Biomimetic MEMS sensor array for navigation and water detection

Oliver Futterknecht[1], Mark O. Macqueen[2], Salmah Karman[3,4], S. Zaleha M. Diah[3] and Ille C. Gebeshuber[1,2,3]

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

[2] Aramis Technologies Sdn. Bhd., 2 Jalan Alam Sutera 1, Bukit Jalil, 5700 Kuala Lumpur, Malaysia

[3] Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Malaysia

[4] Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ABSTRACT

The focus of this study is biomimetic concept development for a MEMS sensor array for navigation and water detection. The MEMS sensor array is inspired by abstractions of the respective biological functions: polarized skylight-based navigation sensors in honeybees (*Apis mellifera*) and the ability of African elephants (*Loxodonta africana*) to detect water. The focus lies on how to navigate to and how to detect water sources in desert-like or remote areas. The goal is to develop a sensor that can provide both, navigation clues and help in detecting nearby water sources. We basically use the information provided by the natural polarization pattern produced by the sunbeams scattered within the atmosphere combined with the capability of the honeybee's compound eye to extrapolate the navigation information. The detection device uses light beam reactive MEMS, which are capable to detect the skylight polarization based on the Rayleigh sky model.

For water detection we present various possible approaches to realize the sensor. In the first approach, polarization is used: moisture saturated areas near ground have a small but distinctively different effect on scattering and polarizing light than less moist ones. Modified skylight polarization sensors (Karman, Diah and Gebeshuber, 2012) are used to visualize this small change in scattering. The second approach is inspired by the ability of elephants to detect infrasound produced by underground water reservoirs, and shall be used to determine the location of underground rivers and visualize their exact routes.

Keywords: MEMS, biomimetics, sensory system, navigation, water detection, polarization

1. INTRODUCTION

There are many occasions, when we need to find a clue where to go. Right from the beginning of humanity it was crucial to navigate from A to B, for example to get from home to the next food source. Navigation without technical devices on land was pretty easy because of defined landmarks to see where we are and where we are heading. On the sea it was harder to detect the exact position, the only clue was the position of the sun and with clear skies, the stars. But the Vikings already had some sort of compass. They where using a gemstone which changes colour when the angle between the point of view and the actual position of the Sun is changing. The navigator (termed *Kendtmann* in the language of the Vikings) was setting the course by gathering all the clues from the polarization, landmarks and fish- and bird migrations. So the Vikings were capable to navigate even at night, just by the information they gathered from the gemstone and the bearing, which the navigator gathered from the home harbour.

Nowadays we developed many different techniques and devices to improve our ability to locate our position and the destination we are heading to. For example; maps and compass or the GPS navigation systems. Insects on the other side have no such equipment to get to their food sources and back home, the honeybee for example. The bee (*Apis mellifera*) is capable to find the way from and to her hive at day and nighttime. Bees are equipped with a very specialized vision;

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they are capable to see the pattern of polarized skylight. This ability in combination with the information from the sun and landmarks are most important for the survival of the species. Their capability is a very efficient way of navigation: it is very compact and energy efficient so, for this purpose, we observe honeybees and aim to configure MEMS that are capable to detect and analyse polarized skylight to use as a cheap, energy efficient way to navigate just like those insects have been doing for about hundred thousand years. Furthermore it is very interesting to see if it is possible that MEMS detect and visualize small traces of water vapor near ground. There are some very interesting ways of tracking H_2O-vapor in the atmosphere and some are very easy to adapt with MEMS.

1.1 Skylight polarization guided navigation

The skylight polarization is defined via two different theories that describe the nature of light. Light can be described as wave and therefore spreads as such but light can also be classified as a particle. Combined, these theories lead to the principle of duality. Especially the theory described by the Rayleigh sky model (focuses on the wave properties of the sunlight) is the base on which we build up the application of the skylight based navigation system [1]. Within the system of the Rayleigh sky model the scattering of the sunlight, the skylight polarization is defined as a parameter changing with the altering angle of the sun over time. This parameter change allows us to build up a mathematical model we can use to define the exact direction we are heading. This is the first step to create an autarc navigation system that is not dependent on satellites or other computational sources.

1.2 Polarization used for water detection

Because of the effect of humidity richer atmosphere on the skylight polarization it is possible to create a system that analyses and extracts a map of humidity richer air masses within our atmosphere. With this information we can create a device that is capable to detect where water vapor descends from the soil and therefore can conclude where water reservoirs are situated. This application comes in very handy in deserted or remote areas where water is a rare resource.

