Transforming Tactile Interfaces: Tri-Axis Force Sensor for Sensory Signal Processing*

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***Abstract*— We developed a soft tri-axis magnetic field based tactile sensor, applicable to the fingertips of a human or anthropomorphic robot hand. The resulting signals pass through a mechanotransduction model to generate artificial neural signals that mimic the touch receptors of human skin.**

I. Introduction

Tactile sensors integrated into artificial hands enable cutaneous user feedback and benefit safe interaction with the environment and dexterous manipulation of objects [1]. We demonstrate the feasibility of a versatile tri-axis tactile sensor with neural signal processing. As a wearable sensor, it enables insights into the neural mechanisms during grasping while it sets the foundation for receptor-specific cutaneous user feedback when integrated into an artificial hand.

II. Methods

As depicted in Fig. 1A, a three-axis magnetic force sensor was designed based on [1] and embedded in a cast-molded ring-shape silicone cover that can be attached to human or artificial fingers (Ecoflex 00-50, Smooth-On Inc., USA). It was composed of a round magnet (Ø2x0.7mm, NdFeB nd45, Magnetkontor, Germany), a Hall sensor integrated circuit (IC) (MLX90393, Melexis, Belgium), and a custom-made PCB (see Fig. 1B). When normal or shear forces were applied, a change in the magnetic field occurred due to the displacement of the magnet (max. distance 5mm). The calibration setup consisted of a Panda robot arm (Franka Emika, Munich, Germany) equipped with a three-axis force sensor (K3D40-50N, ME-Messsysteme, Hennigsdorf, Germany). A total of forty trials, each with three repetitions, were performed, where normal forces F_z (0-10N) and shear forces F_R (0-4N) were applied by the robot at angles between 0° to 315° with respect to the z-axis, using a rectangular probe of 25x25mm. Two fourth order polynomial calibration curves for the estimation of the applied forces $F_z^{'} = f(Br, Bz)$ and $F_r^{'} = f(Br, Bz)$ were fitted using MATLAB (R2022a, Mathworks Inc., USA) based on the normalized magnetic flux B_x, B_y, B_z, and the resulting radial flux B_r. A simplified transduction model was expressed using the Izhikevich model [2], which describes the dynamic adaption of the sensory neuron in response to the membrane current. The force signals were passed through this transduction model to generate neural spikes mimicking human mechanoreceptors.

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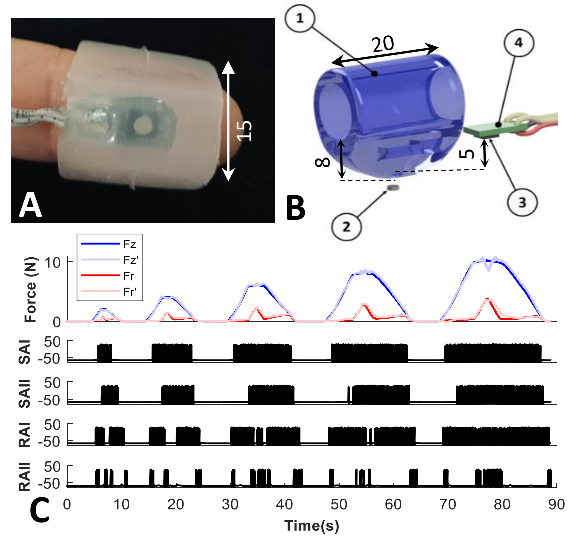

Fig. 1. Panel A: Sensor ring prototype; Panel B: Exploded view (1: silicone ring, 2: magnet, 3: Hall sensor, 4: custom PCB); Panel C: Ground truth (F) and Calibrated sensor signals (F') in normal (F_z) and shear force (F_r) and the respective neural spikes mimicking SAI, SAII, RAI and RAII receptors.

III. Results and Conclusion

A sensor calibration was performed, resulting in $R^2_{Fz} = 99.3\%$ and $R^2_{Fr} = 96.8\%$ and a sensor accuracy of $\overline{\Delta F} z = 0.017 \pm 0.41N$ and $\overline{\Delta F} r = 0.008 \pm 0.22N$. The mean of three trials of force application for 180° angle and the corresponding neural spikes, considering slowly and rapidly adapting type I and II responses are shown in Figure 1C. The SAI is associated with the magnitude of normal force, the SAII relates to the lateral force, while RAI is the first-time derivative of the magnitude of applied force, and finally, the RAII afferent relates to the second-time derivative of the applied force. In the next steps the neural spikes will be generated in real-time and fed into a multi-body musculoskeletal model of a hand in order to assess grasp stability in a user-in-loop scenario. This approach has the potential to advance our understanding of neural mechanisms underlying sensory motor control during grasping and manipulation.

References

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