Main Article
Model-driven development of robot software

Promovendi
A bio-inspired hair-based acceleration sensor

```c
int main(void) {
    int angle;
    while(1) {
        angle = readSensor();
        ...
    }
    return 0;
}
```
Crickets use so-called clavate hairs to sense (gravitational) acceleration to obtain information on their orientation. Inspired by this clavate hair system, a one-axis biomimetic accelerometer has been developed and fabricated using surface micromachining and SU-8 lithography. Measurements show that this MEMS hair-based accelerometer has a resonance frequency of 320 Hz, a detection threshold of 0.10 m/s² and operates around the energy levels of more than 35 dB.

Figure 1: Artist’s reconstruction of the clavate hair-based sensory system of the cricket (Acheta domestica).

For measuring (gravitational) acceleration, numerous types of accelerometers have been realized over the past years using MEMS technology, with applications in e.g. the automotive industry and navigation. Current state-of-the-art commercialized MEMS accelerometers show formidable performance in range, resolution and noise floor. In contrast to the cricket’s clavate system, MEMS accelerometers are usually not hair-based systems and frequently contain feedback electronics. To explore some of the intricacies of the clavate hair system and assess its potential to engineering applications (e.g. automotive industry, robotics and motion tracking), we aim for the design, fabrication and characterization of a bio-inspired accelerometer. Bio-inspired hair-based structures have been exploited earlier with applications in both actuators and sensing of physical quantities, but seldom for inertial measurement.

Design

Mechanically, the hair-based accelerometer can be understood as a so-called inverted pendulum which is subjected to external accelerations. It is described as a second-order rotational-mechanical system with moment of inertia, a rotational stiffness and a rotational damping. Usually, in the models the hairs are treated as cylindrical structures, causing the moment of inertia to depend strongly on the hair diameter and the hair length.

Figure 2: Design (a) and fabrication (b) of the MEMS hair-based accelerometer fabricated by surface micromachining and using SU-8 lithography.

The sensor is fabricated on a silicon-on-insulator wafer. Trenches are etched in the silicon device layer using DRIE. A layer of 200 nm stoichiometric Si3N4 is used for covering and protecting the trenches. The device layer contains two electrodes, which are used for capacitive readout of the acceleration-induced movement. On top of the Si3N4 layer, a sacrificial layer of poly-silicon (1.5 µm) is deposited by LPCVD. The sensor membrane and springs are constructed by depositing and patterning a 1 µm Si3N4 layer on top of the poly-silicon. Aluminium (80 nm) is sputtered on top of the membrane to create the electrodes for capacitive read-out. Our artificial clavate hair is created by two layers of SU-8, to realize both the centre of mass towards the top of the hair structure and a total hair length of about 800 µm with an average diameter of about 80 µm. Finally, to release the membrane the sacrificial poly-silicon layer is removed using SF6 etching. The fabrications results are shown by the SEM image in figure 2b.

Fabrication

The fabrication process for the bio-inspired accelerometer is based upon the process for cricket-inspired bio-inspired hair flow sensors, previously developed in the TST group. A schematic overview of the bio-inspired accelerometer with the materials indicated is shown in figure 2a.

Experimental

First, the frequency response of the hair-based accelerometer was measured using capacitive read-out in the direction perpendicular to the rotational axis. Frequencies within a range of 50–1000 Hz were applied to a shaker used for applying accelerations. A reference accelerometer was used to de-
terminate the externally applied acceleration amplitude. The resulting measured magnitude response of the bio-inspired accelerometer is shown in red in figure 3. Here, the circles represent the measurements and the dashed line exhibits the analytical model base, where the resonance frequency and the quality factor were fitted. We observe good agreement between model and measurements, where the resonance frequency is found to be about 320 Hz.

The sensor’s directivity was measured by rotating it over 360 degrees, with steps of 10 degrees, with respect to the direction of the applied external acceleration, while using capacitive read-out. To this end harmonic acceleration with a frequency of 80 Hz was applied and the output voltage was measured by a multimeter (Keithley 2000). The obtained results are shown in figure 4. We observe that the measurements are in close agreement with the theoretical response for a so-called figure-of-eight. The measurements indicate that the hair-based accelerometer has a maximum responsivity for both 0 degree and 180 degree, which coincides with the direction perpendicular to the rotational axis of the hair sensor.

