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Toward a biomimetic Johnston's organ for touch localization

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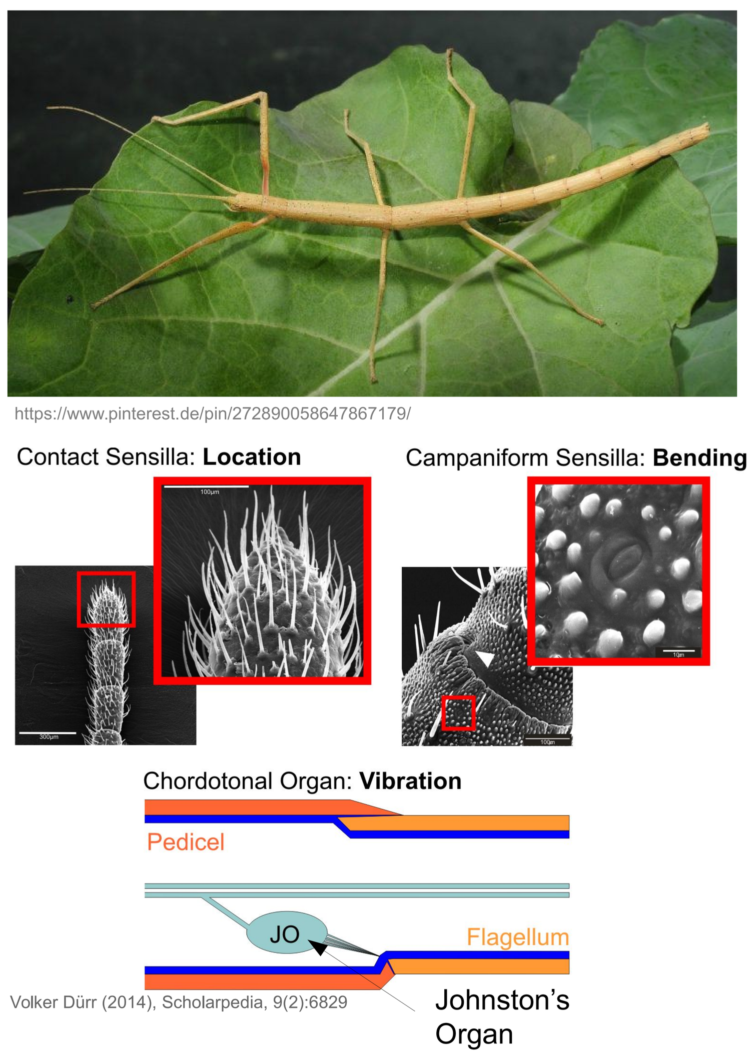
Introduction

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

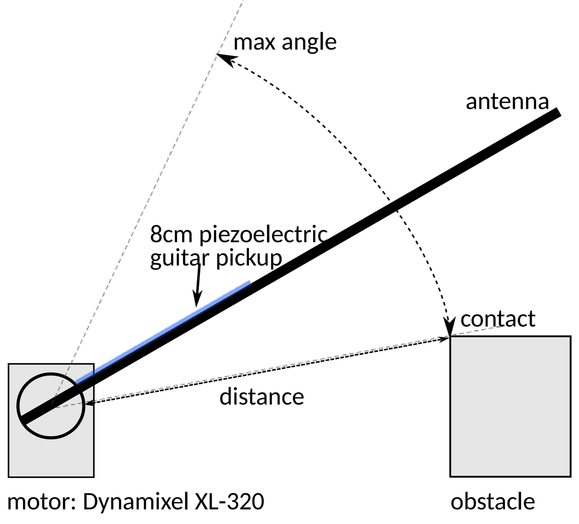
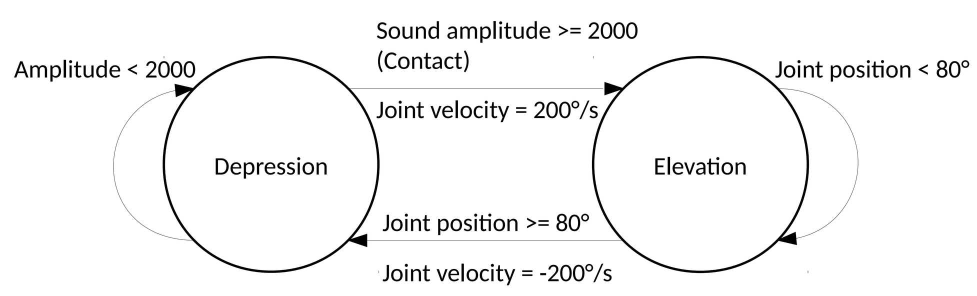


