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Toward a biomimetic Johnston's organ for touch localization

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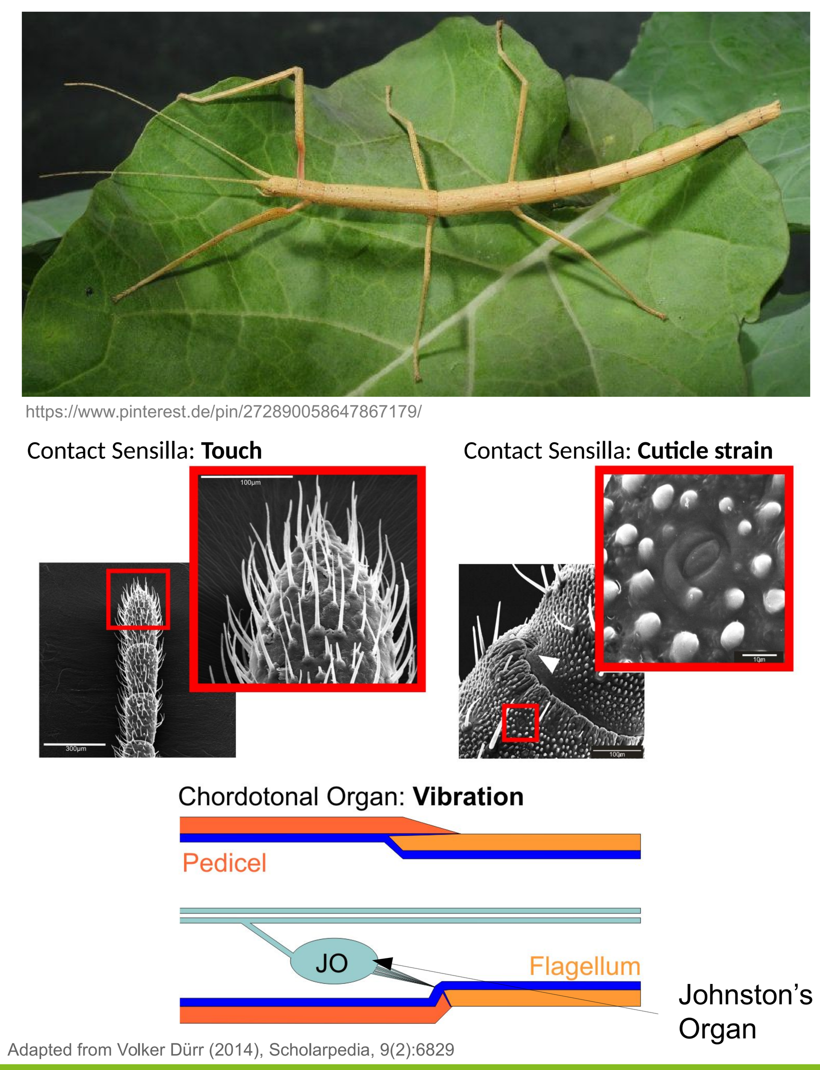
Introduction

Most insects use a pair of antennae to sense their near-range environment. For example, blind-folded 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 long sampling periods required [4], maintaining extended contact phases in a realistic robot scenario appears not practical [5]. Here, we systematically evaluate which frequency bands result in best distance estimation.

