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Toward a biomimetic Johnston's organ for touch localization

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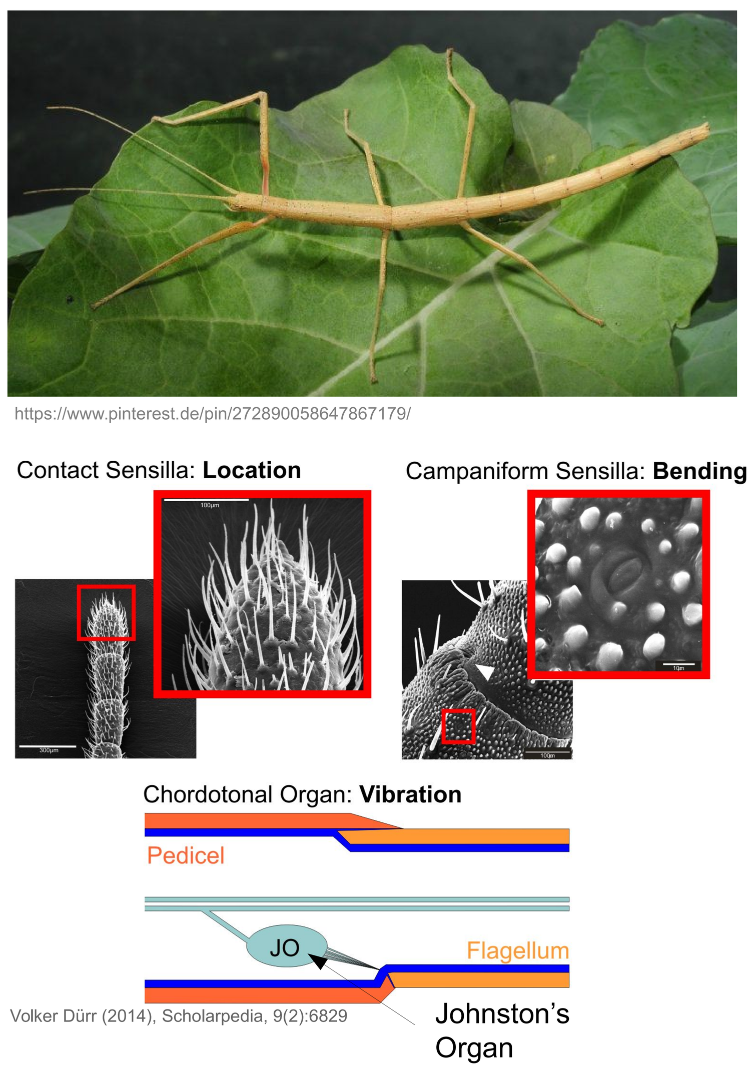
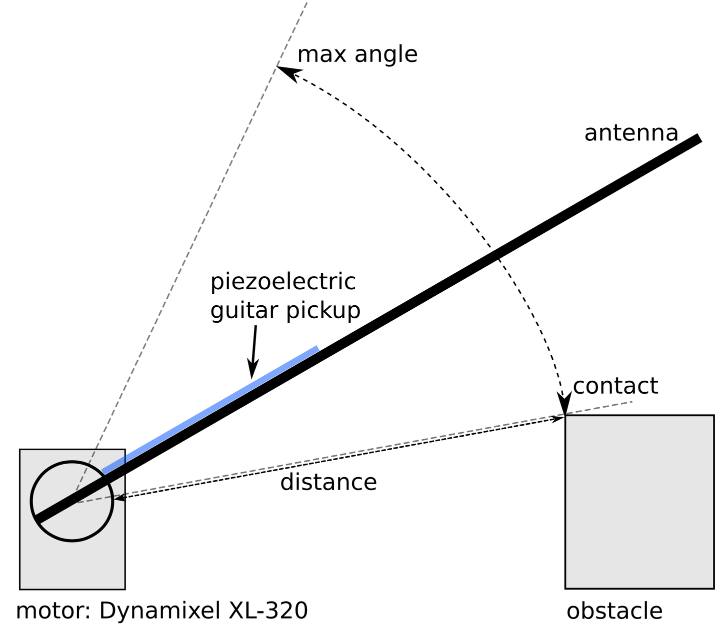
Introduction

