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## Projektarbeit

**MEMS: to assist, enhance and expand human sensory perceptions**

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## 1. Motivation

*“What is first given to us is appearance. When combined with consciousness, it is called perception...”* [1]. Immanuel Kant proposed that our knowledge of the outside world depends on our modes of perception.

The human body is equipped with several senses: we can see, hear, smell, taste, feel touch and sense temperature. These senses consist of organs with specialised cells that offer receptors for certain stimuli. The receptor cells are linked to the nervous system, which is connected to the brain, where the information is finally analysed. The human sensory systems, as well as the human perception that exists today, are the result of billions of years of evolution.

Current MicroElectroMechanical Systems (MEMS) cover the range of human sensory systems and furthermore provide data of even more signals. Not only signals that are too weak for human perceptions, but also signals, which are not covered by the human sensory system can be recognised and converted through MEMS.

Biomimetics, which is an interdisciplinary knowledge field at the crossing point of biology and technology as well as the arts [2], is a promising method in the development of emerging MEMS. Applying certain principles from the biological sensory systems to technological strategies is an encouraging approach to assist, enhance and expand human sensory perception.

Essential and important questions in the field of biomimetics of the senses are: Which senses are available in nature? Which biological sensor systems exist and how are they working? Through the years of evolution the senses of organisms have developed immensely depending on their surrounding and lifestyle of the organisms. To be able to survive every organism is equipped with its specific sensory system- and indeed, in many definitions of life itself, sensing the environment and reaction to it is one of the basic properties of living entities.

The purpose of this project work is to identify functions of biological sensory systems and in the second step suggest possible MEMS applications. Therefore multiple scientific databases are used to find relevant literature about extraordinary sensory systems in nature and their anatomical structures.

## **2. Biomimetics**

Biomimetics aims at identifying the deep underlying principles of materials, structures and processes in living nature, and on subsequent knowledge transfer from biology to engineering and the arts. It seeks to apply certain principles from biological systems to technological strategies and innovative applications. The range of potential use for biomimetics is enormous. Nowadays it includes architecture and design, surface and materials technologies as well as sensors, medical engineering and management [3].

## **3. MicroElectroMechanical Systems**

MEMS are small, integrated devices or systems that combine electrical and mechanical components. They are composed of components between one to 100 micrometers in size, the MEMS devices themselves generally measure from 20 micrometers to one millimeter.

MEMS consist of mechanical elements, sensors, actuators, and electrical devices on a common silicon substrate. With all these components these systems can sense, control, and activate mechanical processes on the micro scale, and function individually or in arrays, thereby generating effects on the macro scale. Current microfabrication technology enables fabrication of large arrays of devices, which individually perform simple tasks, but in combination can accomplish complicated functions [4].

## 4. The Senses

### 4.1. Sight

The human eye has a complex structure consisting of a transparent lens that focuses light on the retina. Rod and cone cells in the retina are the basis for conscious light perception and vision including colour differentiation and the perception of depth. The range of the electromagnetic spectrum that can be detected by the human eye comprises wavelengths between 390 and 750nm, which is called the visible spectrum [5]. The human eye can distinguish about 10 million colours with its trichromatic vision system [6]. Trichromatic colour vision means that there are three different types of photoreceptors, which are labelled according to the ordering of the wavelengths of the peaks of their spectral sensitivities. This quality of perception is adjusted to our surrounding and demands.

Important characteristics of a well and extraordinary developed eye are visual acuity, contrast sensitivity, spatial resolution colour and motion perception. The focus in this chapter will be on different colour perception of specific species.

There are many species that can see frequencies that are outside the human visible spectrum. The reason lies within the different existing types and numbers of photoreceptors containing pigments of different spectral sensitivities. Consequently light from the UV- range up to the IR- range can be detected by organs of many animals. In the following sections, types of animals that can perceive specific ranges of the electromagnetic spectrum are described.

The mantis shrimp (Stomatopod) possesses apposition compound eyes that contain more photoreceptor types than any other animal. These eyes are in almost continuous and independent motion and their morphological structure is quite complex.

There are 16 different cell types contributing to at least three different visual modalities and twelve channel colour vision systems. These twelve narrow colour channels spread evenly through the spectrum from 300 to 700nm. With spectral half bandwidths around 20nm, these are among the sharpest spectral sensitivities in the animal world [7]. Another interesting fact is the mantis shrimp sensitivity in the UV range and they possess more UV photoreceptor than any other animal [8]. To perceive UV light it is necessary that the animals possess ocular media that do transmit UV light.

