Bio-inspired sensing

5/23/2018
Bio-Inspired Sensors

- Visual sensing
  - Compound eye (insects)
  - Ocelli (flies)

- IR sensing (bees)

- Gyroscopes
  - Haltere (flies)

- Chemical sensing
  - Odor (antenna, feet, nose, etc.)

- Electrical sensing (electric fishes, sharks)

- Contact and surface sensing
  - Antenna, whiskers, …

- Flow sensing
  - Body hairs, whiskers, …
Haltere Gyroscopes

- Two halteres for 3D rotational velocity sensing
- Directly connect to flight steering muscles
- Required for stable flight
- $180^\circ$ out of phase oscillation but the same frequency with the wings
THE GYROSCOPIC MECHANISM OF THE HALTERES OF DIPTERA

By J. W. S. PRINGLE

Peterhouse, Cambridge, and the Department of Zoology, University of Cambridge

(Communicated by J. Gray, F.R.S.—Received 18 March 1948)

[Plate 23]

CONTENTS

Figure 9. Calculated curves for the torques present at the base of a haltere oscillating with linear angular velocity for half of each cycle. The relative amplitude of the three derived curves has no significance.
Artificial halteres

Halteres for the Micromechanical Flying Insect *

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Figure 1: Schematic of enlarged halteres of a fly.

Figure 2: Haltere force modulation.

Figure 5: Haltere description and design parameters.

Figure 7: Fourbar actuated haltere at rest.
Artificial haltere

Haltere-Like Optoelectromechanical Gyroscope
Onur Kilic, Hyejun Ra, Onur Can Akkaya, Michel J. F. Digonnet, and Olav Solgaard

Abstract—We report an optoelectromechanical vibratory gyroscope inspired by halteres of dipteran flies. The gyroscope utilizes optical displacement sensing to achieve a Brownian-motion-limited displacement sensitivity without mechanical resonant amplification in the sense mode. This yields a threefold difference between the resonance frequencies of the drive and sense modes, corresponding to a theoretical bandwidth of over 200 Hz, without compromising the sensitivity. Our measurements show a noise-equivalent rotation rate of $3\degree/h/\text{Hz}^{1/2}$ under atmospheric-pressure conditions.

Index Terms—Gyroscopes, microelectromechanical systems, optical interferometry.

I. INTRODUCTION

GYROSCOPES are essential elements in a broad range of applications, including navigation systems and motion-tracking applications [1], [2]. Depending on how gyroscopes are utilized, requirements for performance metrics such as sensitivity, bias stability, and bandwidth vary considerably. The sensitivity is a measure of how small a rotation rate can be...
Artificial halteres

Towards a biomimetic gyroscope inspired by the fly’s haltere using microelectromechanical systems technology

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Figure 6. Design (a) and fabrication (b) of the MEMS haltere-based gyroscope fabricated by surface micromachining and using SU-8 lithography. (Online version in colour.)
Compound eyes

- Individual fixed lenses distributed across the eye.
- Enables rapid temporal response, but at decreased spatial resolution.
Motion detection from compound eyes

Elementary motion detectors (EMD) (Reichardt 1957)
Motion detection from compound eyes

Optic flow as means of depth and speed measurement

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**REVIEW**

Sensory flow shaped by active sensing: sensorimotor strategies in electric fish

Volker Hofmann¹, Juan I. Sanguinetti-Scheck², Silke Künzel¹, Bart Geurten³, Leonel Gómez-Sena² and Jacob Engelmann¹,⁴
Motion detection from compound eyes

Review article

Optic flow-based collision-free strategies: From insects to robots

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Artificial compound eyes

Micro-optical artificial compound eyes

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Figure 10. Diced artificial apposition compound eye. (a) Artificial apposition compound eye in comparison to 1 Euro cent and a traditional single lens objective with the same magnification and approximate length of 20 mm. (b) Artificial apposition compound eye attached to the CMOS sensor array (courtesy of Centre Swiss d’Electronique et de Microtechnique SA (CSEM) Neuchâtel, Switzerland).
Artificial compound eyes