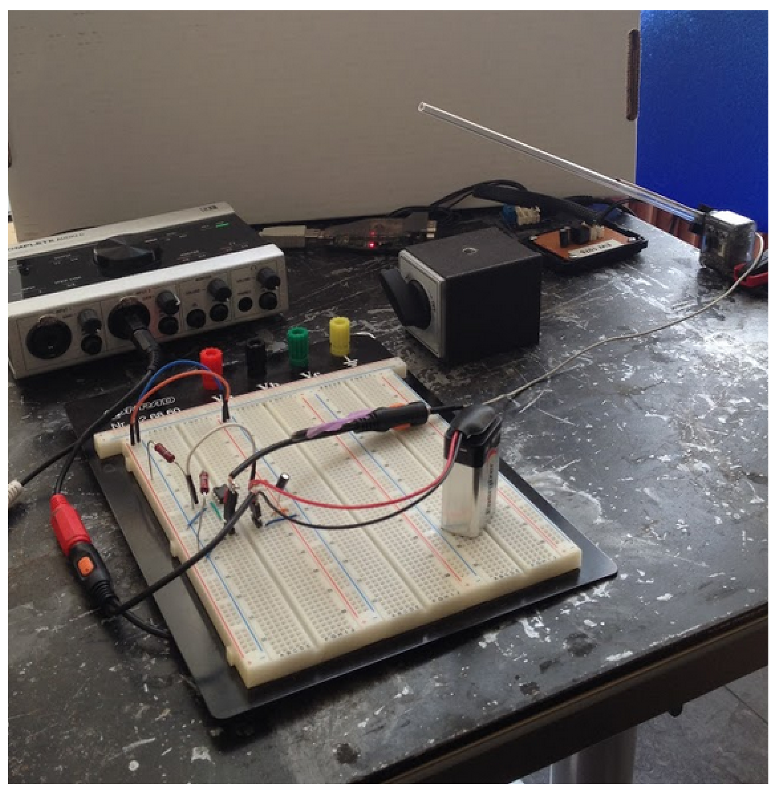
Most insects use a pair of antennae to sense their near-range environment. For example, blindfolded stick insects climb obstacles by finding footholds for their front legs using their antennae [1]. Different types of mechano-receptors present on each antenna may contribute to contact localization. One of these receptors – Johnston's organ – might respond to contact-induced vibrations [2]. Prior approaches to construct biomimetic antennae have shown that vibration characteristics can be exploited to estimate the position of a contact along the antenna, the material and texture properties of the obstacle [3,4,5]. For distance estimation, only low-frequency high-amplitude components have been exploited. Besides increasing latency due to the lasting data segments required [4], maintaining extended contact phases in realistic robot scenarios appear not practical [5]. Here, we systematically evaluate which frequency bands result in best distance estimation.