The colour perception of butterflies is of extraordinary value, too. It is an essential gift to search for nectar. Butterflies find their sources, the flowers, and make their mate choice by using their capacity for color vision [9]. The two compound eyes of butterflies consist of numerous anatomically identical units that are called ommatidias and are arranged in a hemisphere. Most species of butterflies possess three different types of ommatidias that contain nine photoreceptors each with maximal sensitivity in the ultraviolet (350nm), blue (450nm) and green (550nm) wavelength ranges [10]. This is termed “trichromatic vision” and can be found in lots of mammals. The difference to the human trichromatic vision system lies in the different ranges of wavelengths of light that stimulate the photoreceptors. Butterflies colour receptors can perceive colours in a high frequency but cannot detect lower frequencies in the range of red colour. For that reason butterflies are not interested in red flowers.

The Japanese yellow swallowtail butterfly (*Papilio xuthus*) has compound eyes that are furnished with six distinct classes of spectral receptors (UV  $\lambda=360\text{nm}$ , violet  $\lambda=400\text{nm}$ , blue  $\lambda=460\text{nm}$ , green  $\lambda=520\text{nm}$ , red  $\lambda=600\text{nm}$ , broadband  $\lambda=$  almost the whole human visible spectrum) [11].

Bumble and honey- bees possess trichromatic colour processing, too, with three types of spectral receptors in their compound eyes. Similar to most of the butterflies the sensitivity peaks of bumblebees are in the UV ( $\lambda=340\text{nm}$ ), blue ( $\lambda=430\text{nm}$ ) and green ( $\lambda=535\text{nm}$ ) wavelength ranges. Honeybees are highly sensitive in the UV spectrum [12]. The honeybee possesses a trichromatic visual system with UV ( $\lambda=335\text{nm}$ ), blue ( $\lambda=435\text{ nm}$ ) and green ( $\lambda=540\text{nm}$ ) receptors [13][14]. The bees use their UV receptors to detect polarized light and determine orientation for navigation [15]. The green receptors are used for optomotor response [16] and for flight distance estimation [17].

Avian eyes are characterized by the presence of oil droplets within the distal end of the inner segment of their cones, which act as cut-off filters and absorb light below their characteristic wavelength of transmission [18]. Together with their associated oil droplets, birds have at least three to four photoreceptors with spectral sensitivity maxima reaching from 370nm to 580nm [19]. Another feature that increases the complexity of colour perception is the differential distribution of oil droplets across the retina. Pigeons and several other avian species show high UV sensitivity, which they may use to view objects such as plumage or

fruits reflecting UV light [20]. The domestic turkey (*Meleagris gallopavo*) retinae contain five types of rhodopsin visual pigments and five types of oil droplets in seven different types of photoreceptors.

Furthermore, UV sensitivity has also been shown for a variety of fish species like the goldfish, the rainbow trout and the roach. They have photoreceptors that can be stimulated in the UVA wavelength range of 400-320nm with maximum perception at around 360nm.

Some coral reef fish use their UV- light sensitivity for communication [21]. The damselfish *Pomacentrus amboinensis* display UV patterns on their faces and on their fins, and it has the potential for UV vision. With these gifts they can identify conspecifics (members of the same species) and other species of reef fish and communicate with them without being noticed by other fish that are not sensitive to UV light.

Short-wavelength UV light is also scattered more strongly in particulate media than light of longer wavelengths [22]. UV signals travelling through the water are therefore attenuated faster than signals comprising longer wavelengths. Therefore, UV communication is only effective over short distances.

Fish may also utilise UV in other important aspects of life, such as feeding, foraging or mate choice [23].

Perception of UV light is possible for humans who went through cataract surgery. This type of surgery replaces the natural lens of the eye with a plastic lens where UV rays can pass through.

**Potential for principle transfer to sensory MEMS design:**

A possible application would be to create special glasses that allow vision in the UV spectrum. Such glasses could help to determine the status of plants and identify the best harvesting time.

## 4.2 Infrared imaging and sensing – temperature sensing

Humans possess heat receptors over the entire body. These heat receptors are unspecialized free nerve endings that detect changes in temperature as well as steady state temperature. The skin of human hands presents myelinated cold receptors that exhibit a steady state response to continuous stimuli, which are sensitive to pressure and are innervated by the radial nerve [24].