1.3 Microelectromechanical systems (MEMS)

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 microelectronic 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 [2].

Currently, various MEMS are on the market that “sense” mechanical, electromagnetic or chemical signals equivalent to human, animal or plant senses.

2. THE RAYLEIGH SKY MODEL

There are two different theories that describe the nature of light. In one light can be described as a wave and spreads as such, in the other theory light can be classified as a particle – and both theories can be proven. Combined, these theories lead to the principle of duality. For analyzing polarization the wave theory becomes our main objective. Before sunlight reaches our atmosphere it has no polarization, electric and magnetic fields are spreading in every direction. After entering the ionosphere, a defined part of the wavelength will be polarized. The greater the refraction angle, the greater is the part of the polarized light. The Rayleigh sky model describes the observed polarization pattern of the daytime sky. The incoming light wave is reflected by air molecules, dust, aerosols and water, the resulting scattering causes the skylight to have a defined polarization pattern. These patterns are dependent on the celestial position of the sun; and at night by the reflected light of the moon. The light is highly polarized at a scattering angle of 90° from the light source. When the sun is located at the zenith the sky is polarized horizontally along the horizon. During twilight it is maximally polarized along the meridian and vertically at the horizon in the North and South.
This pattern is dependent on the position of the sun. The polarized patterns can be represented by a celestial triangle, based on the sun, zenith and the point of scattering, but the spherical triangle is not just defined by these tree points but also by the interior angles as well: the three angular distances between the sun, zenith and the point defined by the

observer.

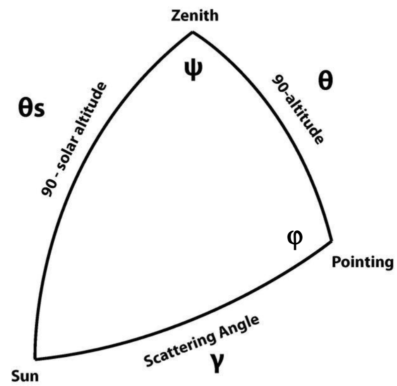

Figure 1: The geometry representing the Rayleigh sky; γ denotes the angular distance between the sun and the point of scattering, θ_S is the solar zenith distance, θ is the angular distance between the observed point and the zenith, φ is the angle between the zenith direction and the solar direction at the observed point and ψ is the angle between the solar direction and the observed pointing at the zenith. [3]

We are focusing on the angular distances of the triangle because those are crucial for the navigation abilities of the honeybee. There are three different models representing the different angles of the celestial triangle. There is the angle at the sun between the zenith direction and the pointing, dependent on the changing pointing and symmetrical between the Northern and Southern hemispheres, furthermore the angle at the zenith between the solar direction and the pointing which rotates around the celestial sphere. But the most interesting is the angle at the observed pointing between the zenith direction and the solar direction: it is essential because of the dependency on the changing solar direction as the sun moves across the sky. Because the pattern of polarized skylight is changing by the movement of the sun and is even reliable at twilight, it is a perfect way to navigate. The best example is the halicitid bee (*Tribe Halictini: Agapostemon*),

Figure 2: Picture of an *Agapostemon* part of the *Halictidae* bee family.
These halictids are active only at dusk or in the early evening.[4]

which inhibits the rainforests in Central America and scavenges before sunrise and after sunset. This bee leaves its nest approximately 1 hour before sunrise, forages for up to 30 minutes and accurately returns to its nest before sunrise. It acts similarly just after sunset. Thus this bee is an example of an insect that can perceive polarization patterns throughout astronomical twilight. Not only does this case exemplify the fact that polarization patterns are present during twilight, but it remains as a perfect example that when light conditions are challenging the bee orients itself based on the polarization patterns of the twilight sky [5].