To describe the sensor’s signal-to-noise ratio (SNR) as a function of acceleration amplitude as well as the sensor’s detection threshold, the signal and noise powers are considered. The signal is assumed to have a linear relationship with respect to the acceleration amplitude, given by a coefficient. This coefficient is directly related to the sensor’s rotational angle and therefore has a dependency on the acceleration frequency. Experiments to determine the sensor’s linearity were performed by choosing first a specific acceleration frequency (80 Hz) and then by varying the acceleration amplitude.

Figure 4: Measured directivity of the hair-based accelerometer using capacitive read-out at an acceleration frequency of 80 Hz.

Subsequently, from the measured output rms-voltage the sensor’s detection limit and linearity are derived. The results are shown in figure 5, where the points represent the measurements, the solid line represents the analytical model, and the dashed lines indicate the constant equivalent noise amplitude and ideal linear response asymptote. We observe that for accelerations with amplitudes of more than 0.10 ms\(^{-2}\), indicated by the intersection of the asymptotes, the hair-based accelerometer exhibits a clear linear relationship with the applied acceleration. Below this amplitude, the sensor’s output is dominated by noise (SNR<1).

To get some insight in the accelerometer’s noise performance and stability, an Allan variance measurement was performed. The zero-acceleration output rms-voltage was measured with a time interval of 20 ms for a period of 2 h using a multimeter (Agilent 34401A) connected to LabVIEW. The results of the subsequently calculated Allan deviation are shown in figure 6, together with asymptotic lines for both the velocity random walk and the bias instability. From the linearity measurements, the error on full-scale (i.e., the measurement taken at highest acceleration of 6.12 ms\(^{-2}\), see figure 5) was calculated and found to be 3.3%. By considering the detection threshold and the full scale acceleration amplitude, the bias instability for determination of orientation using the Earth’s gravitational field.

Conclusions

A biomimetic accelerometer has been developed and fabricated using surface micro-machining and SU-8 lithography, inspired by the clavate hair system of the cricket. We showed that this MEMS hair-based accelerometer has a resonance frequency of 320 Hz, a detection threshold of 0.10 ms\(^{-2}\) and a dynamic range of more than 35 dB. Further, the accelerometer has a clear directivity and a bias instability of 5×10^{-3} ms\(^{-2}\).

Figure 6: Measured Allan deviation using capacitive read-out.

Discussion

Generally, the susceptibility for (gravitational) acceleration is used by crickets for determination of their position and orientation. The hair-based accelerometer described in this work allows in principle also for determination of orientation using the Earth’s gravitational field. That is, by measuring the projection of the Earth’s gravitational acceleration on the angle of rotation of the accelerometer with respect to Earth can be determined. However, since the fabricated accelerometer has limits with respect to resolution, an error in this angle will result. Based on the experimental data, this error is calculated to be in the order of 0.7 degrees for accelerations well below resonance, which emphasizes the potential use of this accelerometer to determine orientation. Notice that this value approaches the resolution of the cricket’s clavate hair system of 0.1 degree.

As we have shown in figure 4, the hair-based accelerometer has strong directivity. In our MEMS version, this directivity stems from both the mechanical design, which primarily allows rotation around the torsional axis of the sensor, and the differential capacitive read-out, which causes a strong reduction of signals caused by tilting of the hair. As a consequence, multiple hair-based accelerometers may be used simultaneously to sense accelerations in 3D. In crickets, filiform hairs have been shown to have preferential directions of rotations with ratios in stiffness of ‘hard over easy’ directions between 4 and 8. It was demonstrated previously that such directivity exists in the cricket’s clavate hairs. Additionally, it was shown that crickets use the many clavate hair-sensors on their cerci for determination of their orientation relative to the gravitational field and that they do so both with respect to roll (rotation around the longitudinal axis of the animal) and pitch.

Further reading: