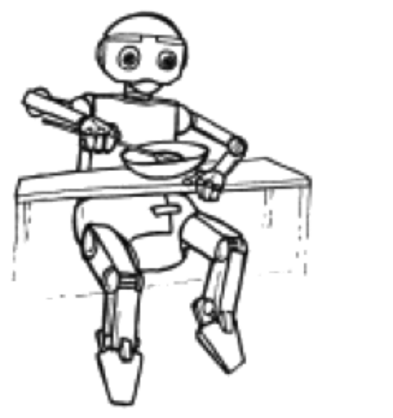


Vibrotactile Recognition of Surface Textures by a Humanoid Robot

Vladimir Sukhoy, Ritika Sahai, Jivko Sinapov and Alexander Stoytchev
Developmental Robotics Laboratory, Iowa State University
{sukhoy, ritika, jsinapov, alexs}@iastate.edu

IOWA STATE UNIVERSITY

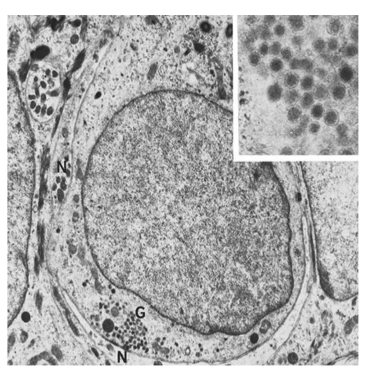
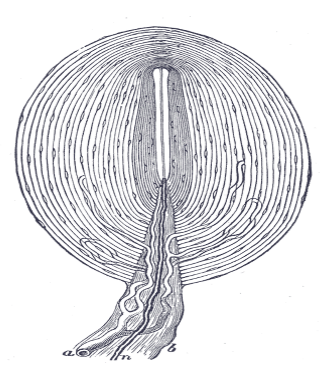
Summary

This study investigates the use of a vibrotactile sense for surface texture recognition by a humanoid robot. The sensor is an artificial fingernail with an attached 3-axis accelerometer, which the robot uses to scratch different surfaces. Our method combines frequency-domain analysis of the acceleration measurements with the Support Vector Machine (SVM) learning algorithm to recognize surfaces.

Motivation I

Vibrotactile Modality in Humans

There is evidence that humans use two different sensory modalities to represent surface roughness: a tactile modality for coarse surfaces and a vibrotactile modality for finer surfaces.[1]

tactile modality	vibrotactile modality
perceives spatial variations primarily via SA1 mechanoreceptors. Scale $\geq$ 200 pm	perceives cutaneous vibrations primarily via Pacinian afferents. Scale $\leq$ 200 pm
	

Source of the SA1 cell picture: Wolf K., Goldsmith L.A., Katz S.I. Gilchrest B.A. Paller A.S. Leffel D.J. Fitzpatrick's Dermatology in General Medicine. 7th Edition. McGraw-Hill Professional, 1997.

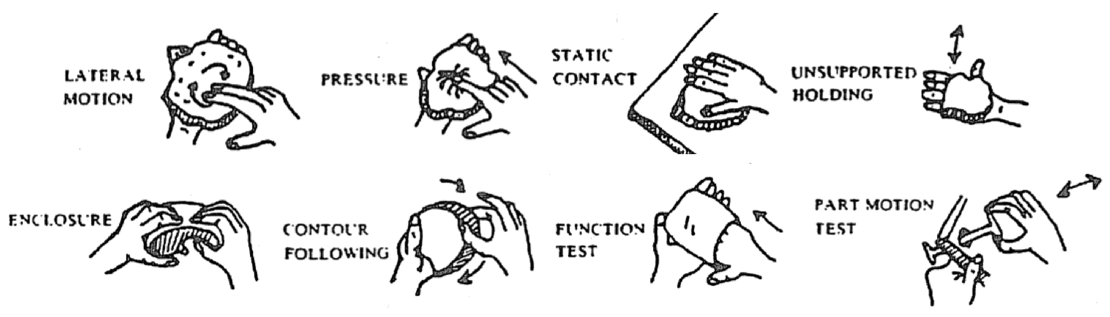
Motivation II

Exploratory Behaviors

- Motion is required to produce the vibrations.
- Humans use exploratory behaviors to recognize objects from tactile interactions.[2]