There are several animals and insects that possess a variety of thermoreceptors, which aid them in hunting, feeding and survival. These receptors work in differently than the human ones and their sensitivities vary between species.

Infrared reception appears in snakes of the family Crotaline (the pit vipers) and the families Boidae (the boas) and Pythonidae (the pythons). They possess heat- sensitive pit organs that allow accurate and precise targeting of endothermic prey and may serve to localize cool thermal retreats [25]. Through the thermal information perceived by the pit organs, these snakes can detect objects by their irradiance contrast with a thermal background. Thermal information ultimately merges spatiotopically with visual information in the optic tectum [26][27]. The infrared and visual systems are involved in prey detection by boids and pitvipers, but the eyes are not necessarily required [28].

Pit organs absorb IR radiation in two major atmospheric windows: the 3-5 $\mu\text{m}$  range (high temperature window) and the 8-12 $\mu\text{m}$  range (low temperature window) which matches the IR emission of targeted prey [29]. They exhibit greater absorption in the 8 – 12 $\mu\text{m}$  range than in the 3–5 $\mu\text{m}$  range. The infrared radiation emitted from vertebrates with a surface temperature between 30–40°C has its maximal emission at approximately 10 $\mu\text{m}$ . The receptors in the pit organs are able to detect very small changes in temperature. The rattlesnake (Crotaline snake) pit organ is capable of detecting a 0.003°C change in the temperature of water flowing over the pit organ. The IR- organ of boid snakes can distinguish as little as 0.026°C change in temperature [24].

The infrared receptors are terminal nerve masses of the trigeminal nerve arrayed in a monolayer in a membrane suspended inside each pit and irrigated by a dense capillary network [30].

Crotaline snakes like the rattlesnake, cottonmouth and copperhead possess two facial pits located on either side of the face between the eye and the nostril. These pits differ markedly from the boid snakes' pits in number, location and morphology, but the electrophysiological



responses are extremely similar. Boids like the python possess as many as 13 pairs of labial pits located on their upper and lower jaws [24].

The pit organ micropit and plate dimensions play an important role in the ability of the pit organs to detect infrared radiation.

Forrest fire-seeking beetles (*Melanophila acuminata*) locate forest fires by IR – detecting pit organs in order to lay their eggs in freshly killed conifers. The larvae of the beetle can develop only in the wood of trees recently killed by a fire. Forest fires as far as 60-100 miles away can be detected by two IR detecting pit organs located on either side of their thorax near their middle legs [31]. The beetles detect IR radiation emitted by forest fires presumably in the 2–5 $\mu\text{m}$  atmospheric window with irradiances down to 60 $\mu\text{W}/\text{cm}^2$ , with a peak response at approximately 3 $\mu\text{m}$ . This corresponds to source temperatures between 600 and 1000°C (high temperature window) in which forest fire burns. Detection of these wavelengths at great distances is possible because the atmosphere readily transmits IR wavelengths ranging from 3-5 $\mu\text{m}$  [32].

The two pit organs are elliptical in shape and are on average 450 $\mu\text{m}$  long by 200 $\mu\text{m}$  wide and 108 $\mu\text{m}$  deep. Each pit organ consists of 50 to 100 densely packed dome shaped sensory organs or sensilla (12–18 $\mu\text{m}$  in diameter) present in the pit floor.

The fire-seeking beetles' pit organs are thermomechanical receptors that convert IR electromagnetic radiation to mechanical energy.

The wings of several butterflies play a very important role in thermoregulation like in gaining heat from the sun and protecting themselves from overheating and undesirable convection. The amount of heat can be varied by adjusting their wing position and is important to maintain the body temperature between 30 and 40°C in order to sustain their flight and feeding activity [33]. Thermoreceptors are located in the wings and antennae of butterflies to protect them from heat damage.

Blood sucking bugs (*Triatoma infestans*) possess thermoreceptors that enable them to perceive the radiant heat of a warm source and estimate its temperature at a distance, when seeking homeothermic prey [33].

### **Potential for principle transfer to sensory MEMS design:**

An analysis of the extremely sensitive snake imaging forming IR detector should provide insight for the development of new technologies that will result in greater sensitivity, operation at higher temperatures and reductions in size and weight.

Infrared sensors with operating modes like the fire-seeking beetle could be used as annunciator of forest fires or alternative excellent heat measuring devices. Furthermore it could be possible to invent MEMS for blind people that allow to “see” their endothermic environment, like some snakes do through their pit organs.

