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On the Way to the Bionic Man: A Novel Approach to MEMS Based on Biological Sensory Systems

Salmah B. Karman[1,a], M.O. MacQueen[2,b], Tina R. Matin[1,c],
S. Zaleha M. Diah[1,d], Jeanette Mueller[3,e], Jumril Yunas[1,f], Teresa Makaruk[4,g]
and Ille C. Gebeshuber[1,4,h]

[1]Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Malaysia

[2]Aramis Technologies, 2 Jalan Alam Sutera 1, Bukit Jalil, 57000 Kuala Lumpur, Malaysia

[3]trustroom, Servitengasse 24/11, 1090 Wien, Austria

[4]Institute of Applied Physics, Vienna University of Technology, Wiedner Hauptstrasse 8-10/134, 1040 Wien, Austria

[a]salmah_5298@yahoo.com, [b]mark@aramis-tech.com, [c]tina.r.matin@gmail.com, [d]musnaliza@yahoo.com, [e]jeanette@trustroom.com, [f]jumrilyunas@gmail.com, [g]t_mak@gmx.at, [h]gebeshuber@iap.tuwien.ac.at

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Abstract. The human senses are of extraordinary value, but we cannot change them, even if this proves to be a disadvantage in our modern times. However, we can assist, enhance and expand these senses via MEMS. This paper introduces data for a push-pull analysis method based on a concise summary of senses in organisms and MEMS sensors that already have reached the market, giving an overview where current MEMS technology excels (available solutions) and where natural sensor systems excel. It provides a knowledge base for further development of MEMS sensors.
Some animals and even humans (with artificial lenses after cataract surgery) can see in the infrared and ultraviolet range; related MEMS with IR/UV sensitivity might assist us to determine the status of organisms. The hearing capabilities of bats (ultrasound) can inspire echolocation in man. Butterflies have exquisite thermoregulation; this might lead to MEMS that are better protected from overheating. Mice can smell important information about another mouse's immune system and mosquitoes detect minuscule amounts of carbon dioxide and lactic acid; thereby inspired MEMS could serve as medical or environmental scanners. The senses for magnetism, vibrations and electroreception that are used by animals might satisfy the need for MEMS in navigation and orientation. MEMS that are skillfully added to the human body can provide additional perceptory data. Future research will identify where already available MEMS excel and which outstanding properties of sensory systems can easily be replicated by 'off the shelf' systems.

Introduction

Biomimicry and biomimetics deal with knowledge transfer from living nature to technology [1,2,3]. Three methods that can be employed in biomimetics are BioTRIZ [4], the Biomimicry Innovation Method (BIM, [5]) and Discover – Develop – Design (3D, a method that has been recently developed at UKM IMEN) [6].

The human body is equipped with various general senses: we can smell, hear, taste, feel touch, see and sense temperature. These senses are of extraordinary value but we cannot change them even if this proves to be a disadvantage in our modern times. However, we can assist, enhance and expand these senses via MEMS (Fig. 1). MEMS technology enables microdevices fabricated from silicon or related materials through micromachining processes based on microelectronics or semiconductor fabrication technology. Some examples of MEMS devices are accelerometer, pressure sensor, micromirror, microswitch and others that can be used in automotives, medical, military, telecommunication and aerospace applications. Current MEMS cover the range of the human sensory system, and additionally provide data about signals that are too weak for the human sensory system (in terms of signal strength) and signal types that are not covered by the human sensory system (Fig. 1).

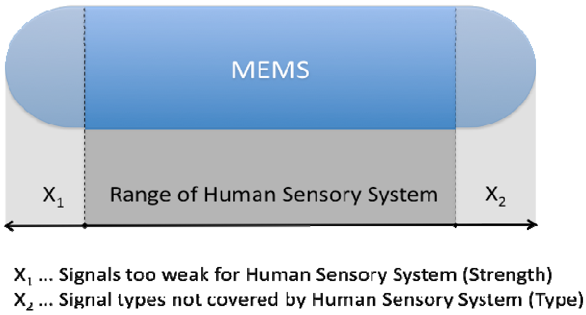

Figure 1. Functional regions of smart MEMS sensors compared to the human sensory system.

Senses in Organisms

As a human being we can see, hear, smell, taste, feel touch and sense temperature but there are some other organisms (animals and even plants) who have more and/or different senses and sometimes wider sense bandwidth than people.

Seeing. Electromagnetic waves with wavelength within the 390-750nm range are called visible light and can be detected by human eyes. The ability of the human eyes to detect the electromagnetic spectrum is more limited than some other species. Mantis shrimps detect 300-700nm with their compound eyes. Also most of the butterflies, bumble and honey bees, some birds and even gold fishes can see the UV range as well.

Temperature sensing. Heats receptors detect changes in temperature and are located in different part of the body, dependent on the species. Thermoreceptors aid animals in hunting, feeding and survival and in some animals and insects there are more sensitive thermoreceptors than in the human body. Snakes use sensitive pit organs mostly for hunting prey (feeding), some species detect changes as little as 0.003˚C. Forest fire-seeking beetles use their temperature sensitivity (IR) between 3 and 5µm to locate forest fires to lay their eggs in freshly killed trees. They sense temperature between 600 and 1000˚C (high temperature window). Thermoregulation sensors that gain heat from the sun, and also protect them from overheating, equip some butterfly wings. Thermoreceptors help bloodsuckers to locate animals and estimate their temperature.