Miniature curved artificial compound eyes

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Fig. 1. Artificial and natural curved compound eyes. (A) Image of the CurvACE prototype. The entire device occupies a volume of 2.2 cm³, weighs 1.75 g, and consumes 0.9 W at maximum power. (B) Illustration of the panoramic FOV of the fabricated prototype. The dots and circles represent the angular orientation and acceptance angle Δp of every ommatidium, respectively. Compound eye of the extinct trilobite Erbenochile erbeni (22) (C) and of the fruit fly Drosophila melanogaster (D). [(C) Reprinted from ref. 22 with permission from AAAS; (D) Reprinted from ref. 44 with permission from AAAS.]
Event driven cameras

- Asynchronous readout of pixel intensity changes.
- Faster temporal response.
- No information if no motion.
Event driven cameras

A Unifying Contrast Maximization Framework for Event Cameras, with Applications to Motion, Depth and Optical Flow Estimation

Guillermo Gallego, Henri Rebecq, Davide Scaramuzza

rpg.ifi.uzh.ch

University of Zurich  
ETH Zürich
Department of Neuroinformatics

Department of Informatics
Ocelli

- Simple intensity detector
- Possibly used to orient with respect to sun or sky polarization
Ocelli

We designed a simple bio-inspired vision sensor

1 mm
Electrical Sensing

- Fish producing weak (< 1 V) electric signals (electric organ discharges (EODs)) with a specialized electric organ creating an electric field around their body

- Objects within the field altering the EOD-induced current

- *Electroreceptor* cells distributed over the entire body can sense voltage.

- Active *electrolocation* = Detection, localization and analysis of objects performed by monitoring self-produced electric signals

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early 1950s: Hans Lissmann from the University of Cambridge demonstrated that certain African fish produce weak electric signals in the water using their electric organ
Active Electrolocation

- Detect objects that are less than ~12 cm away and have electric properties that are different from those of the surrounding water.

- Within this range, the fish can also perceive the distance of objects (depth perception):
  - Independent of object parameters such as size, shape and material
  - Analyze the objects’ electrical properties

- Can independently determine the capacitive and resistive components of objects
  - Discriminating between living and non-living matter (capacitance is a property of living organisms)
Integration of vision and electrical sensing

Dynamic modulation of visual and electrosensory gains for locomotor control

Erin E. Sutton¹, Alicant Demir², Sarah A. Stamper¹, Eric S. Fortune² and Noah J. Cowan¹
Integration of vision and electrical sensing

Dynamic modulation of visual and electrosensory gains for locomotor control

Erin E. Sutton¹, Alican Demir¹, Sarah A. Stamper¹, Eric S. Fortune² and Noah J. Cowan¹

Figure 5. Fish response reveals multisensory enhancement. Each marker represents the average gain across fish for a single profile at a single conductivity compared to the gain to the coherent stimulus at the same amplitude and conductivity. Data falling close to the line represent conditions in which the gain to a single stimulus was equal to the gain to a coherent stimulus. The fish showed significantly higher gain to cross-modal (coherent) stimulus than a probe stimulus to a single modality, regardless of modality, amplitude or conductivity ($p = 2.013 \times 10^{-13}$, one-way ANOVA).
Finding and identifying simple objects underwater with active electrosense

Yang Bai¹, James B. Snyder², Michael Peshkin¹ and Malcolm A. MacIver¹,²,³

Fig. 9. Robotic positioning system, SensorPod, sensing electronics and test objects. (a) Bottom half of the SensorPod, showing position of custom sensing boards. (b) One of six sensing boards that process the signals from the 35 total sensing electrodes (only 10 used in this study). (c) The positioner is able to move the SensorPod (white cylindrical object attached via shaft) in X, Y, Z and ϕ. (d) Some of the test objects included 3D printed plastic objects (red), off-the-shelf rubber (black) and plastic spheres (white).
Electric sensing in robotics
GhostBot

- Designed for studies of the neural control, sensing, and biomechanics of the weakly electric fish
  - Swimming by traveling waves on ~30 fin rays
  - 45 cm long robot with 15 cm/s speed
- Electrolocation sensing

http://www.neuromech.northwestern.edu/uropatagium/
Flow sensing

- Lateral line detects flow properties along the body.

