

Investigating Slip-Induced Frequency Relationship in Dual-Channel PVDF Sensor Applied to Robotic Grippers

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Summary:

Robotic handling implements sensors (pressure, tactile, acoustic) for slip sensing and regulating grasping forces. We investigated dual-channel PVDF acoustic sensors embedded in a compliant gripper and characterized them in the frequency domain across 159 grasp trials (72 slip, 87 non-slip). Slip was shown to significantly alter the frequency-selective relationship between the inner and outer sensors, which is absent below 100 Hz and strongly amplified above it (effect size up to 0.97). A threshold model was developed and achieved 81.7% cross-validated accuracy in distinguishing slip from no-slip events.

Keywords: Sensors, slip detection, robotics, signal processing, MEMS

Title

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Background, Motivation and Objective

One of the challenges in robotic grasping is sensing slippage for reliable object manipulation and damage avoidance, for which optical, pressure, tactile, and acoustic sensors are common approaches [1]. Piezoelectric polyvinylidene fluoride (PVDF) sensors have been deployed for slip detection [2] but have lacked robustness [3]. Multi-channel configurations are one solution to improve accuracy, reliability, and repeatability attributed to their ability to cancel out noise [4]. We instrumented two independently acquired PVDF channels on the inner and outer surfaces of a fin-ray finger, providing a low-cost and convenient solution for slip sensing, and investigated the frequency-domain relationship between the two channels as well as their correlation with slip events.

Description of the New Method or System

A compliant Fin Ray gripper [5] (Fig. 1) was instrumented with two PVDF sensors (TE Connectivity Measurement Specialties DT4-028K/L), each connected to one channel of the charge amplifier with the exact same configurations (OPA2134, Fig. 2), and output AC-coupled to a UGREEN USB audio interface sampling at 48kHz using a NVIDIA Jetson Orin Nano. For each of 159 grasp trials performed by a myCobot 280 robotics arm, spanning three object types (Fig. 3), a 1 second segment was extracted from the onset of the lifting motion and labeled with

visual inspection. Power spectral density was estimated per channel using Welch's method (4096-sample Hann windows, 50% overlap), from which spectral centroid (1), bandwidth (2), and energy (3) in three frequency bands (10-100, 100-2000, 2000-10000 Hz) were calculated per trial.

Results

Inner is systematically higher than outer in both conditions (Fig. 4); slip trials show 10-15 dB higher overall PSD across the broadband spectrum than no-slip.

As shown in Tab. 1, in slip trials, inner exceeds outer across all five features. Under no-slip, this holds for centroid and Band 1/2 energy, but reverses for bandwidth (114.9 vs 223.8 Hz). Slip, therefore, does not merely amplify an existing bias, but restructures which channel dominates.

Accordingly, the inter-channel energy difference is significantly larger during slip than no-slip in Band 2 and Band 3, with no difference in Band 1 (Tab. 2; Fig. 4), which is directionally consistent across all three tested objects, suggesting a structural rather than object-specific origin. Beyond statistical characterization, we tested whether this spectral relationship supports a coarse slip/no-slip distinction.

A single fixed-threshold classifier on Band 2 ΔE achieved 81.7% accuracy and an F1 score of 0.79, indicating the relationship carries directly usable information even without a learned model. Fusing the full feature set (centroid, bandwidth, all bands) across a broader sensing and control pipeline is the subject of ongoing system-level work.

