decision rule is used (Sec. 3.2), in which the accumulated probability for a percept must cross a minimum value before making a decision. Mean location errors for active perception improve with mean decision time (Fig. 9b), reaching near perfect accuracy at a mean decision time of 5 contacts. Conversely mean errors for passive perception remain the same as at the first contact, because the robot then cannot move to gather new data (Fig. 9b, white histogram). Thus, overall, the mean location errors for active perception with a probability-threshold crossing decision rule improves faster with mean decision time than having a preset decision time.

5 Discussion

In this paper, we proposed a new design of active tactile whiskered robot, the actuated 'TacWhisker' array, and used the robot to investigate active touch on a simple localization task where the robot orients its array onto a stimulus while perceiving its location. The actuated TacWhisker array has a simple design in which a 3D-printed optical tactile fingertip (the TacTip [10, 11]) is modified have whiskers protruding from the tactile surface, with an actuation module that pulls a tendon running through a surface groove to protract the whiskers together (Figs 3,4). Here a morphology comprising two rows of five whiskers was used, although other (symmetric) layouts are readily attainable with this design. The use of a single motor to actuate all whiskers vastly simplifies the robot, and bears analogy with the principal component of rodent whisking which is to synchronously protract and retract all whiskers together.

The tactile robot successfully performed a simple active localization task, where a rod stimulus is placed randomly in the whisker field and the robot moves to whisk directly onto the rod while simultaneously perceiving the rod location (Fig. 8). The control is based on an action selection policy that tries to centre the rod in the middle of the whisker field, based on intermediate estimates of the rod location [6]. Several methods for perceiving location were compared (Fig. 9), and the active localization with a threshold-crossing decision rule found to be best, in that the perceptual errors improved most rapidly with successive whisks (unlike passive perception where the errors did not improve).

Curiously, although the sensing is dominated by the whisker motion, this does not affect performance on this simple task. Comparable localization acuity is attained with and without self-motion compensation (2.0 mm vs 1.6 mm), by subtracting a reference signal that leaves the perturbations due to object contact (Fig. 8b). This raises questions about how the brain solves this problem for rodent whisking, where a related issue of self-motion compensation occurs [15]. That said, this self-motion is likely less pronounced in other whiskered robots (for example, Shrewbot), where the effect appears due primarily to the whiskers' inertia rather than the actuation mechanism.

Our intention is to apply our actuated TacWhisker robot to other active perception tasks. Preliminary results have also shown the TacWhisker is effective on estimating object shape while localizing on the object, using an experiment like the 'where' and 'what' tasks described in ref. [6]. Moreover, the whiskered robot can also be applied to navigation and exploration tasks, which are primary functions of the rodent whisker system [16]. Overall, the robot promises to give a simple embodiment of whisker-based active touch to give insight into the mechanisms underlying perception in the mammalian brain.

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