## **4.3 Hearing**

Hearing is the ability to perceive sound by detecting vibrations. The range of hearing for a human is 20 to 20.000 Hertz, although there is considerable variation between individuals.

Sound is a sequence of pressure waves that propagate through compressible media such as air or water.

The human ear has three main sections, which consist of the outer ear, the middle ear, and the inner ear. Through its complex construction it can transduce mechanical vibrations into signals of impulses that are sent to the brain (mechano-electrical transduction) [34].

There are lots of animals with different hearing abilities. Although the hearing ranges of most species overlap to a large degree, considerable variation occurs in high- and low-frequency hearing as well as in absolute sensitivity. The hearing ranges of nine species of laboratory mammals are compared with those of humans in Figure 1, which shows both the 60- and 10-dB hearing ranges for each species [35].

Most of the mammals have better high frequency hearing than humans, especially small species like the mouse. With 85.5kHz, its upper limit of hearing is more than two octaves higher than the 17.6kHz upper limit of humans at a sound pressure level of 60dB. The main reason is that small mammals make use of the high frequency sound localization cues which is provided by the attenuating effect of their head and furthermore by their small pinna. The pinna is the external part of the ear in humans and other mammals.

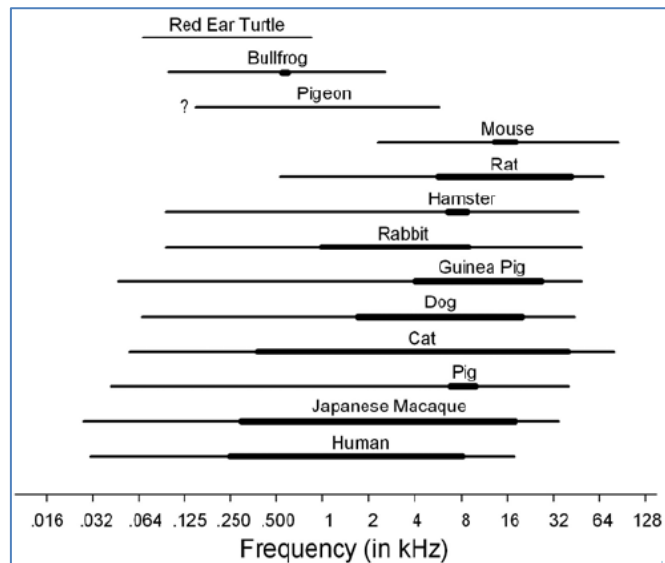


Figure 1: The hearing ranges of laboratory animals compared with those of humans. Thin lines indicate the range of frequencies that can be detected at 60 dB sound pressure level; thick lines indicate the range that can be detected at 10 dB. From [35].

Mice produce and hear sounds out of the other predators' frequency ranges to their advantage for communication.

Another important characteristic is the range of "good hearing", which include the frequencies that are audible at 10 dB. For the above-named laboratory mammals these frequencies are shown in Figure 1, too, marked with thick lines. The ranges vary in size as well as the frequencies that are encompassed. With 6.6 octaves, cats have a very broad range of good hearing. The range of good hearing is affected by the external ear or pinna, which can amplify or attenuate sound in certain frequency bands. Additionally, cats possess upright and curved ears, which direct and amplify the sounds in an excellent way. Dogs have a wide hearing range and special ears in the same way. Simultaneously to humans they move their ears towards the sound to maximize reception and consequently have a range of hearing from approximately 40 to 60.000Hz. In the wild they use their hearing capabilities to hunt and locate food [36].

Sounds that are too high for us to hear are labelled as „ultrasonic“, whereas those that are too low are named „infrasonic“.

Furthermore there are animals that use their fine hearing ability and its connected sound acuity for orientation. Bats for example have mastered the night skies largely by using

ultrasonic echolocation to perceive their surroundings. With a hearing range between 20 and 120.000Hz they can avoid obstacles by hearing echoes and detect their insect prey [37]. They use different frequency modulated calls and consequently they assess the echo when the calls bounces back. The spectrum of echoes is affected by the shape of a target, by the target's distance, by the target's motion, by the target's location in the transmitting and receiving beams and by interference among overlapping echoes reflected by concomitant clutter [38].

Dolphins and whales are further species that utilize echolocation to determine the position of objects and for communication. It enables the marine mammals to “see” in a much more complex way than it might seem.