3. DETECTORS FOR POLARIZED SKYLIGHT

Apart from the sun, the polarization pattern of the sky offers insects a reference for visual compass orientation. The detection of the oscillation plane of polarized skylight is mediated exclusively by a group of specialized ommatidia (which are the small units that build up the compound eye) situated at the dorsal rim area (DRA) of the compound eye. The physiological specification of the DRA goes along with characteristic changes in ommatidial structure, providing actual anatomical hallmarks of polarized skylight detection, that are readily detectable in histological sections of compound eyes. The presence of anatomically specialized dorsal rim ommatidia in many other insect species belonging to a wide range of different orders indicates that polarized skylight detection is a common visual function in insects. The key function of the DRA of the compound eye for E-vector perception has been demonstrated in four insect species by behavioral experiments (for example in the honeybee, *Apis mellifera*: Wehner and Strasser [5]). As shown by electrophysiological recordings, the dorsal rim ommatidia of this species share a number of physiological properties that makes them especially suitable for the detection of polarized skylight: each ommatidium contains two sets of homochromatic, strongly polarization-sensitive photoreceptors with orthogonally arranged analyzer directions. As revealed in the honeybee, which has nine instead of eight long receptor cells, it is the three UV-receptors that mediate polarization vision in the bee, forming large rhabdomeres (light-conducting axle rods) with orthogonal microvillar orientations (microvilli are thin threadlike cell processes used to maximize the surface). In addition, the DRA of *Apis* has straight retinulae as opposed to the regular retinuale that are twisted about their long axis. This allows a higher absorption of the UV-waves because the ray can enter the ommatidium without reflections within the retinuale. So in honeybees the strict alignment of the microvilli along the rhabdom was shown to boost polarization sensitivity of the UV-receptors [5].

3.1 Compound eye of the honeybee

Now for many invertebrate animals these patterns are crucial to determinate their position, because when the sun is hidden behind clouds, trees or the horizon they rely on the information provided by the patterns of polarized skylight. The interesting fact is, that the E-vector patterns correspond more closely to predictions based on first order (Rayleigh) scattering at 650nm and 500nm than to 350nm (UV-Spectrum). Most insects, including the honeybee, respond to polarization patterns only at UV wavelengths, which seems to be inefficient but on the other hand the quality of those patterns is increasing when the sun is hidden behind clouds, trees or the horizon. Under those special and difficult conditions ultraviolet light has advantages over longer wavelengths, because the resulting reflections present more troublesome interference at longer wavelengths than in the UV [6].

The compound eye of the honeybee is a very complex system which is capable to perceive UV-light and analyze the polarized skylight pattern. It is made up of very small units called omatidia, each ommatidium contains an optical system and seven to eight receptor cells. In the insects, rhabdomeres from several retinula cells may fuse to form a central, closed rhabdom; but in certain bee's eyes there is no fusion, and the rhabdomeres remain isolated from one another and this spatial isolation permits each retinula cell to act as an individual receptor [7]. There are many studies about the orientation of the honeybee showing the ability of the bee to navigate. Some studies use a horizontally arranged hive containing a single comb. The hive can be moved in the x and y directions, covered by a Plexiglas hemisphere equipped with coverable windows through which when they are opened, either natural sky light or artificially polarized light can be presented to the bees. For the artificial light source a Xenon arc with heat filters, diffusers, spectral light filters and polarizers are used. Also a TV camera, monitor and video recorder are installed. With this installation Russel and Wehner discovered that honeybees should be able to orient correctly whenever they can view at least two E-vectors in the sky [8].

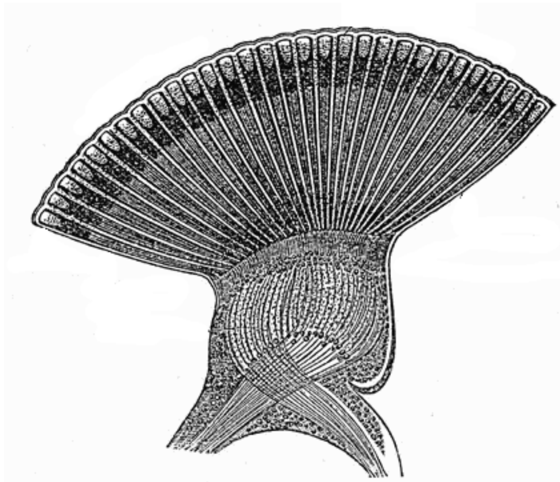

Figure 3: Picture of the compound eye. [9]

However, even under such apparently unambiguous stimulus conditions, bees make mistakes. This holds true even if they have had the chance to view the full E-vector as it occurs in the sky and thus cannot rely on memorized images of the E-vector patterns so what they seem to use instead is a celestial map that provides not a correct but an approximate compass information about the actual E-vector patterns in the sky.

3.2 What does an Insect see

The eye of *Apis mellifera* is an array of photo receptors, each at an angle to the next, so its perception is just like the human eye, except that it is not inverted. The architecture of the eye tells us a little about what the bee actually abstracts from the panorama. It is also not sufficient to determine whether bees recognize patterns or just gather a series of cues to navigate to the target[10].