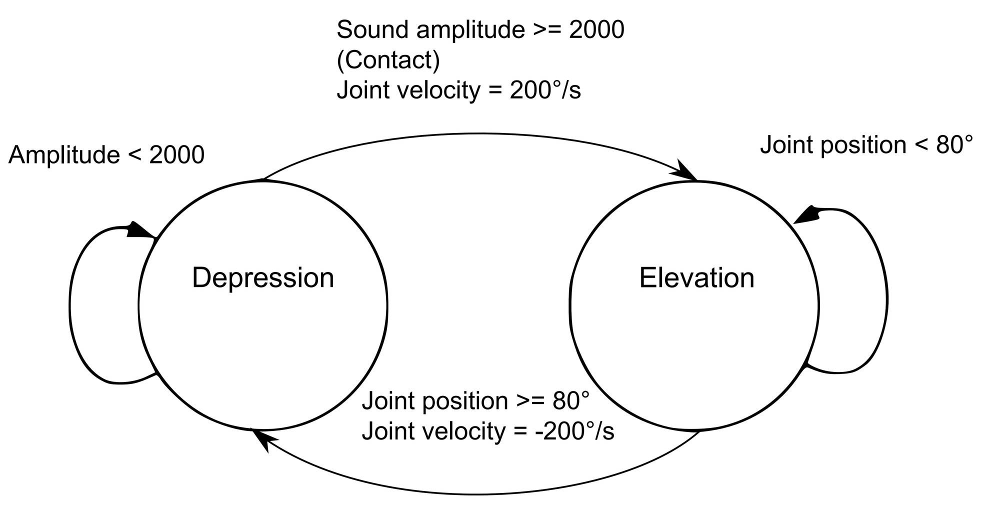
Data acquisition

Experimental Setup

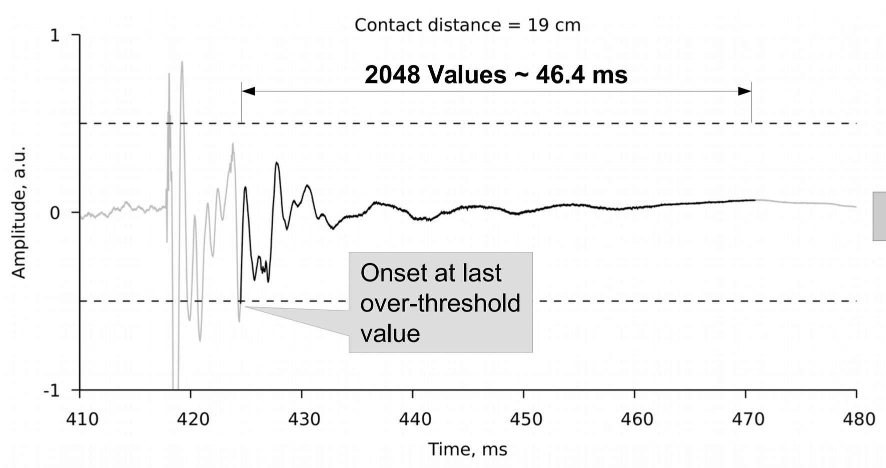




Contact distances	5, 7, 9, .., 23 cm
Contacts per distance	50
Sample rate	44100 Hz
Sample format	16 bit integer
Antenna	25 cm plastic tube
Sensor	8 cm piezoelectric pickup
Voltage buffer	11MΩ input impedance
Audio interface	NI Komplete Audio 6
Servo motor	Dynamixel XL-320
Antenna operator	2-state finite state machine