"the hand and the brain is an intelligent device in that it uses motor capabilities to greatly enhance its sensory functions".[2]

"purposive hand movements appear critical for haptically experiencing the world outside ourselves".[2]



The list of exploratory behaviors observed in humans during the process of tactile object recognition.[2]

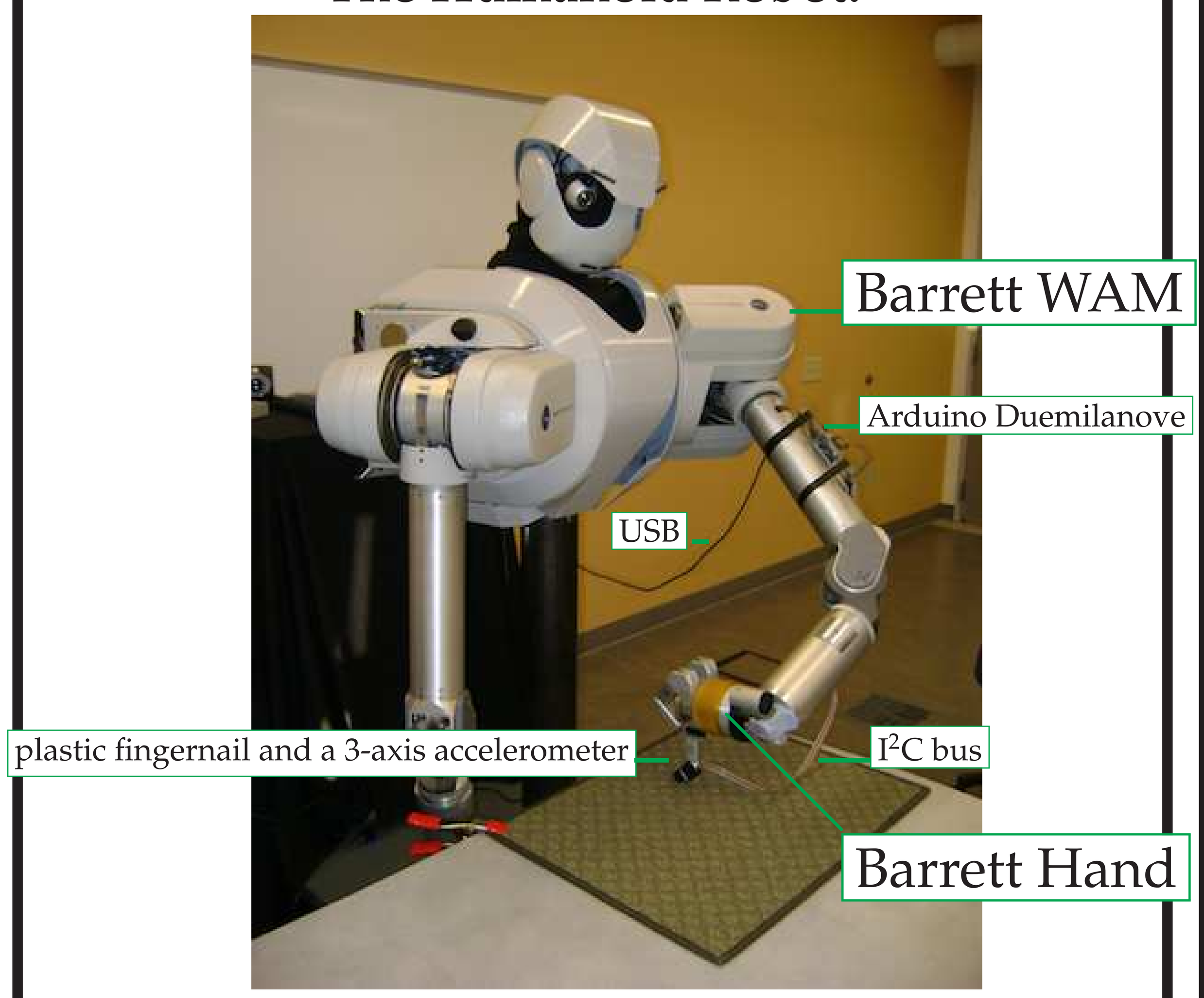
Exploratory behaviors applied to surfaces were observed in human infants as young as 6 months old.[3]

Related Work

- Kuchenbecker[4] proposed using accelerometers, strain gauges and other types of contact sensors to record tactile sensations with the idea of reproducing them later.
- Howe and Cutkosky[5] suggested detecting slip from the readings of a 3-axial accelerometer.
- Hosoda et al.[6] used a robotic finger to apply two exploratory behaviors to objects. The finger contained polyvinylidene fluoride (PVDF) films and strain gauges sensors.
- de Boissieu et al.[7] used three-axial force sensors embedded in an artificial finger that was mounted on a plotter to discriminate between 10 different types of paper.