Below the photo receptors, the next components of the sensory mechanism are small feature detectors that are one, two or three ommatidia wide that respond to light intensity, direction of passing edges or orientation of edges displayed by parameters in a pattern. At the next stage responses of the feature detectors for area and edges are summed in various ways in each local region of the eye to form several types of local internal feature totals, here called cues. Cues representing the units of visual memory in the bee, at next stage summation implies that there is one of each type in each local eye region and that local details of the pattern are lost [11].

So insects have developed many different forms of analyzing the polarized skylight for clues to determine their traveling vector. To get a closer look on how the honeybee uses the E-vector for their navigation from the hive to their food sources and back, lets recapitulate the main tools empowering such a great ability. The E-vector pattern in the sky can be described most conveniently by a sun-related system of coordinates determined by the Rayleigh Sky model described above. On how the honeybee uses this information can be extrapolated form the hypothesis, that bees are supposed to memorize the E-vector pattern last seen, and later match the current image (i.e. the actual pattern when they fly back) with the memorized one. Therefor bees should be able to orient correctly whenever they can view at least two E-vectors in the sky (two E-vectors are crucial when identical directions of polarization occur twice at the elevation they orient on [8]). But there is still one problem to fully understand on how bees really use E-vector information. Rossel and Wehner's research showed that bees (even when they see the full E-vector pattern) still make navigation mistakes, so it seems that they are using not directly the information given by the E-vector. Instead they build up some sort of celestial map providing approximate compass information about the actual E-vector patterns [8]. With this information the honeybee can approximate the way from and back to their hive including the information form the inner celestial map and landmarks they memorize before they flew off.

Actually the Honeybees are also able to detect magnetic fields for that we can also assume that bees also use this ability for navigation purpose. But Prof Chu created macroscopic robots that uses biomimetical translation of polarization for navigation. See:"Lambrinos et al. [12] invented a GPS independent polarization compass model that mimics the principle of the desert ant navigation system. Chu and co-workers enhanced this polarization compass principle [13–17] and improved the error measurement."

3.3 Techniques Vikings used for Nautical Navigation

There are not many clues how the Vikings managed to navigate across the open ocean for thousands of miles without conventional instruments. But in many sagas are descriptions of so called sun stones and some sort of bearing board used by the Viking navigators to guide them across the North Atlantic. The Vikings mostly sailed in summer, this habit supports the theory, because then the Northern latitudes are experiencing long days and short nights. So the Vikings were depending more on the sun than on the stars for navigation. So it was common to use a crystal that is able to even change color by the angle the sunbeam is entering the crystal for example a Cordierite or a crystal that is known for its double refraction like the Icelandic spar.

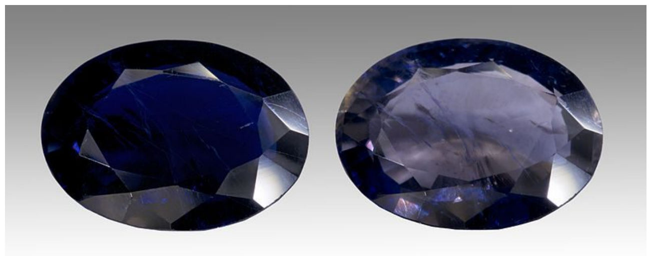

Figure 4: Picture of a Cordierite crystal. Left under normal light, right image in polarized light [18].

For the last form of navigation, it is crucial that the sun itself is visible, so that the sunbeam hits the device directly. While the first sort of crystal needs only the polarization of the sunbeam that leads to the change of colors even when the sun is not directly visible, Karlsen build a device that holds the crystal over a mirror, so the observer does not need to hold the sunstone overhead and look up the sky. The Vikings also needed to invent a scheme to get their bearings and guide their ships across the ocean. They divided the horizon into eight sections, which they called attir, which stands for "main directions". This directions where based on the Norwegian West coast, which runs approximately North to South. The horizon board is simply a board upon which the main directions are indicated and the azimuths of sunrise and sunset over the sailing season on a certain latitude. It mainly shows how the information about the sun can be interpreted within these eight sections of the horizon and can be put to use in navigation. Furthermore the Vikings did not refer to latitude by degrees but by the name of landmarks and places located at the appropriate latitude. So instead of saying latitude 62° North, they used the name Stad, Norway, as the destination they were sailing from, and the name of their destination, Thorshavn, Faeroe. So the horizon board gives the approximate direction and with the information the navigator gathered from the home harbor (for example; Landmarks, clues from other navigators, etc.) he was able to figure out a provisional route to a destination across the ocean, as recorded in the sagas. The horizon board visually demonstrates the direction of the rising and setting sun during May, June and July at a given latitude. Small holes on the edge of the horizon board were used with wooden pegs to mark the direction to the sun. One clue of how the Vikings were using the Sunstone is the saga of the "Grey Goose"; however, Leif K. Karlsen [19] showed that this form of navigation is practicable and working at least for the summer months when the hours of sunshine are exceeding over hours when the sun is not shining. Using a Cordierite, which does not need the direct sunlight, could be an improved way for navigation. But therefore we need different techniques and devices to visualize the change of the skylight polarization within the wavelengths of UV-light. To enhance those theories archeologists just discovered a sunstone on an old Viking warship wreck [20].