Carausius morosus



Data acquisition

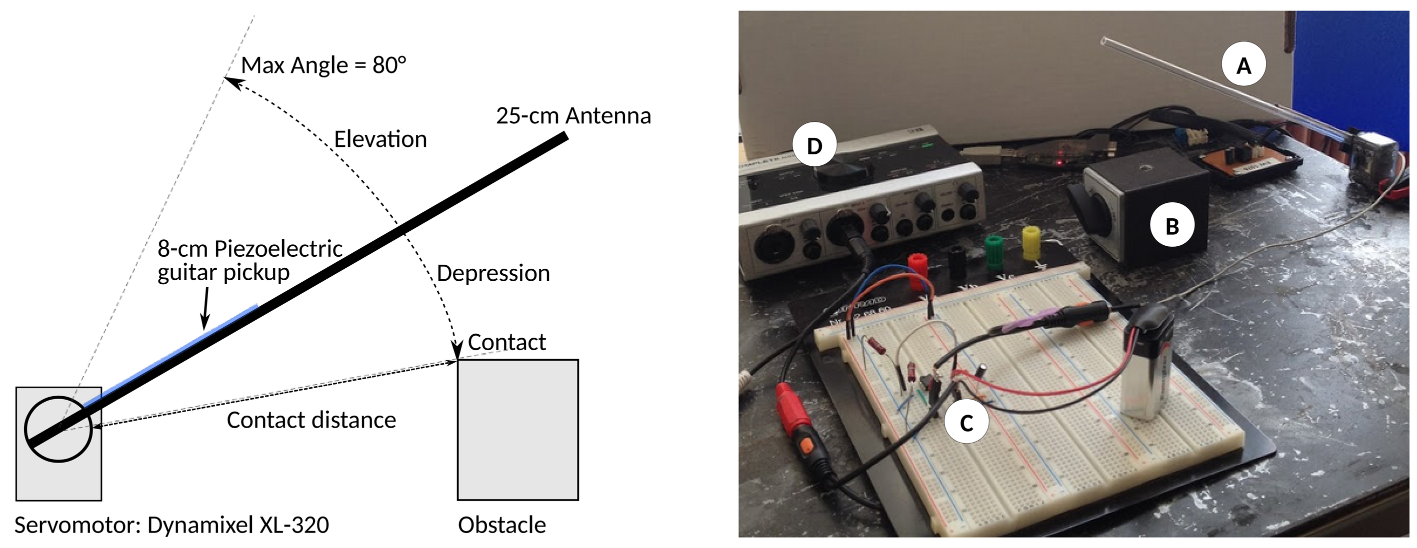
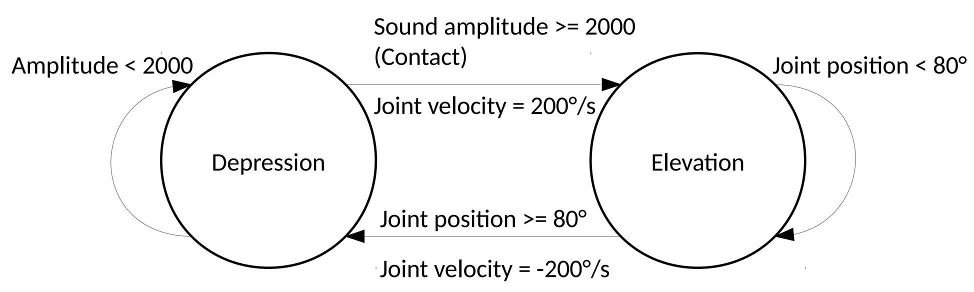


Figure 1: Experimental setup. (**A**) Antenna. (**B**) Obstacle. (**C**) Voltage buffer (11 MΩ input impedance). (**D**) Audio Interface (Native Instruments Komplete Audio 6).