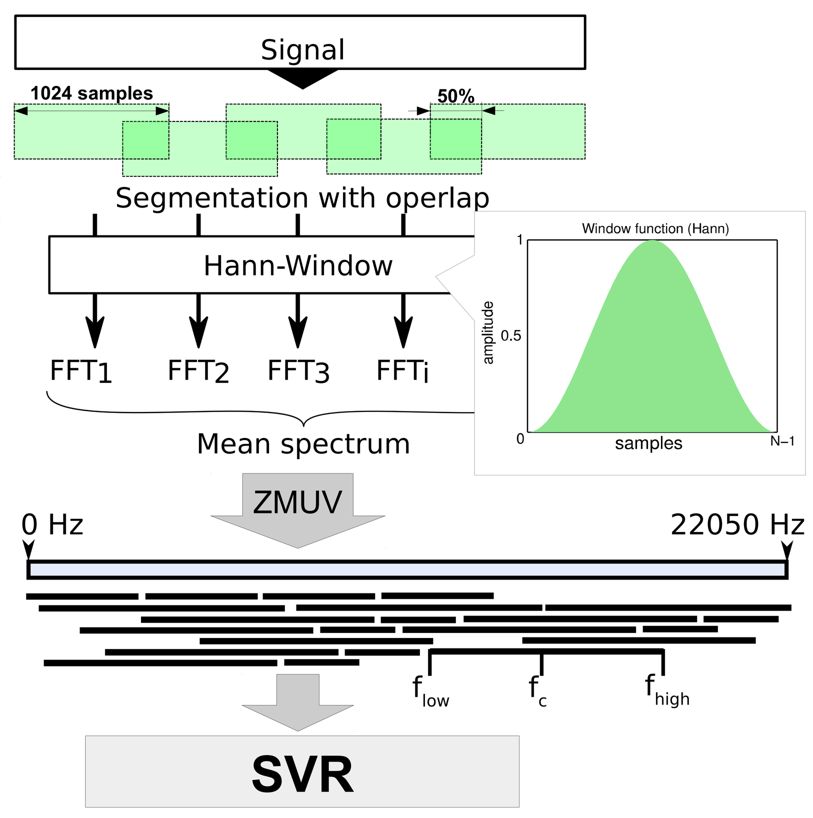


Data processing



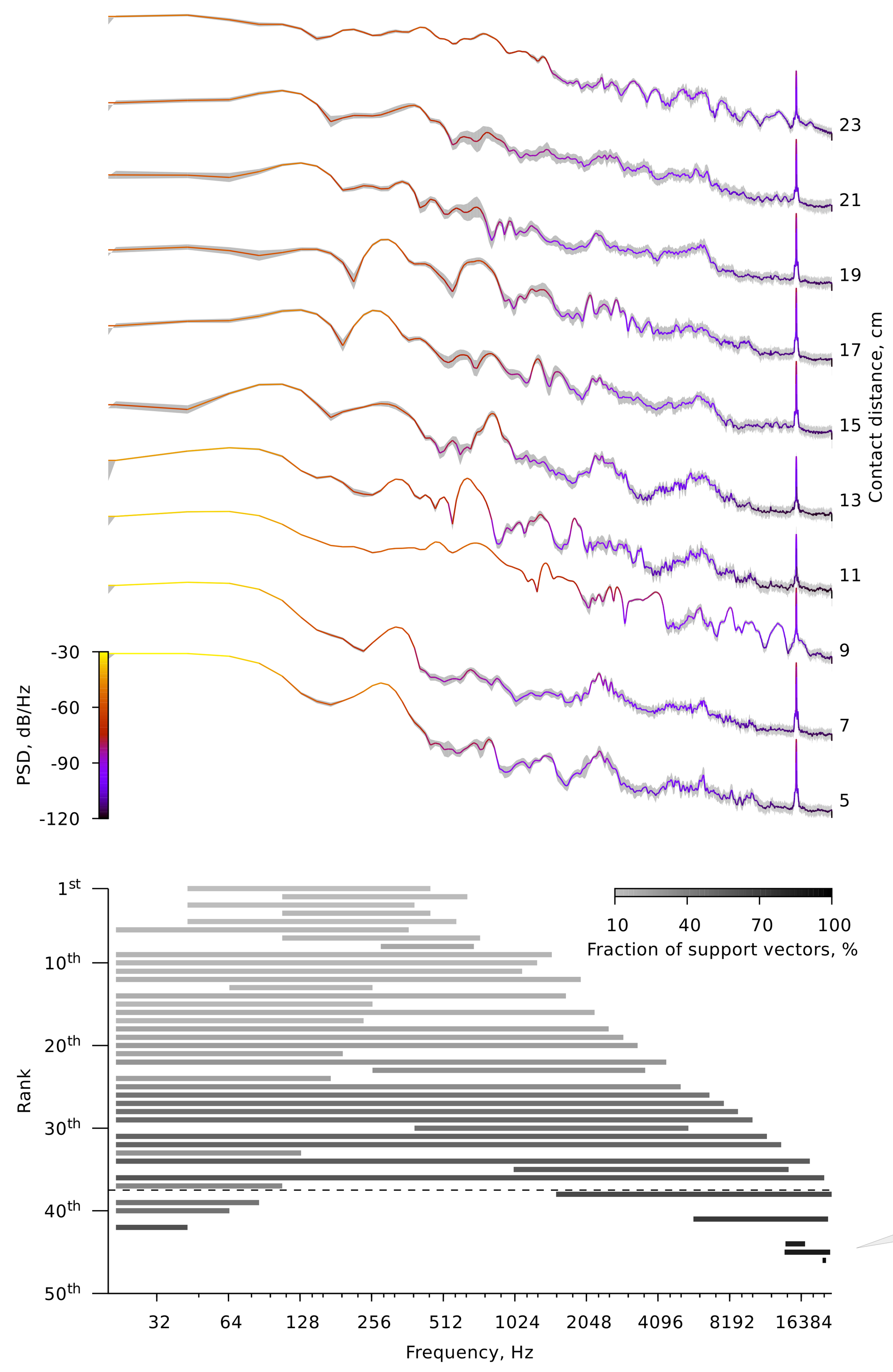
1) Cut out contact events
2) Power spectral density estimation using Welch's method
3) Zero mean unit variance scaling (ZMUV)
4) Slice spectra into every possible band defined by its center frequency f_c and fractional bandwidth (FBW)
5) Support vector regression (SVR)