Figure 3: Setup of the antenna and the motor, moving the antenna between obstacle and max angle.

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
Voltage buffer	11MΩ input impedance
Audio interface	NI Komplete Audio 6

Finite-state machine controller



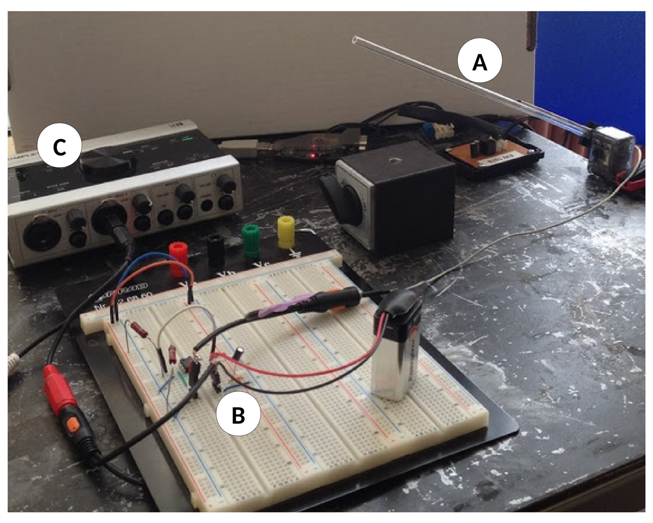
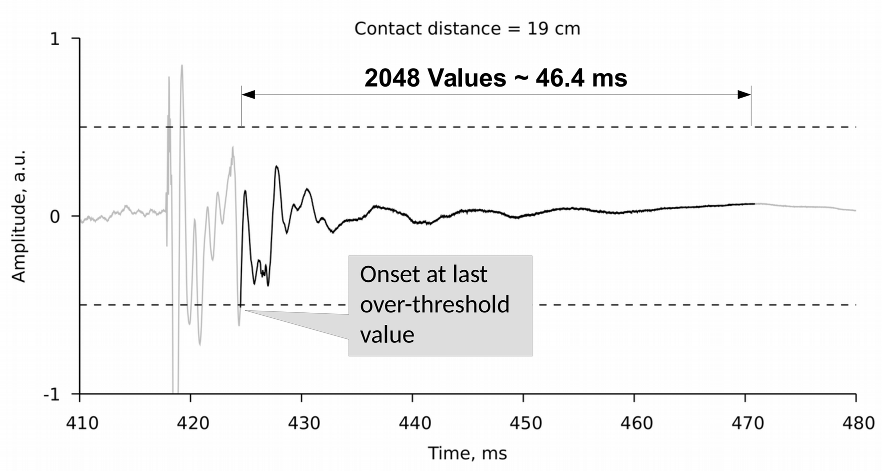
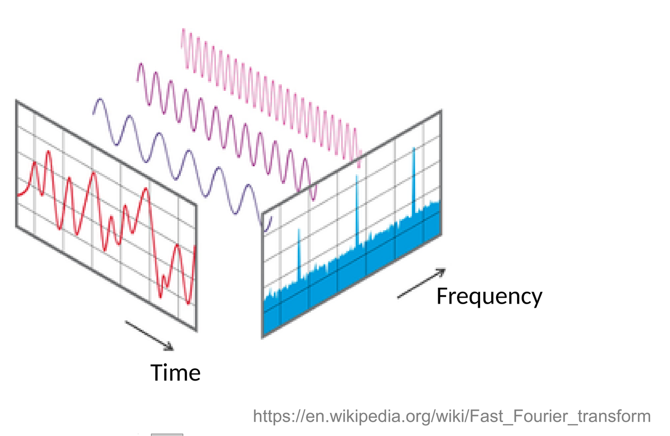


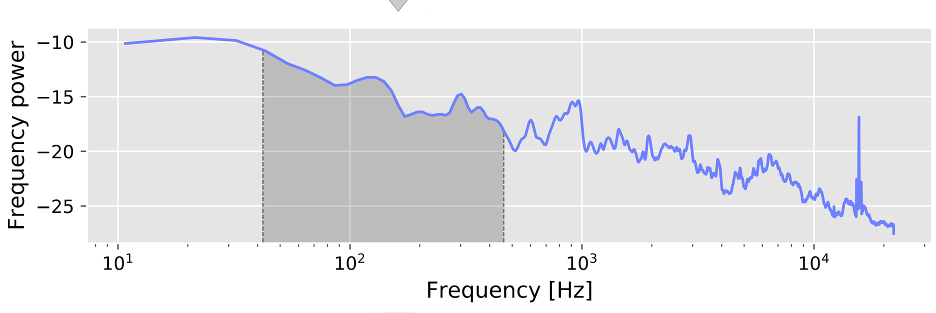
Figure 4: Experimental setup with the antenna **A** whose vibrations get picked up by the sensor, modulated by the voltage buffer circuit **B** and digitalised by the audio interface **C**.

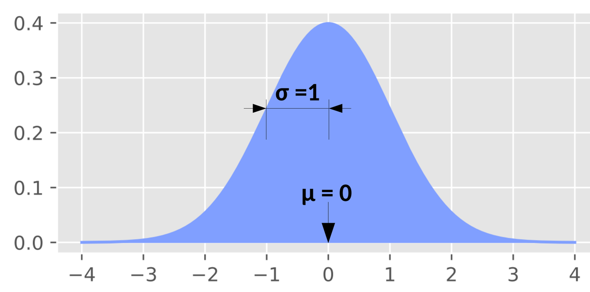
Data processing





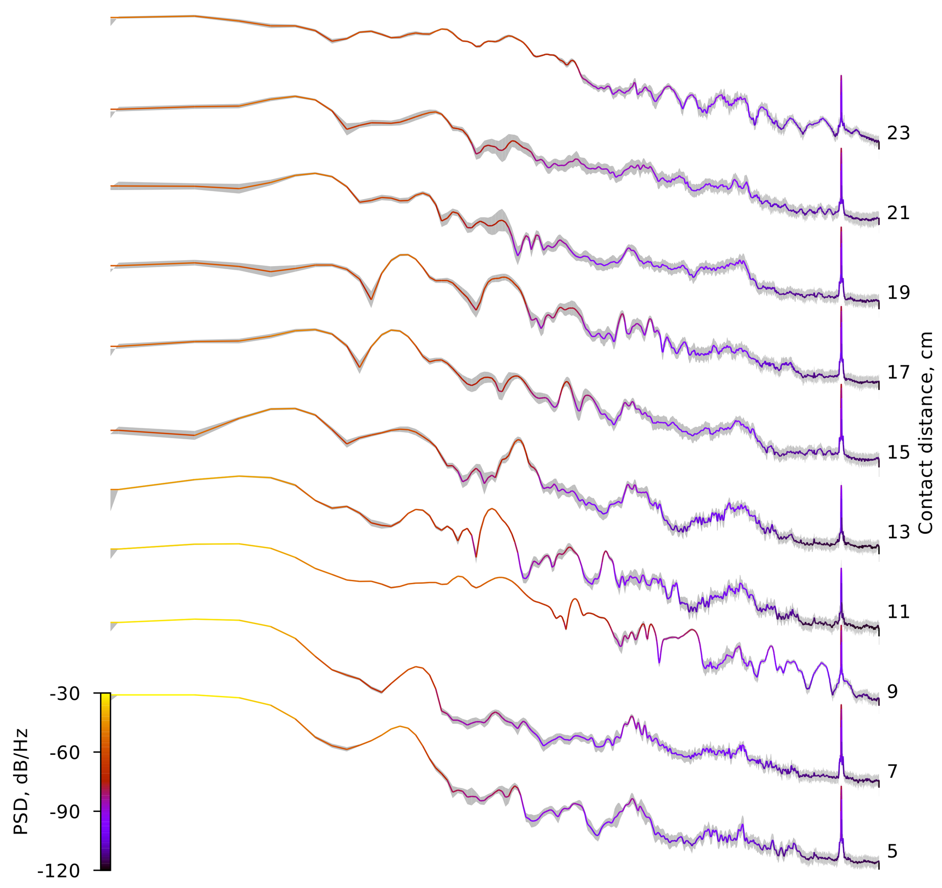
1) Contact events
2) Power spectral density estimation (PSD)
   - Welch's method
   - 50% overlapping Hann windows
3) Systematic spectrum slicing
   - center frequency:
     (low freq. + high freq.) / 2
   - fractional bandwidth:
     (high freq. - low freq.) / center freq.
4) Data standardization
   - mean = 0
   - variance = 1
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: γ = 1 / spectrum length