Long-distance communication of acoustic cues plays an important role for social identity in elephants. They use infrasonic calls with low fundamental frequencies less than 30 Hz because of the unusual resilience of such low frequencies to attenuation [39]. In these mammalian calls, a wide range of acoustic characteristics typically carries information on individual identity and social meaning.

In a previous research it was demonstrated that elephants respond to the playback of recorded infrasonic calls from distances of 1.2 and 2km. Furthermore, in Zimbabwe it was observed that elephants can communicate over distances up to 5km under conditions where visual and olfactory signals are not possible [40].

**Potential for principle transfer to sensory MEMS design:**

Ultrasound and infrasound could be used to enhance human hearing capabilities.

Furthermore it would be possible to create a detector for earthquakes, volcanic eruptions, tsunamis, typhoons or nuclear explosions with MEMS. In addition it would be possible to produce devices for divers that allow better orientation under water.

## 4.4 Olfaction

Olfaction is the sense of smell. Human can recognise thousands of different smells and are able to detect odours the single molecule level. The olfactory system of humans consists of several millions of olfactory sensory neurons arrayed in a sensory epithelium located inside the nasal cavity. Each of these sensory neurons expresses one of approximately 240 odorant receptor genes. It is not a spectral sense, but rather consists of a large number of sensors with different specificities and affinities [41]. Humans possess approximately five to six million olfactory receptors.

For many animal species the detection of odours eliciting attraction or avoidance reaction can be important for life or death.

Olfaction is a dog's primary special sense, which is said to be a thousand times more sensitive than that of humans. Dogs possess around 220 million olfactory receptors, which are ultimately connected with the highly developed olfactory lobe in the dog's brain. They have the Jacobson's organ, which consists of a pair of elongated, fluid-filled sacs that open into either the mouth or the nose. It is located above the roof of the mouth and behind the upper incisors (narrow-edged teeth at the front of the mouth) and is important to recognize other animals and people [42].

The sense of smelling is extremely important for moths. Their olfactory organs are their two antennae, which consist of hundreds small hair (sensilla trichodea) with lots of olfactory receptors. Each pheromone olfactory neuron projects a dendrite into the hollow space of a sensillum [43].

In many species of moths, sex pheromones play a central role in reproduction. The females release the pheromone and the males follow the pheromone plume upwind. Male moths can locate female moths pheromones over a distance of 20km. The olfactory system in the males is remarkably sensitive and highly selective toward the structures of individual components and the overall blend composition.

Also butterflies have a well-developed sense of smell. Sense receptors located in their antennae, feet, and some other parts of the body help them to find food and mates.

The olfactory system of the mouse is its best-developed and most important sense. The main olfactory epithelium of the mouse is a mosaic of 2000 populations of olfactory sensory neurons. They can detect important information about another mouse's immune system that may aid them in mate selection, embryo implantation, prevention of inbreeding and other behaviours. They also detect specific molecules in the urine from other mice.

Also ticks have an extraordinary sense of smell, so that they can detect when the proper host draws near. Their olfactory perception is given through the so-called "Haller's organ", which is placed on the end segment of the first of their four pairs of legs. That organ allows the tick to detect special chemical compounds like ammoniac, butanoic acid and carbon dioxide [44]-[45].

Mosquitoes smell with their antennae too and their sense of smell is extremely sensitive to carbon dioxide levels in the air. This helps the blood-feeding insect to find its hosts. When they get closer to the host, the odours of other compounds, especially lactic acid emitted from the skin surface, allow them to find and identify the host.

A shark's primary sense is a keen sense of smell. These marine animals possess two nostrils that are located on the underside of their snout. Water continually flows through the nostrils, giving the shark olfactory information. It can detect one drop of blood in a million drops of water and can smell blood from 0.4km away. Sharks are also attracted to the chemicals found in the guts of many species. Some sharks, like the nurse shark, possess sensory projections near the nostrils and mouth called nasal barbells. These barbells are whisker-like feelers that greatly increase their ability to sense prey [46].

**Potential for principle transferto sensory MEMS design:**

MEMS could be installed in refrigerators to signal foul and mouldy food. Moreover, detectors could be produced, which are able to distinguish clean and dirty clothes. In addition it would be possible to create detectors that tell human when rooms should be aerated.