$$FBW = \frac{f_{high} - f_{low}}{f_c} \qquad f_c = \frac{f_{low} + f_{high}}{2}$$



SVR parameters	
Training	35 spectra
Testing	15 spectra
Error margin ε	0.5 cm
Penalty C	10
RBF kernel	γ = 1 / spectrum length

Results



Mean Power Spectral Density (PSD)

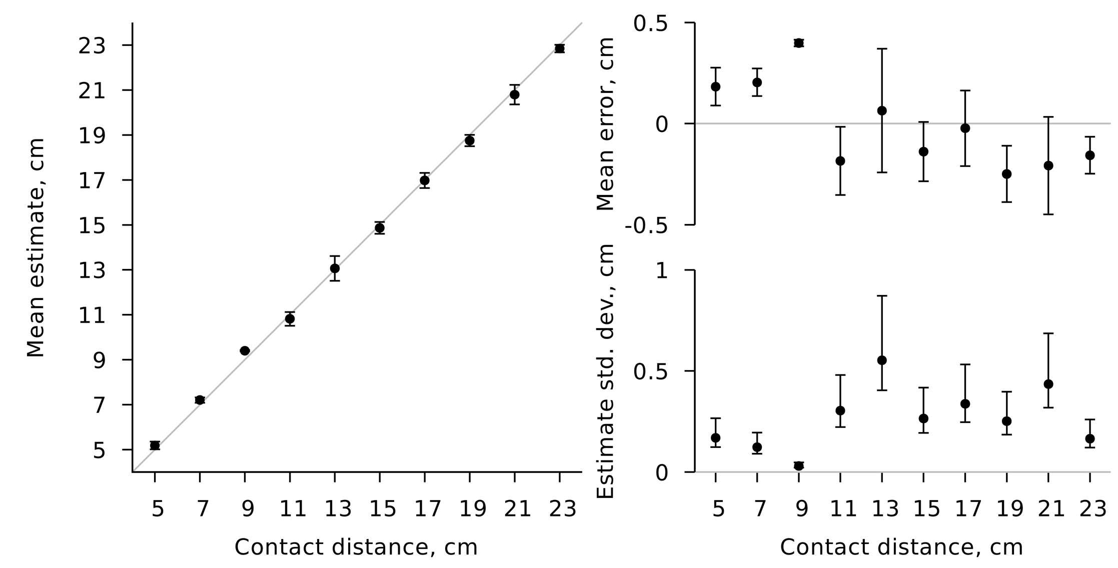
- Consistent profile per distance with low standard deviation (grey shades)
- Distance-dependent spectral changes:
  - < 640 Hz smoth transitions 640 – 5000 Hz high variability
  - > 5000 Hz similar low-power plateaus
  - ~16 kHz peak at sensor's resonance frequency