Lateral line system of fish

Horst BLECKMANN¹ and Randy ZELICK²

¹Institute of Zoology, University of Bonn, Bonn, Germany and ²Department of Biology, Portland State University, Portland, USA

Figure 1: The lateral line periphery. The drawing shows the pores of the lateral line canals (circles) and the spatial distribution of superficial neuromasts (dots) in the bittling, Rhodeus sericeus natrix (Cyprinidae). In most fish species, one canal runs above the eye (supranasal), one below the eye (infraorbital) and one on the lower jaw (mandibular). Note that in Rhodeus the trunk canal does not run the full length of the body. We are grateful to A. Schmitz for providing the drawing.
Flow sensing

Sensing the Neighboring Robot by the Artificial Lateral Line of a Bio-inspired Robotic Fish

Wei Wang¹, Student Member, IEEE, Xingxing Zhang², Jianwei Zhao³, and Guangming Xie¹, Member, IEEE,

Fig. 1. The robot prototype with an artificial lateral line. (a) Overall configuration of the robot. (b) Distribution of pressure sensors around the surface of the body from top view. (c) The pressure sensor.
Flow sensing

Artificial Lateral Line Design for Robotic Fish

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Fig. 1. Exterior look of the BAUV.

Fig. 7. Polyvinylidene Fluoride (PVDF) films with bent pins.
Insect Strain/Force Sensors

- Mechanoreceptors in insects
  - **Phasic response**: When stimulated, firing once when activated and again when deactivated
  - **Tonic response**: Firing repeatedly as long as a stimulus persists

- Trichoform sensilla (hair)
  - Detect touch and air movements

- Campaniform sensilla (flex receptors)
  - Oval discs found in many locations such as base of the wings, halteres, etc. that work like strain gages
Whiskers of Rodents as Touch Sensors
Features of Whiskers

• Sensing at the base of the whisker

• Rodents use a set of roughly 30 whiskers on each side of the snout, touching surfaces through a 5–15 Hz forward-backward motion known as “whisking”

• Can detect static and dynamic interactions with surfaces to detect obstacles AND their surface roughness/texture.

• Bending of whisker and associated strain at base can inform where contact is made along the whisker.
Seal Whisker for Prey Detection

- Dolphins and whales: *ecolocation*

- Whiskers can detect flow created by passing fish
  - Two harbor seals were trained to chase a miniature submarine. After the seals learned the task, the team placed a mask over their eyes and ear plugs over their ears before launching the sub. The seals quickly began tracking the sub and closely followed the wake of a sub taking a curved path.
Whisker Sensors in Robotics

An Artificial Whisker Sensor for Robotics

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Abstract

In this paper, we present a first series of experiments with prototype artificial whiskers that have been developed in our laboratory. These experiments have been inspired by neuroscience research on real rats. In spite of the enormous potential of whiskers, they have to date not been systematically investigated and exploited by roboticists. Although the transduction mechanism is simple and straightforward, and the whiskers are currently used in a passive way only, the dynamics of the sensory signals resulting from the interaction with various textured surfaces is complex and has a rich information content. The experiments provide the foundation for future work including active sensing, whisker arrays, and cross-modal integration.

Figure 1: Basic schematic of an electret microphone and a microphone preamplifier circuit. The necessary bias circuitry for the electret microphone is shown on the left. The deflection of the circular membrane, in response to a change of pressure, is measured by the change of capacitance. The related change of voltage is fed into a standard microphone preamplifier circuit (middle). Right: Experimental device used to perform the experiments described and analyzed in this paper.
Whisker Sensors in Robotics

Review

Biomimetic vibrissal sensing for robots

Martin J. Pearson\textsuperscript{1,*}, Ben Mitchinson\textsuperscript{2}, J. Charles Sullivan\textsuperscript{1}, Anthony G. Pipe\textsuperscript{1} and Tony J. Prescott\textsuperscript{2}