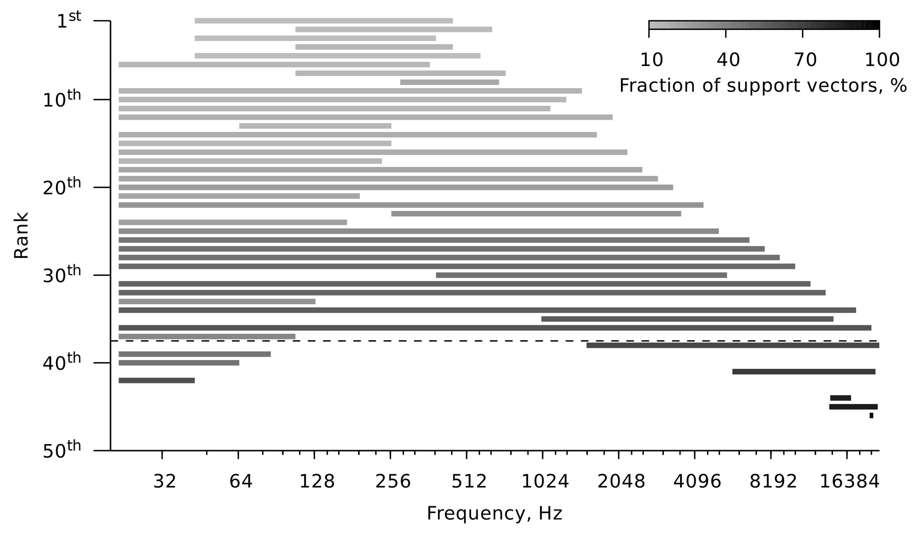
SVR → 18.7 cm

Results



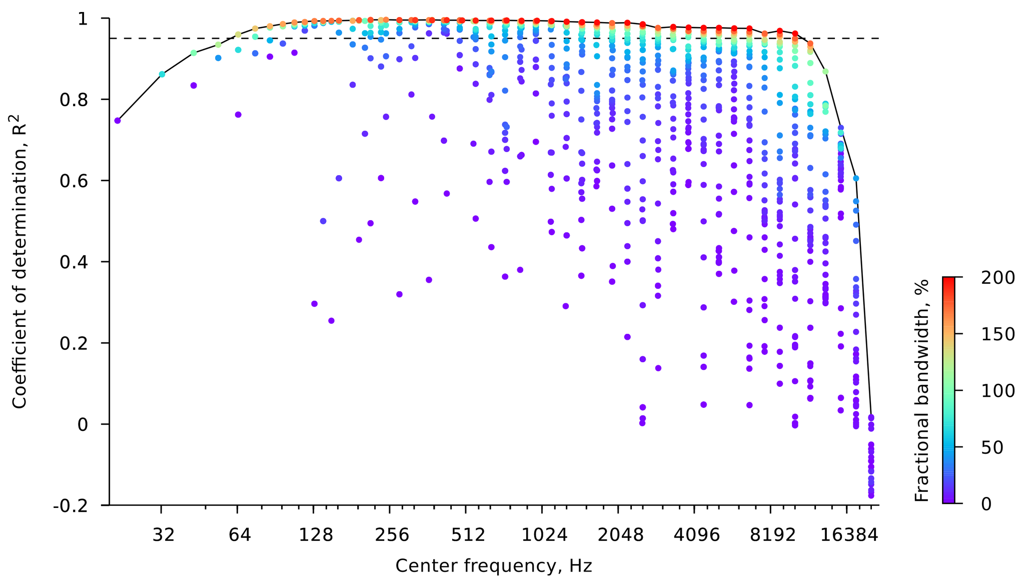
Mean Power Spectral Density (PSD)