## 4.5 Vibration- Sensing

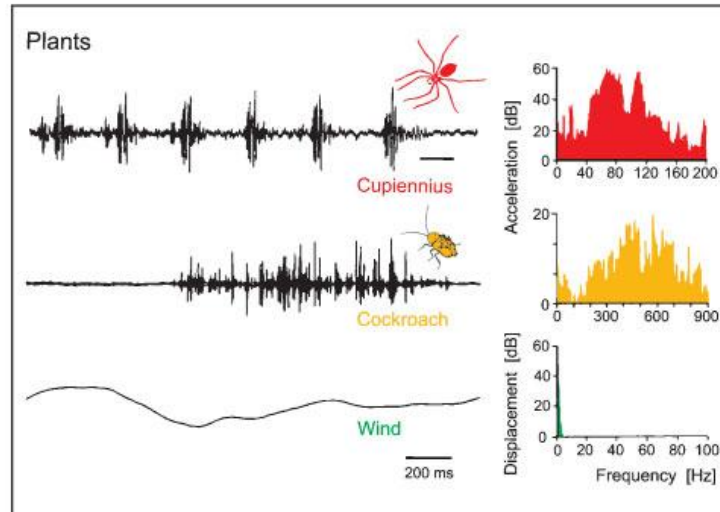
Tactile stimuli, in this case vibratory stimuli, can be sensed by the human skin. The skin possesses mechanoreceptors that are part of the so called “somatosensory system”, which enables humans to perceive vibrations. The sole of the foot and the back of the hand are the most sensitive parts of the skin. Trained humans can perceive an oscillation in the range from 100-200Hz of just 1 $\mu$ m amplitude [47].

There are four receptor types located in the glabrous skin that react on mechanic deformation of the skin. These receptors have different features and densities [48], depending on receptor type and location [49].

Spiders can distinguish slight signals between vibrations of the wind and struggles of prey with the help of their mechanoreceptors. Most spiders have hundreds of thousands of hairs on their exoskeleton that respond to various signals [50]. Nevertheless spiders possess more than just one source of vibration sensitivity. Of particular interest is the so-called metatarsal organ, a well constructed lyriform organ most sensitive for vibration sensing. Besides, spiders have strain gauges (slit sensilla), airflow detectors (trichobothria) and touch receptors (tactile hairs). Possessing maybe the best vibration sensory system in the animal kingdom is very important for the species for prey capture and survival. Lots of spiders identify and locate their prey by means of vibration stimuli received through their web or another solid material such as the ground or plant structure [51].

Spiders are exposed to three types of vibrations that differ in regard to the spectrum of the frequencies the vibrations contain (Figure 2):

- The frequency spectra of vibration generated by typical prey animals of spiders are between 400 and 900 Hz.
- The frequency spectra of the background noise with low frequencies (like wind) is well below 10Hz
- Frequency components of the male vibratory courtship signals are close to 100Hz.



*Figure 2: The vibrational environment of a spider in its natural habitat when sitting on its dwelling plant. Left: oscillograms, right: frequency spectra of typical signals. From top to bottom: male courtship vibration, prey (cockroach) crawling on the plant, and vibrations due to wind. From [52].*

A cockroach can streak at 70-80 times a second while rapidly changing direction to escape a predator.

The cerci of the cockroach, a pair of small appendages at the end of the abdomen of arthropods, are covered with identified sensory hairs that detect air movements. A pair of long hairs at the hissing cockroach's back helps them from not being caught or eaten. When something moves behind the cockroach, it produces a tiny breeze of air. The breeze is picked up by the cockroach through many tiny wind sensitive hairs on its cerci and consequently the cockroach jumps forward to escape. The smallest gust of hair that generates escape behaviour is 12mm/s with an acceleration of 600mm/s. Different hairs have different biases, which means that wind from certain direction moves just specific hairs [53].

Sand scorpions (*Smeringurus mesaensis*) live on dry sand and use their sensitive vibration and chemosensory systems on the sand surface for prey capture and for finding prospective mates. Basitarsal compound slit sensilla, a unique structure present only in scorpions, and mechanosensory hairs on each leg allow scorpions to detect and locate the source of substrate vibrations produced by small arthropod prey [54].

Loose sand conducts compressional and surface (Rayleigh) waves at relatively low velocities (95-120m/s and 40-50m/s) compared to other natural substrates. In addition, small,



constricted hairs on their pedipalps, called trichobothria, are responsive to very near-field movements and allow scorpions to precisely locate their prey during capture [55].

Harbor seals are large carnivorous marine mammals, which often live in dark and turbid waters where their vibrissae, or whiskers, play an important role in orientation.