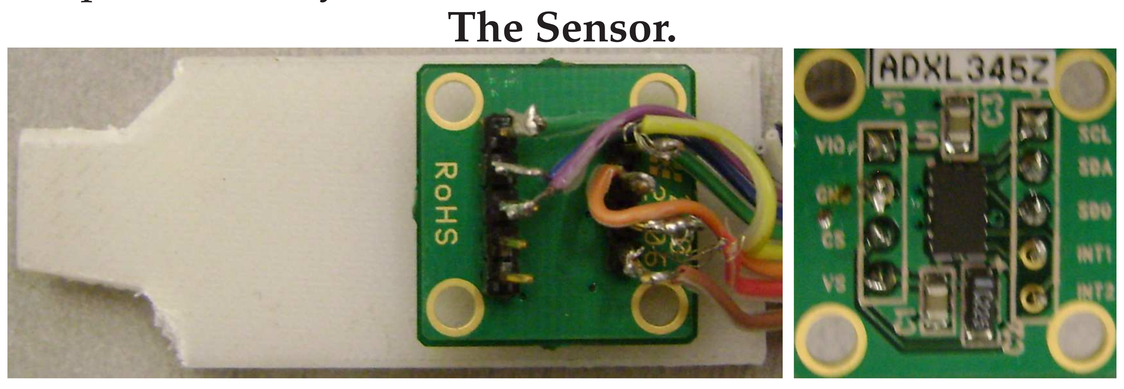
Experimental Setup

The Humanoid Robot.



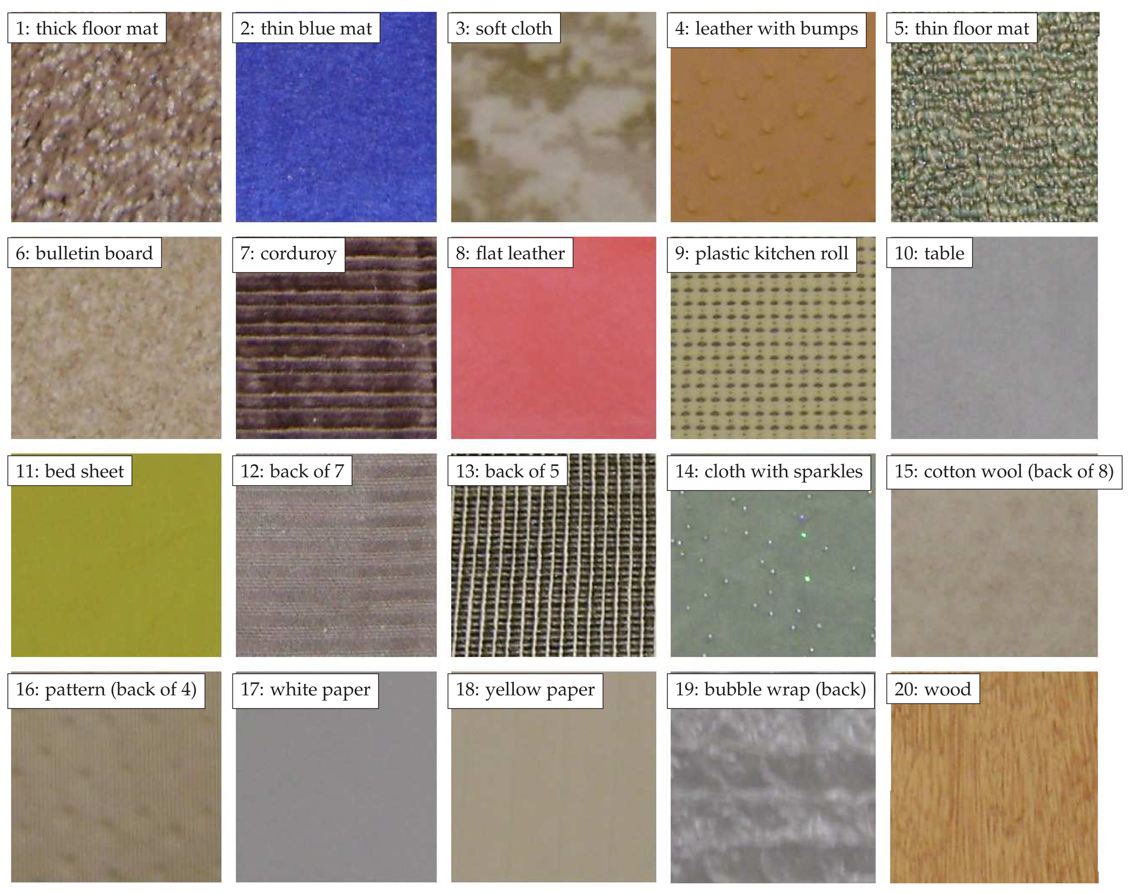
The accelerometer data was recorded at 400 Hz. With each surface the robot performed **10** trials. Each trial consisted of **5** scratches (**3** lateral and **2** medial) executed at different velocities. Thus, the total number of behavioral interactions performed by the robot was $\mathbf{21 \times 10 \times 5 = 1050}$.