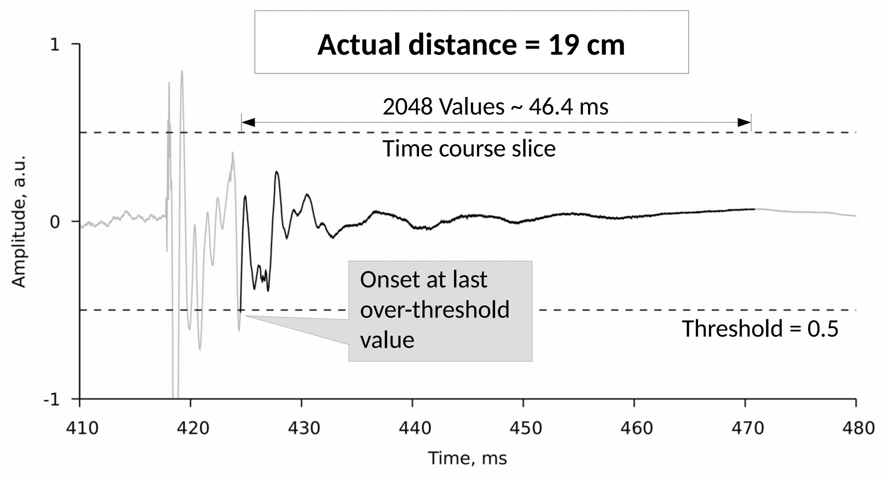
Dataset parameters

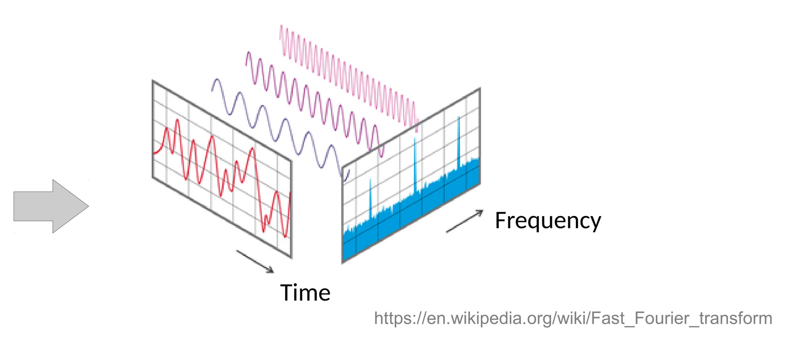
Contact distances	5, 7, 9, .., 23 cm (N = 10)
Contacts per distance	n = 50
Sample rate	44100 Hz
Sample resolution	16 bits

Finite-state machine controller

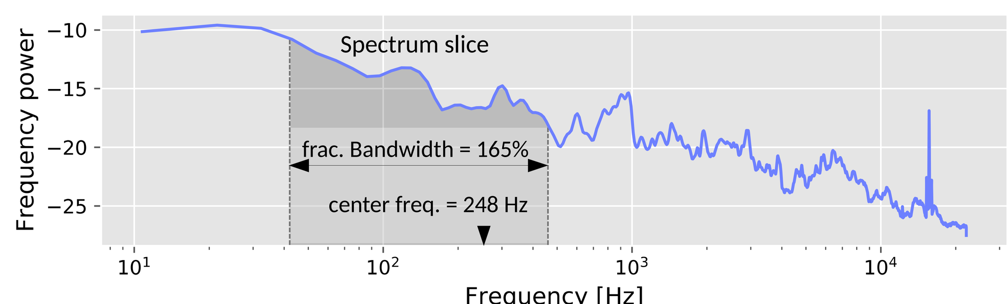


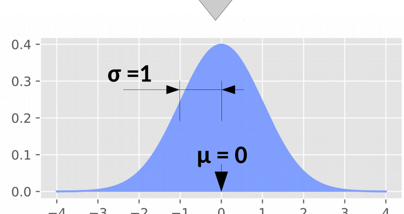
Data processing





1) Time course slicing
2) Power spectral density estimation (PSD)
   - Welch's method
   - 50%-overlapping Hann windows (width = 1024)
3) Systematic spectrum slicing
   - center frequency = (low freq. + high freq.) / 2
   - fractional bandwidth = (high freq. - low freq.) / center freq.
4) Data standardization
   - zero-mean shift
   - unit-variance scaling
5) Support vector regression (SVR)
   - training: 35 spectra per distance (70 % dataset)
   - testing: 15 spectra per distance (30 % dataset)
   - error margin, ε = 0.5 cm
   - penalty, C = 10
   - RBF kernel with γ = 1 / spectrum length