A harbor seal uses its sensitive vibrissae to find food, especially in dark, deep waters or at night. Besides detecting and discriminating objects by direct touch, harbor seals use their whiskers to analyze water movements, for example those generated by prey fish or by conspecifics. Even the weak water movements left behind by objects that have passed by earlier can be sensed and followed accurately (hydrodynamic trail following) [56]. The harbor seals whisker possesses a specialized undulated surface structure, which effectively changes the vortex street behind the whiskers and reduces the vibrations that would otherwise be induced by the shedding of vortices from the whiskers.

Vibration detection thresholds were found to decrease with frequency up to 1000Hz and remain relatively constant thereafter [57].

#### **Potential for principle transfer to sensory MEMS design:**

The detection of weak or strong water movements could be used to get more knowledge about water currents near the coastline in order to avoid people drifting into deep water levels.

## **4.6 The magnetic sense**

A large variety of animals possess a magnetic sense that they often use in long-distance navigation. True navigation by animals is likely to depend on events occurring in the individual cells that detect magnetic fields.

At any point on the Earth's surface, the magnetic field can be described as a vector in three-dimensional space (Figure 3). The geomagnetic field is very weak and its intensity varies from 25-65 $\mu$ T between the magnetic equator and pole [58]. The direction of the resulting vector varies between being parallel and perpendicular to the Earth's surface at the magnetic equator and poles.

The scientific literature reports on animals with separate magnetite-based magnetoreceptor cells that are specialised for magnetic field direction and intensity. It can be predicted that

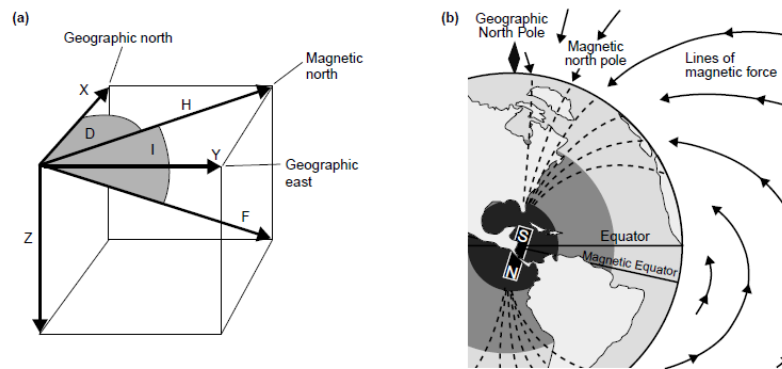


Figure 3: (a) the elements of the total magnetic field vector ( $F$ ) at the surface of the earth. The total field vector can be resolved into components (arrows) in the  $X$  (north),  $Y$  (east) and  $Z$  (vertical) axes. The vector component in the horizontal plane ( $H$ ) points in the direction of a handheld compass needle. The declination ( $D$ ) is the angle between the  $H$  and  $X$  elements whereas the inclination ( $I$ ) is the angle between the  $H$  and  $F$  elements of the field. (b) The main field of the earth (produced in the core). From [60].

animals should be able to reconstruct the total field vector accurately and with high sensitivity.

The map and compass' hypothesis of Kramer states that animals must first determine their position relative to their goal (the 'map' step) and then set a course for the goal (the 'compass' step) [59].

Although the use of the geomagnetic field for directional information is well established experimentally, it is not known by which biophysical mechanism magnetoreception is achieved.

The magnetic sense could be detected in more than 50 species and some of them are listed below:

- birds (migratory birds, pigeons, ...)
- invertebrates (honeybee, bumblebee, butterfly, ...)
- mollusc (snail, mussel, ...)
- fish (trout fish, eel, ray, salmon, ...)
- whales, sharks
- sea turtles
- cows, deers
- salamanders, geckos, earthworms,...

### **Potential for principle transfer to sensory MEMS design:**

MEMS with magnetic sensors can be used for mobile navigation and enable advanced location-based services. In mobile phones or cars they could be utilized as digital compasses. Furthermore they indicate the direction in which a person or vehicle is moving, even when GPS is not available.

## **4.7 Electroreception**

Electroreception is the ability of lots of fish to perceive electrical impulses. Their electrical sense is used for electrical communication [61], for passive electrical sensing of prey [62], and for active electrolocation [63].