The Sensor.



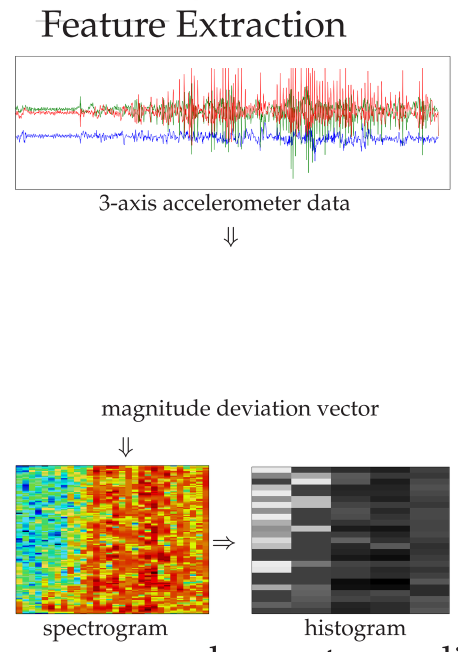
Left: the plastic fingernail with the attached accelerometer. Right: the other side of the accelerometer board (the ADXL345 is in the center).

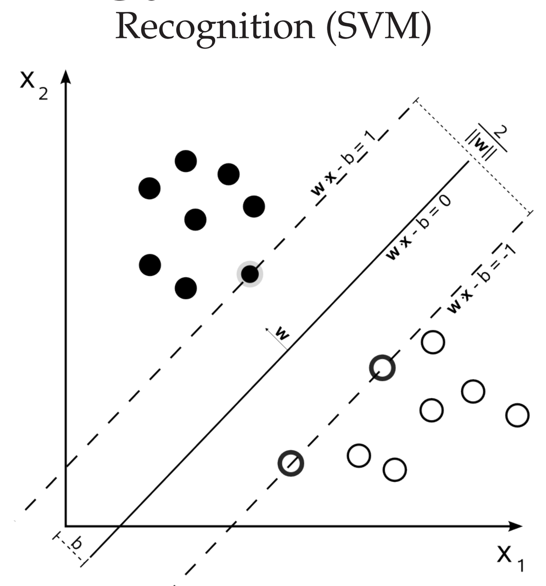
Surfaces



Surface 21 is the control condition corresponding to the robot scratching in mid-air.

Learning Methodology





- Given raw accelerometer readings in vectors X, Y, Z,
- compute the magnitude vector $M_i = \sqrt{X_i^2 + Y_i^2 + Z_i^2}$,
- compute the smoothing acceleration vector S from M using running averages over a window of size 100,
- compute the magnitude deviation vector $D = M - S$,
- apply DFT with a window of size 100 to D,
- from the spectrogram, compute the 25×5 histogram,
- use the histogram as a feature vector by SVM with polynomial kernel of exponent 2 to perform the recognition.