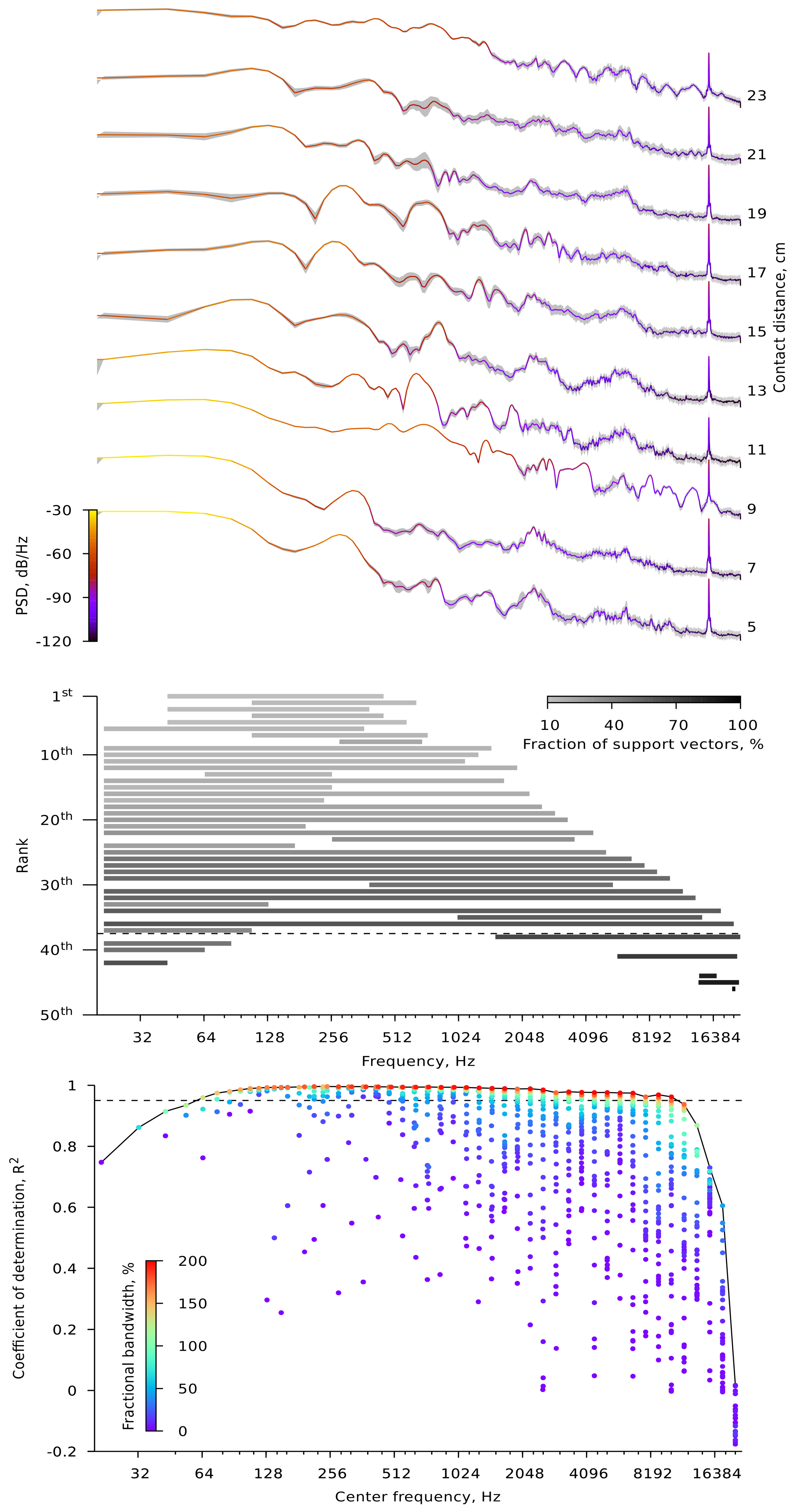




SVR

Predicted distance = 18.7 cm

Results



Power spectra

- Consistent profile per distance
- Distance-dependent spectral changes:
  - < 640 Hz smooth transitions
  - 640 – 5000 Hz high variability
  - > 5000 Hz homogeneous low-power plateaus
  - ~16 kHz peak at sensor's resonance frequency