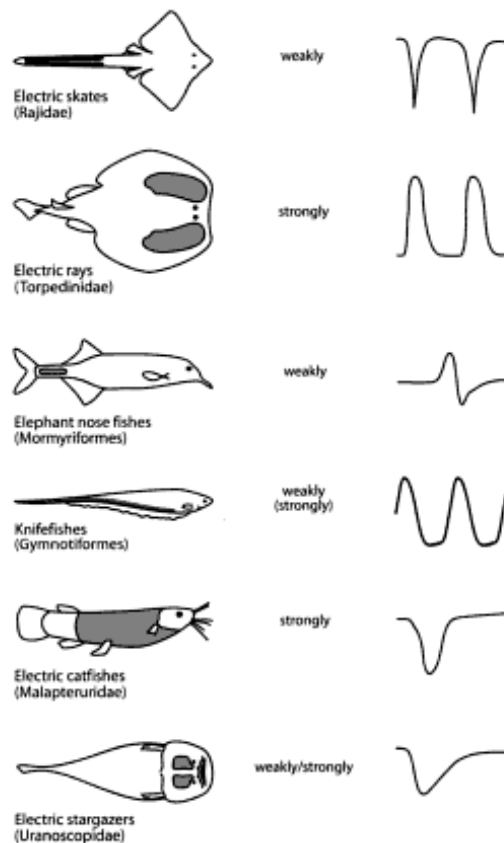
Active electrolocation is the sensing of objects in the environment as distortions in the electric field generated by a fish's own electric organ discharge (EOD). This perception is very important for fish living in murky waters with low visibility.

Based on the voltage of the emitted discharge, electric fish are commonly classified as weakly electric or strongly electric. The electric organs generating either low or high voltage or high current pulses are modified from muscle cells or from branched nerve endings. The fish can produce voltage ranges from a few Volts to over 700 Volts. Electric organ cells, also called electrocytes, maintain a standing electromotive force between inside and outside by ion pumps, like ordinary cells. They can be discharged by brief signals under brain control. Figure 4 shows six groups of electric fish and their produced electrical signals.

The strongly electric torpedo ray (*Torpediniformes*) generates up to 50V and 1kW of electricity from large, paired, kidney-shaped electric organs. These strong EODs are used for both defence and to subdue prey [65]

In contrast, skates possess small, paired electric organs within the tail, which emit intermittent weak EODs of variable amplitude (tens of millivolts) [66]. These weak EODs are used in intraspecific communication [67].

Active electroperception provides information about target distance, target conductivity and target direction.



*Figure 4: Representatives of six groups of electric fish. In addition to a line drawing of a fish and an indication of the location of the electric organ (gray tint), an oscilloscope trace of one or two characteristics pulses is given. From [64].*

Sensing the weak bioelectric fields generated by other animals is called passive electroreception. It is a specialized sense found in a large range of aquatic vertebrates primarily designed for the detection of weak bioelectric fields produced by the muscle contractions of other aquatic organism.

Electroreceptive sensory organs can be broadly categorised into two distinct classes, which are ampullary (DC detectors) and tuberous (AC detectors). Primarily they are based upon the cellular morphology of the receptor organs and secondarily on their respective frequency tuning characteristics [68]. Ampullary receptors are broadly tuned to low frequency fields (0.1–25Hz), while tuberous receptors are tuned to higher frequency fields from 50Hz to over 2kHz [69]. The ampullary electroreceptors detect animate and inanimate electric fields, by measuring minute changes in potential between the water at the skin surface and the basal surface of the receptor cells.

The “ampullae of Lorenzini” are complicated specialized skin sense organs characteristic of sharks and rays. They consist of electroreceptor cells that are connected to the seawater by pores on their snouts and other zones of the head.

Other fish species like polypterids, eels, catfish and lungfish possess electrosensory tuberous organs.

**Potential for principle transfer to sensory MEMS design:**

Electrosensing and -location could be used in devices for target location and orientation (special cameras) in muddy waters, blood and other places with special conditions like high temperatures or pressures. Furthermore these devices could determine parameters like material properties, thickness and material defects.

## **5. Summary**

In the primary sections a selection of different biological sensor systems that are available in nature are described. At the end of each chapter some propositions are mentioned, how the received knowledge could be transferred to sensory MEMS design.

This project work is just a small part of a big research project called “Biomimetic Development of a New Generation of MEMS in Medicine” at the “University Kebangsaan Malaysia”. The aim of the project is to modify and adapt existing MEMS designs via biomimetic knowledge transfer of outstanding sensory perception. Therefore, researches in the Malaysian rainforest will be made to approach animated nature for inspiration and to find a range of product ideas.

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