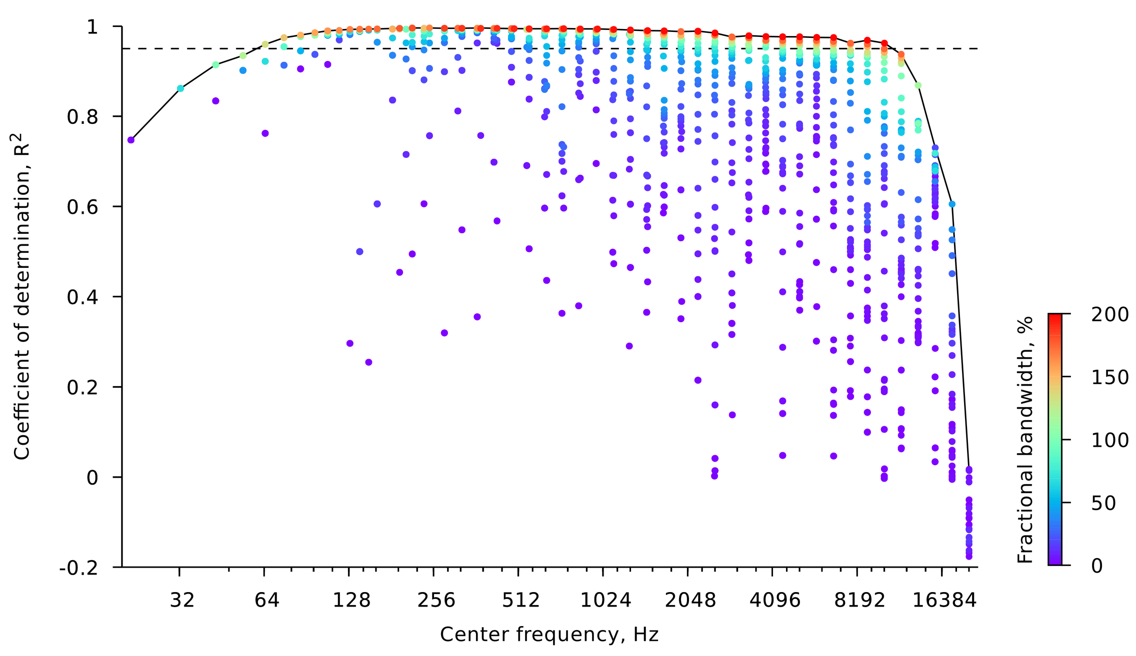
Support vector regression

- Best frequency bands for prediction
- Best: 43 – 452 Hz (R^2 = 0.996)
- 8 best bands below 640 Hz
- Only 4 out of 9 bands > 200 Hz with R^2 > 0.95
- Few wide bands starting at 20 Hz

Accuracy and precision of the best band (43-452 Hz)

- Ø-Error < 0.5 cm
- Estimate std. dev. < 0.5 cm
- 8 best bands below 640 Hz
- Distances < 10 cm high precision, less accuracy
- Distances > 10 cm less precision, high accuracy





Prediction performance for each frequency band

- High scores R^2 > 0.95 for
  - bands with center frequency f_c < 10 kHz
  - Narrow bands within low frequencies
  - Wide bands within high frequencies
- Performance drops in the upper halb of the frequency range

Conclusion and Future work

- Contact distance can be estimated from various frequency bands, including high-frequency ones.
- Power level also varies with contact distance, this is exploited by SVR
- In realistic scenarios, power level may vary with other unpredictable factors like antennal and/or obstacle speed
- How does our method generalize when antennal speed is varied?
- Mainly the lower half of the spectrum encodes exploitable distances information (up to ~ 10 kHz)
- The best frequency band for prediction which is also quite narrow, reaches from 43 – 452 Hz. Its R^2 score is 0.996.

[1] Schutz and Dürr (2011) Biomech stick insect antenna: Damping properties, JMBBM V 4 I 8, pp. 2031-2042
[2] Staudacher, E; Gebhardt, M J and Dürr, V (2005). Antennal movements and mechanoreception: Neurobiology of active tactile sensors. Advances in Insect Physiology 32: 49-205.
[3] Kim DE, Möller R (2004) A biomimetic whisker for texture discrimination and distance estimation. From animals to animats, 8, 140-149.
[4] Hoinville, Harischandra, Krause & Dürr (2014). Insect-inspired tactile contour sampling using vibration-based robotic antennae. Living Machines 2014, 118-129.
[5] Ueno, Svinin & Kaneko (1998). Dynamic contact sensing by flexible beam. IEEE/ASME Transactions on Mechatronics, 3(4), 254-264.