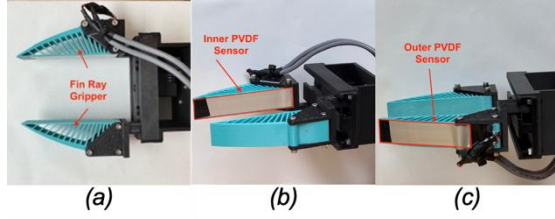


Fig. 1 Hardware setup of the Fin Ray Gripper (a), attached with inner (b) and outer (c) PVDF Sensors

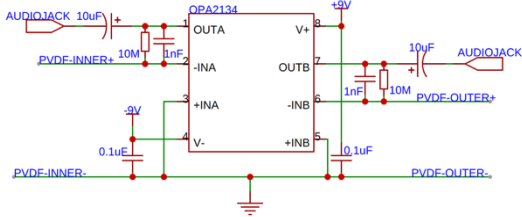


Fig. 2 Schematic for OPA2134 Amplifier Circuit

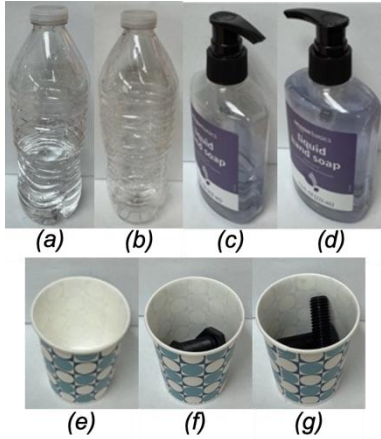


Fig. 3 Object used for slip data collection, including plastic water bottle (a: 243.51g, b: 10.77g), hand soap bottle (c: 215.25g, d: 289.84g), and paper cup (e: 2.29g, f: 61.78g, g: 68.14g)

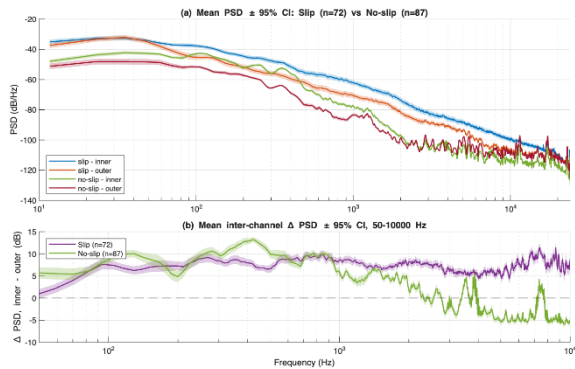


Fig. 4 (a) Mean PSD ($\pm 95\%$ CI) of inner and outer channels for slip ($n=72$) and no-slip ($n=87$) trials. (b) Mean inter-channel PSD difference (inner - outer, dB) $\pm 95\%$ CI, 50-10000 Hz, for slip vs no-slip trials.

Tab. 1 Inner vs outer statistics, slip ($n=72$)/no-slip ($n=87$); note the sign reversal for bandwidth and Band 3 (ES, rank-based). ES = effect size; energy in a.u.

Feature	Slip: In/Out	No-slip: In/Out	ES: Slip/NS
Spectral centroid (Hz)	108.9/72.9	126.6/111.0	0.88/0.38
Spectral bandwidth (Hz)	182.4/133.4	114.9/223.8	0.83/-0.86
Band 1 energy (10-100 Hz)	0.047/0.040	0.0071/0.0063	0.31/0.44
Band 2 energy (100-2000 Hz)	0.023/0.008	0.0051/0.0007	1.00/1.00
Band 3 energy (2000-10000 Hz)	6.0e-4/1.4e-4	4.35e-7/3.24e-7	1.00/-0.54

Tab. 2 Inter-channel energy difference (ΔE), slip vs no-slip (Mann-Whitney U). ES = effect size.

Band	Slip	No-slip	p (ES)
Band 1 (10-100 Hz)	5.3e-3	7.2e-4	0.107 (n.s.)
Band 2 (100-2000 Hz)	1.56e-2	4.37e-3	<0.001 (0.75)
Band 3 (2000-10000 Hz)	8.45e-5	1.1e-7	<0.001 (0.97)

Equations

$$f_c = \frac{\sum f \cdot P(f)}{\sum P(f)} \quad (1)$$

$$BW = \sqrt{\frac{\sum (f - f_c)^2 \cdot P(f)}{\sum P(f)}} \quad (2)$$

$$E_{band} = \sum_{f_1}^{f_2} P(f) \quad (3)$$

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