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



Best frequency bands for prediction

- 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



Prediction performance for each frequency band

- High scores (R^2 > 0.95) for
  - 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 7: *Top*: Mean spectrum of all contacts for every recorded distance; *Middle*: Frequency bands best performing in the prediction. Dashed line marks R^2-score of 0.95. *Bottom*: Prediction performance for the center frequency with color coding representing the fractional bandwidth.

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

- Average errors < 0.5 cm
- Estimate spread < 0.5 cm (except at 13 cm)
- 8 best bands below 640 Hz
- Distances < 10 cm higher precision, less accuracy
- Distances > 10 cm lower precision, higher accuracy

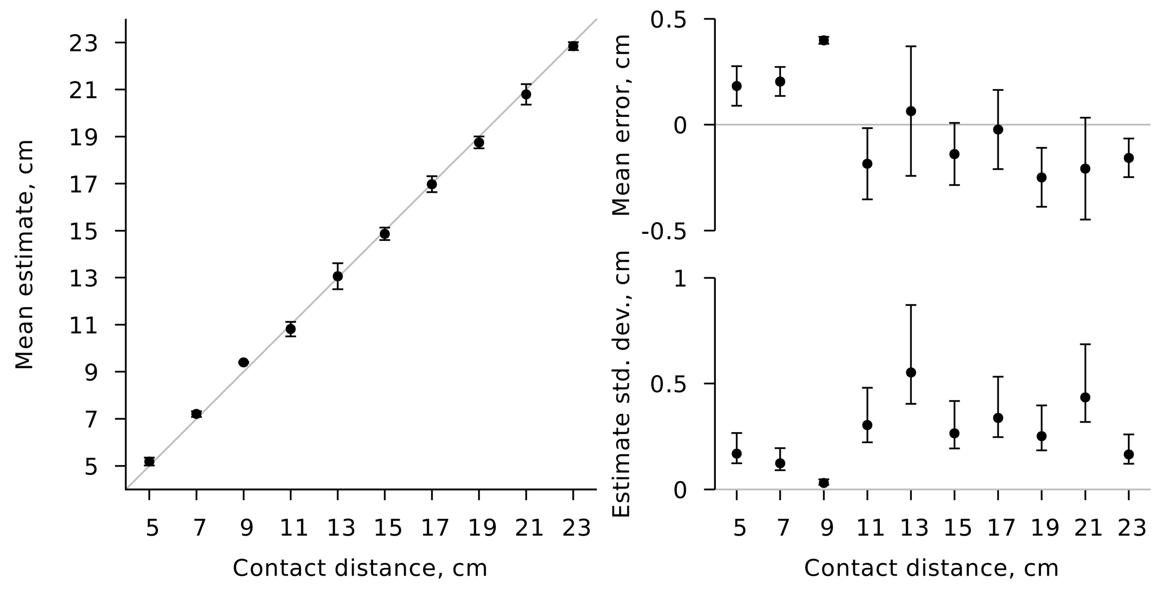


Figure 8: *Left:* Prediction accuracy of the best performing band (43-452 Hz) in the prediction for each distance. *Upper right:* Mean error with spread for each distance. *Lower right:* Variance of the predicted distance is mostly below 0.5 cm.

Conclusion and Discussion

- Contact distance can be estimated from various frequency bands, including relatively 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?

[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.
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[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.