Hearing. Humans can hear between 200 to 20000 Hertz. Most mammals have better high frequency hearing than humans, and there are some who have the ability to communicate in low frequency domains. Mice can hear ultrasound up to 85.5 kHz, more than two octaves higher than humans. Other examples include dogs (up to 60kHz) and cats (up to 64kHz). Bats use their hearing ability to hunt their prey (20Hz-120kHz). Dolphins and whales use echolocation to communication. Elephants are masters in using infrasonic calls at frequencies less than 30Hz.

Smelling. Humans can recognize thousands of different smells and detect odours on the single molecule level, with approximately five to six million olfactory receptors (Fig. 2). Dogs have about 220 million olfactory receptors. For some insects such as moths, butterflies, ticks and mosquitoes smelling is extremely important, to finding mates and food. Within the small mammals, the olfactory system of the mouse excels: mice detect important information about another mouse's immune system, assisting them in mate selection. Even in marine world the sense of smell has some applications. Sharks for example can detect one drop of blood in a million drops of water and can smell blood from 0.4km away.

Figure 2. We can only vaguely imagine which strange world opens to this woman smelling a rose when she is equiped with MEMS to enhance and expand her olfactory possibilities. Image Source: “The Soul of the Rose” by John William Waterhouse, public domain image.

Feeling touch and vibration. The skin is the receptor organ in the human body for sensing tactile stimuli or vibration. Trained humans can perceive an oscillation in the range of 100-200Hz of just 1μm amplitude. Spiders, cockroaches and sand scorpions are extraordinary in this respect. Crustaceans use their extra ordinary ability to hunt, escape predators and find prospective mates. Harbor seals use their sensitive vibrissae or whiskers to find food in the dark, in deep waters or at night. They analyze water movement and can thereby distinguish prey fish and conspecifics.

Magnetic sense. A large variety of animals use this sense in long distance navigation. Researchers have described more than 50 species with magnetic senses, such as migratory birds, honeybees, butterflies, snails, fish, sea turtles, cows, deer, salamanders, geckos, earthworms, …

Electroreception. Especially fish exhibit electroreception. They use this sense for communication and hunting. They can emit signals from a few Volts to over 700 Volts via their electric organs. They can sense the passive electrical signal of prey and their active electroreception provides target distance information useful for active electrolocation, target conductivity and direction.

MEMS Sensors

Seeing. Seeing is based on the detection of electromagnet waves. Electrically tunable Fabry-Pérot filters for near-UV, visible and near-IR based on spectrometers are offered by VTTMEMSFFAB, PerfectLight display technology is offered by Pixtronix and a MEMS interferometer by ASM.

Temperature sensing. In temperature sensing, infrared electromagnetic waves are detected, e.g., in the MEMS temperture sensor.

Hearing. In hearing, deflections are detected. MEMS examples for devices in this area comprise microphones (example: the STA321MP audio processing chip by ST Micro Electronics), cochlear implants, micro-acoustic components, abnormal sound and vibrations detectors, hearing aid devices, vibration sensors (e.g., gyroscopes from the company ADI) and MEMS speakers (e.g., the Digital Sound Reconstruction platform from the company Audio Pixels Limited).

Smelling. In olfaction, chemical signals are detected. The MEMS equivalents are gas sensors, for example from the companies Universal Semiconductor and VTTMEMSFAB. There are also MEMS gas analayzers based spectrometers.

Feeling touch and vibration. Similar to the case in hearing, feeling touch and vibrations needs deflection measurements. There is a multitude of systems in this area on the market. Examples comprise pressure sensors, vibration analysors (that works via acceleration sensors, e.g. from the companies Invensense and ADI), vibration sensors based on gyroscopes (company: ADI), tilt sensors (company: ADI), rotation sensors (company: ADI), sensors in ballistic munition e.g., from the U.S. Army Research Laboratories and shock sensors (e.g., the ADIS16334 Low-profile Six Degree of Freedom Inertial Sensor by ADI).

Tasting. As in olfaction, in tasting chemical signals are detected. Spectrometer based liquid and solid analysers (both from VTTMEMSFAB) are already on the market, as well as a MESMEMS chemical sensor that functions via a capacitative chemical sensor.

Magnetic sense. Similar to seeing and temperature sensing, in the magnetic sense, electromagnetic waves are detected. There are various MEMS devices on the market that can be used for this purpose. Examples comprise MEMS magnetometers, the geomagnetic sensor (HSCD Series 3-axis Geomagnetic Sensor with Angular Velocity Detection by Alps Electric), silicon magnetic sensors (iSuppli's MEMS, Electro IQ, Small Times) and the magnetic sensors offered by Infotek.

Electroreception. Also here, electromagnetic waves are detected. Examples for MEMS on the market comprise the adaptive transducer (based on a biological sensory mechanism) by C. Wangcharoenrung and R.G. Longoria from Texas (research status), tactile displays and a device for neural control based on locomotion in weakly electric fish.

Outlook: Push-Pull Analysis

On the market the consumers usually 'pull' the goods or information - they create a *demand*, while the offerers 'push' their products toward the consumers – they create a *supply*. In the next step the market needs concerning MEMS to assist, enhance and expand human sensory capabilities shall be investigated in relation to the available technological potential (cost effective). Pull from the market defines what the customers require regarding assistance, enhancement and expansion of human senses. The available solutions or the technological potential for the creation of solution are assessed (push). Two aspects shall be of particular interest: Where do current MEMS excel (available solutions)? Where do natural sensor systems excel (replicable by off the shelf systems)?

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