Embodied hyperacuity for robot touch

Nathan F. Lepora, Uriel Martinez-Hernandez, Mat Evans, Lorenzo Natale, Giorgio Metta, Tony J. Prescott

***Abstract*— Hyperacuity is a general aspect of animal perception that uses the population response across overlapping sensory receptors to perceive at higher acuity than the sensor resolution. Following a recent demonstration of hyperacuity in robot touch [1], we here demonstrate hyperacuity for both a biomimetic fingertip and a region of tactile skin. Our study clarifies some design principles that improve tactile perception.**

I. INTRODUCTION

Although hyperacuity is most widely studied in vision, it also occurs for touch and audition, and may be considered a general aspect of human/animal perception. For example, Braille reading involves perceiving spatial patterns of a finer resolution than the spacing between touch receptors in the fingertips [1]. Thus, nature has discovered design principles that allow perceptual systems to operate at finer acuity than might be expected from the receptor density. These principles give lessons for robotics when optimizing sensor accuracy.

In a recent study, we gave the first demonstration of hyperacuity in robot touch [2] using a biomimetic fingertip [3] constructed for the iCub robot [4]. Here we follow that study by showing hyperacuity over a region of tactile robot skin, and also present an improved dataset for validating hyperacuity on the fingertip. We conclude by discussing the design principles necessary to achieve hyperacuity. These principles represent good practice for optimizing sensor acuity while keeping within manufacturing and cost constraints.

II. METHODS

Data collection: Two tactile sensors were used to gather data [3]: (i) a fingertip-shaped sensor of dimensions 1.5 mm long by 13 mm wide (Fig. 1); and (ii) a flat region of tactile skin approximately 60 mm wide (Fig. 2). These sensors were designed as a fingertip and palm sensor for the iCub humanoid robot [4], and utilize a capacitive sensing technology for pressure over multiple taxels [3]. The present experiments test their position sensing capabilities with a Cartesian robot designed to probe the acuity of tactile sensors [5] (test stand for experiments shown in [2, Fig. 1] and [6, Fig. 1]). Fingertip sensor data was collected by tapping briefly (0.1 sec) against a smooth metal rod (dia. 4 mm) while moving the fingertip gradually with 1600 taps spanning a 16 mm range of positions (Fig. 3). Skin sensor data was collected by tapping the sensor with a metal probe (dia. 4 mm) while moving the probe so that 800 taps span a 40 mm position range (Fig. 4).

This work was supported by EU Framework project EFAA (ICT-270490).
NL, UMH, ME and TP are with SCentRo, University of Sheffield, UK. Email: {n.lepora, uriel.martinez, mat.evans, t.j.prescott}@sheffield.ac.uk
LN and GM are with IIT, Italy. Email: {lorenzo.natale, giorgio.metta}@iit.it

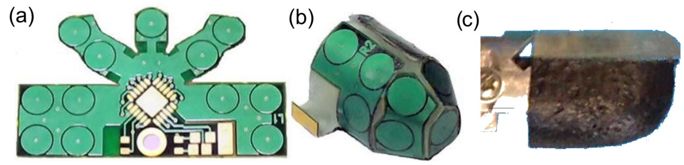

Fig. 1. Construction of tactile sensor shaped like a human fingertip.

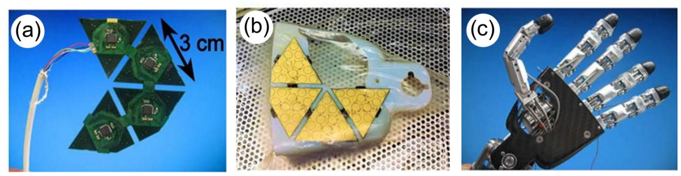

Fig. 2. Construction of area of tactile skin for the palm of a robot hand.

Data analysis: We used a Bayesian perception method for classifying position that relates to sequential analysis models of perceptual decision making in neuroscience and psychology [7], [8], and has been applied successfully to robot tactile perception [2], [9], [10], [11], [6]. The method implements a recursive Bayesian update of the beliefs for each perceptual class (here position) until reaching decision threshold. The likelihoods for the position classes, here every 1 mm, were constructed from training data, and then the Bayesian classifier was applied to distinct test data to assess real-time performance. A Monte Carlo method (1000 iterations per data point in Fig. 5) gave accurate statistics on the mean absolute errors and reaction times. Further methodological details can be found in the above citations.