Best frequency bands for distance estimation

- Best of all: 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, all starting at 20 Hz

Performance of each frequency band

- High scores (R^2 > 0.95) mostly for fractional bandwidth > 100%, i.e. from narrow bands within low frequencies to wide bands within higher frequencies
- Performance drops in the upper half of the frequency range (center frequency > 10 kHz)

Figure 2: (*Top*) Mean contact power spectra for each contact distance (n = 50). Shaded area, standard deviation; PSD, power spectral density. (*Middle*) Best-prediction frequency bands (sorted in descending R^2-order). Bands above the dashed line correspond to R^2 > 0.95. (*Bottom*) Prediction performance of support vector regression for periodograms of systematically varied frequency bands. Solid line, best-prediction frequency bands (see M*iddle*) over varying center frequency; dashed line, R^2 = 0.95.

Performance of the best band, 43-452 Hz

- Average errors < 0.5 cm
- Estimate spread < 0.5 cm (except at 13 cm)
- Distances < 10 cm higher precision, lower accuracy
- Distances > 10 cm lower precision, higher accuracy

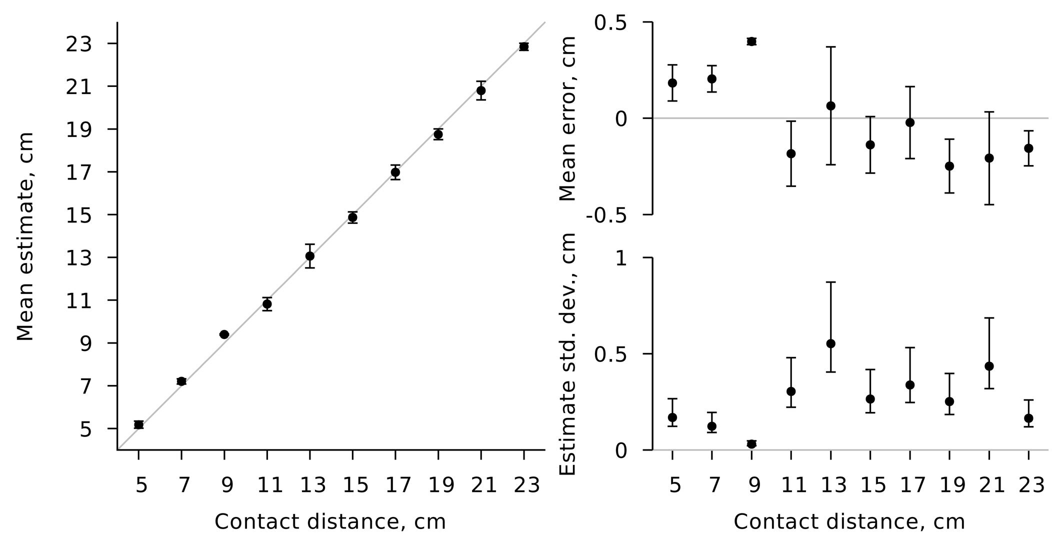


Figure 3: Prediction (*left*), accuracy (*upper right*), and precision (*lower right*) versus contact distance for the highest-score frequency band, 43–452 Hz (R^2 = 0.996). Error bars, estimate standard deviation (*left*) and 95%-confidence intervals (*right*); grey lines, ideal values.

Conclusion and Discussion

- Contact distance can be estimated from various frequency bands, including relatively high ones.
- Power level also varies with contact distance, this would be exploited by any regression method
- 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?

[1] Schütz, C., Dürr, V. (2011). Active tactile exploration for adaptive locomotion in the stick insect. Proc. R. Soc. Lond. B 366 (1581):2996-3005.
[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.