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Profile Whisker Sensor

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Extracting Object Contours with the Sweep of a Robotic Whisker Using Torque Information
Whisking for movement detection

Sensory prediction on a whiskered robot: a tactile analogy to "optical flow"

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FIGURE 2 | Computing slope and curvature over multiple vibrissae. The inset in the middle of the figure emphasizes that spatial distance R is measured from the base of the whisker to the point at which the whisker contacts the object. (A) In the single whisker method, we imagine that the rat compares sensory data acquired from a whisker with the data it remembers having acquired on the previous timesteps. The rat-estranged grey indicates the location of the rat at time 1, and the rat in black outline indicates the location of the rat at time 2. Having translated slightly forward, (B) In the multiple whisker method, we imagine that the rat compares data across whiskers in the array at a single point in time. Both methods (A) and (B) can be used simultaneously to explore those different spatial states in parallel.
Antennae

- Odor and motion sensing

- Mechanosensory input from the antennae serves a similar role with halteres during flight in hawk moths, which are four-winged insects.
Antennae as motion sensors

Antennal Mechanosensors Mediate Flight Control in Moths

Sanjay P. Sane, Alexandre Dieudonné, Mark A. Willis, Thomas L. Daniel

A

Backwards

B

Crashes

C

Collisions

D

Backwards

E

Crashes

F

Collisions

Normal flagella

Ampulated flagella

Reattached flagella

Reamputated flagella
Artificial antennae for motion sensing

Estimating attitude and wind velocity using biomimetic sensors on a microrobotic bee

Sawyer B. Fuller, Alexander Sands, Andreas Haggerty, Michael Karpelson, and Robert J. Wood
Antennae for wall following

Cockroach antenna

- Tactile sensing using specialized mechanoreceptors for detecting contact and strain on filamentous support structures such as animal vibrissae or arthropod antennae.

- Vision-based methods are computationally expensive and can fail under low light conditions or high air-particle content.

The antennae of the cockroach is actuated by its first two proximal segments: the Scape (S) and Pedicel (P). The Flagellum (F) possesses 150-170 passive segments.
Cockroaches actively probe their surroundings by sweeping their antennae through the environment.

During rapid locomotion, however, the base is held more-or-less fixed, while the long, passive (unactuated) flagellum bends in response to objects in its environment.

Achieving rapid maneuvers in response to environmental stimuli.

The faster they run, the closer they position themselves to the wall.

Vision-based methods are computationally expensive and can fail under low light/low visibility conditions.
Cockroach wall following

RESEARCH ARTICLE
Locomotion- and mechanics-mediated tactile sensing: antenna reconfiguration simplifies control during high-speed navigation in cockroaches

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Legged Mobile Robot Antenna

A Biologically Inspired Passive Antenna for Steering Control of a Running Robot

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Fig. 2. Sprawlette, a hexapedal robot, and its simple artificial antenna.

A Bio-Inspired Antenna

Fig. 5. A simple model of Sprawlette making contact with the wall using its antenna. We assume that the distance $y$ from the front right corner of the robot to the wall is a monotonic function of the resistance $R_T = \sum R_i$ of our artificial antenna sensor.
Dynamical Wall Following for a Wheeled Robot Using a Passive Tactile Sensor

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Fig. 2. *Robot schematic*: A robot, with wheel base $2w$, moves in the plane with configuration $q = (x, y, \theta, \alpha_1, \alpha_2)$, where $(x, y, \theta) \in \text{SE}(2)$ specifies the relative configuration of the robot frame axes, $(x_r, y_r)$, to the world frame axes, $(x_w, y_w)$, and the wheel angles (not shown) are given by $(\alpha_1, \alpha_2) \in S^1 \times S^1 = T^2$. Attached to the robot at $(x_0, y_0)$ relative to the robot frame is an antenna that measures the look-ahead distance, $\hat{x}$, and distance-to-wall $\hat{y}$. The link angles $\phi_i$ denote the angle of the $i^{th}$ link with respect to the $(i - 1)^{st}$ link, and each antenna link has length $\ell_i$ and $i = 1, 2, 3$. 