III. RESULTS

Inspection of raw data: For the fingertip (Fig. 3), at the beginning of the data set only the taxels at its base are in contact, then the middle taxels and finally the taxels at its tip. Each taxel has a broad, Gaussian-shaped receptive field about 8 mm across with centers spaced about every 4 mm. For the palm (Fig. 4), a similar pattern of taxel activations is also apparent, with contacts initially starting to the left of the palm and moving across to the right. The broad overlapping Gaussian-shaped receptive fields are now around 16 mm diameter with centers about every 5 mm. For both the fingertip and palm, the geometry of the overlapping receptive fields implies that multiple taxels will be activated simultaneously. Thus, the hardware construction implies that stimuli will be coarse-coded over multiple sensor outputs.

Classification results: The Bayesian perception method was applied to both the fingertip and palm data. Position acuity for the fingertip reached approximately 0.3 mm for 10 taps and for the palm approximately 0.5 mm, estimated from

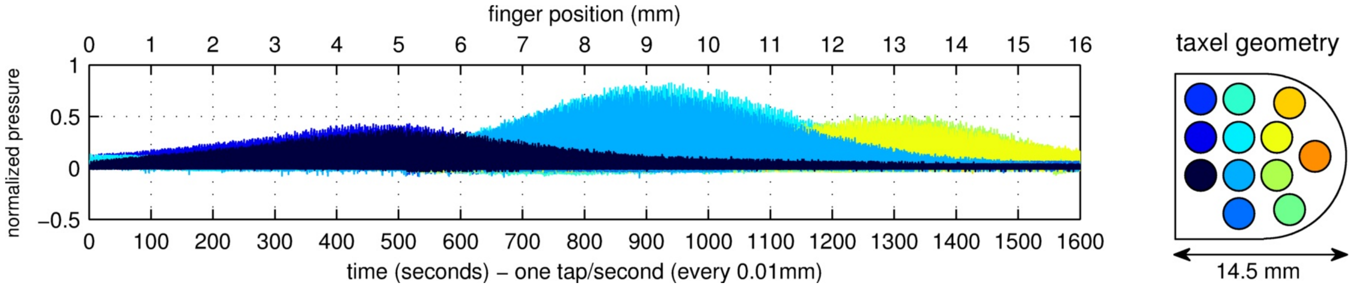

Fig. 3. Tactile data recorded as the fingertip taps against a test rod (dia. 4 mm) at constant rate of 1 tap/second, with 0.01 mm move across the rod after every tap to span a 16 mm range of positions. Taxels are represented in distinct colors depending on the taxel position shown on the diagram to the right.

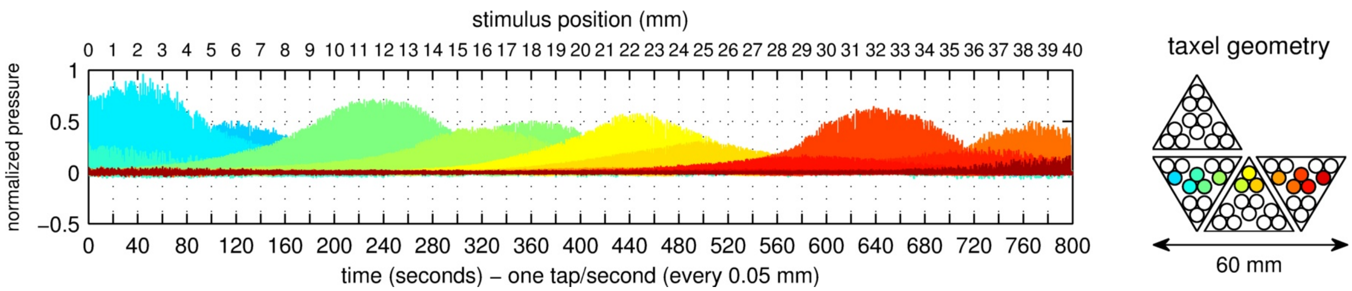

Fig. 4. Tactile data recorded as the tip of a rod (dia. 4 mm) taps against the area of tactile skin at constant rate of 1 tap/second, with 0.05 mm movement after every tap to span a 40 mm range of positions. The color coding of the taxels by their location is shown on the diagram to the right.

the mean absolute errors of the classified positions (Fig. 5). Given that the taxel spacing for the fingertip and palm is approximately 4 mm and 5 mm respectively, both tactile sensors demonstrate hyperacuity with an approximately ten-fold improvement over taxel resolution.