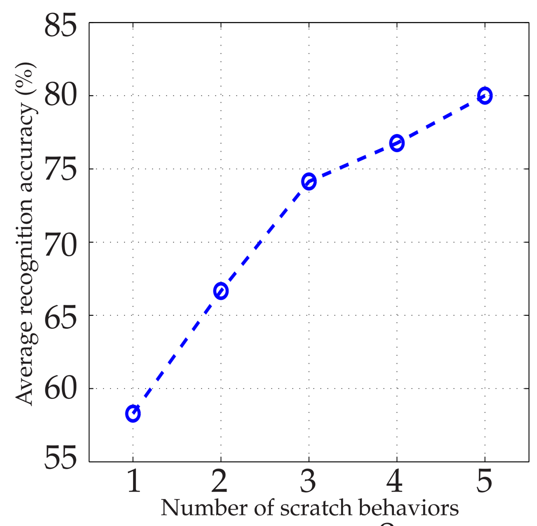
Recognition Results

- 10-fold cross-validation.
- Faster scratches usually resulted in better accuracy than slower one's.
- For each scratch the recognition accuracy was significantly better than random (chance accuracy is $1/21 \approx 4.76\%$).

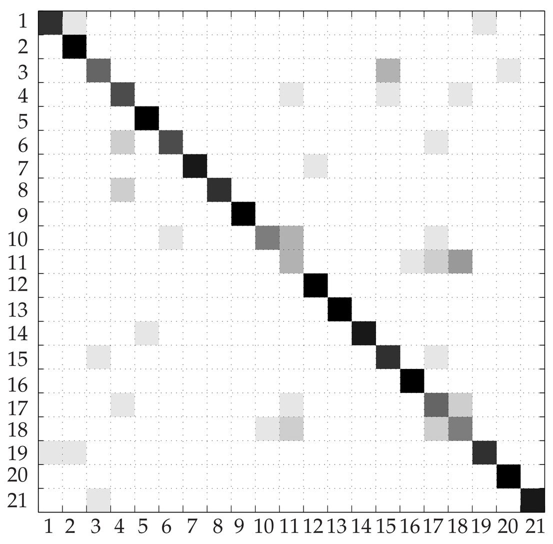
Accuracy for Single Behaviors

Scratch Type	Accuracy
Lateral (fast)	64.8%
Lateral (med.)	65.7%
Lateral (slow)	58.6%
Medial (fast)	56.7%
Medial (slow)	45.7%
Average	58.3%

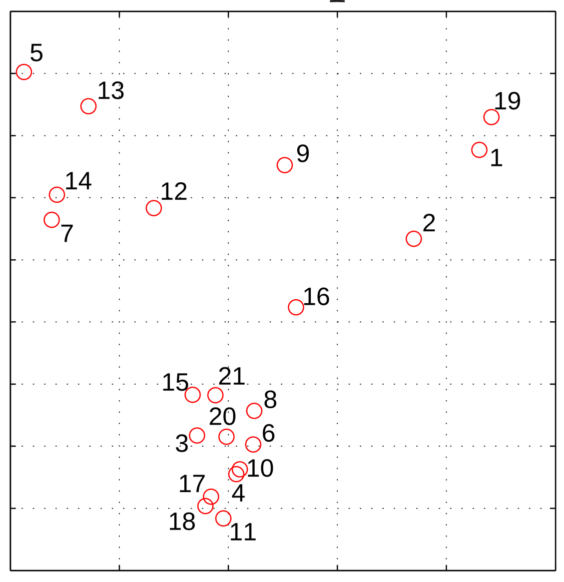
Combining Behaviors



The Confusion Matrix



Isomap[8]



The Isomap is a 2D embedding of the distance metric computed from the confusion matrix. Groups of similar surfaces that were confused often:

- the thin surfaces – the two paper surfaces (17 and 18), the bed sheet (11) and the table (10).
- the softest surfaces – cloth (3), wool (15) and air (21).

Conclusions and Future Work

- We evaluated the effectiveness of a robotic vibrotactile sense for surface recognition tasks.
- By combining data from two or more behaviors the robot was able to achieve higher recognition accuracy than for any single behavior alone.
- When the robot used all five exploratory behaviors the accuracy reached 80%.

Analysis of the confusion metric for different surfaces indicates that in many cases the surfaces that are most similar to each other (e.g. the two papers) are often confused by the robot. **This fact suggests that a robot could build a meaningful surface categorization from vibrotactile data.**

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