IV. DISCUSSION

The position hyperacuity of the fingertip and palm was due to Bayesian perception being able to utilize the population response across multiple taxels to interpolate between taxel locations. It arose from both the implementation of Bayesian perception and the physical properties of the tactile sensors, and hence we refer to it as embodied hyperacuity.

Given the approximately ten-fold improvement in position acuity over taxel resolution, to sub-millimeter precision over $\sim$5 mm taxel separation, the construction of these touch sensors represents good practice in tactile sensor design. In contrast, other design approaches that merely increase taxel density without attending to the receptive field properties will not be an efficient way of improving sensor accuracy. In general, sensors should be able to achieve hyperacuity if they have multiple, overlapping, broad but sensitive receptive fields. We envisage that these design principles should become central to the construction of cheap and accurate tactile sensors .

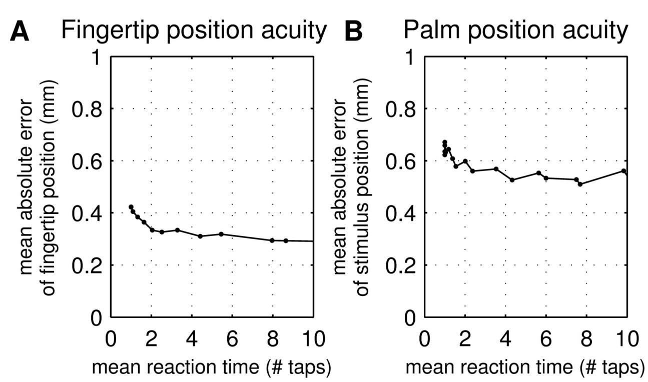

Fig. 5. Position acuity against mean reaction time for: (A) fingertip; (B) palm area of tactile skin. Results implicitly depend on a decision threshold.

REFERENCES

[1] J.M. Loomis. An investigation of tactile hyperacuity. *Sensory Processes*, 3:289–302, 1979.

[2] N.F. Lepora, U. Martinez-Hernandez, H. Barron-Gonzalez, M. Evans, G. Metta, and T.J. Prescott. Embodied hyperacuity from bayesian perception: Shape and position discrimination with an icub fingertip sensor. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, pages 4638–4643, 2012.

[3] A. Schmitz, P. Maiolino, M. Maggiali, L. Natale, G. Cannata, and G. Metta. Methods and technologies for the implementation of large-scale robot tactile sensors. *IEEE Trans Robotics*, 27(3):389–400, 2011.

[4] G. Metta, G. Sandini, D. Vernon, L. Natale, and F. Nori. The icub humanoid robot: an open platform for research in embodied cognition. In *Proc. 8th Workshop on Intelligent Systems*, pages 50–56, 2008.

[5] M. Evans, C.W. Fox, M.J. Pearson, N.F. Lepora, and T.J. Prescott. Whisker-object contact speed affects radial distance estimation. In *Robotics and Biomimetics (ROBIO)*, pages 720–725, 2010.

[6] N.F. Lepora, U. Martinez-Hernandez, and T.J. Prescott. Active touch for robust perception under position uncertainty. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, 2013.

[7] J.I. Gold and M.N. Shadlen. The neural basis of decision making. *Annu. Rev. Neurosci.*, 30:535–574, 2007.

[8] N. Lepora and Gurney K. The basal ganglia optimize decision making over general perceptual hypotheses. *Neural Computation*, (24):2924–2945, 2012.

[9] N.F. Lepora, C.W. Fox, M.H. Evans, M.E. Diamond, K. Gurney, and T.J. Prescott. Optimal decision-making in mammals: insights from a robot study of rodent texture discrimination. *Journal of The Royal Society Interface*, 9(72):1517–1528, 2012.

[10] N.F. Lepora, M. Evans, C.W. Fox, M.E. Diamond, K. Gurney, and T.J. Prescott. Naive bayes texture classification applied to whisker data from a moving robot. *Neural Networks (IJCNN), The 2010 International Joint Conference on*, pages 1–8, 2010.

[11] N.F. Lepora, J.C. Sullivan, B. Mitchinson, M. Pearson, K. Gurney, and T.J. Prescott. Brain-inspired bayesian perception for biomimetic robot touch. In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pages 5111 –5116, 2012.