3.4 Realisation of polarization navigation in MEMS

A polarization-based navigation device can be realized by using the geometrical connection between the three points of the Rayleigh sky model (see Figure 1), using an optical angle detection MEMS. The apparatus found fitting for this purpose is a light angle detector MEMS. It is already patented in the US [21] and mainly consists of two optical detectors, the first is placed in front of a coating or layer with optical transmission ability, this layer transports the beam to the second detector, the refraction developed by the coating defines the characteristics of the measured data. The difference in the light characteristics measured at the respective detectors therefore provides an indication of the angle of incidence of the light beam.

Using this MEMS and applying the law of cosines to the spherical triangle gives:

$$\cos(\gamma) = \sin(\theta_s)\sin(\theta)\cos(\psi) + \cos(\theta_s)\cos(\theta) \quad (1)$$

This equation is used to calculate the scattering angle between the observed pointing and the sun. For θ_s is the solar zenith distance (90°- solar altitude), ψ is the angle between the solar direction and the observed pointing at the zenith, θ is the angular distance between the observed pointing and the zenith (90° - observed altitude) and γ is the angular distance between the observed pointing and the sun.

This equation reaches a singularity at the zenith where the angular distance between the observed pointing and the zenith θ_s, is zero. Here the orientation of polarization is defined as the difference in azimuth between the observed pointing and the solar azimuth. The scattering plane is the plane through the sun, the observer, and the point observed (or the scattering point). The angle located at the zenith between the solar direction and the observed pointing is the scattering angle. This angle of polarization is always perpendicular to the scattering plane. [22] With this information it is possible to calculate the angle dependent grade of polarization:

$$\delta_{polarization} = \frac{I\| - I\perp}{I\| + I\perp} \Rightarrow \frac{1-cos^2(\alpha)}{1-cos^2(\alpha)} \qquad (2)$$

It is correlated to the angle α=90°-θ which is the angle between the observed pointing and the sun. Therefore we could use the same clues as the honeybee, to provide enough information for ground navigation.

4. DETECTION OF WATER VAPOR

Meteorology goes back to the time of Aristoteles, where every form appearing in the sky was a meteor (Greek, for floating in the air). Aristoteles described weather phenomena like clouds, rain, etc., which were unpredictable and not directly calculable from the laws of nature known then. The more far away stars were seen predictable and the main task for astronomy, the border for them was the moon. With time, weather became a little bit more predictable and forecasts where made by observation of the weather and keeping track of the changes. Nowadays we keep track of clouds by using data from various sources, for example weather balloons, satellites or radar facilities. Accumulation of the data and calculating with floating formalism we obtain a forecast that is up to 65% accurate. This techniques, using radar to actually detect water vapor in the atmosphere could be used to detect water near ground. To be exact, the water vapor that leaves the soil layer. This could be used to trace water in the desert, finding the course of a dried out river and preventing dying from thirst. Also there could be a possibility to detect the ideal place to dig a well.

4.1 Methods of cloud detection

Currently there are two ways to keep track of clouds, firstly, the visible satellite imagery (VIS) and the second the infrared imagery (IR). Where the visible imagery is produced by the sun's rays reflection off clouds, IR images are produced by sensing the emitted radiation coming off clouds. The temperature of the cloud will determine the wavelength of radiation emitted from the cloud. For our attempt to locate water exhalation from ground, the IR detection is the most convenient way of detection, because the amount of water descending from the ground is not enough to be visible to the naked eye. The question resulting is, if the emitted radiation of the water vapor exceeds the detection threshold of the device. There are some more ways to detect water vapor, for example the use of silicon oxide or an gravimetric hygrometer.

Absorption hygrometer: includes a hygroscopic (water affine) material which changes its properties when getting in contact with vapor. Best known is the hair hygrometer that works with a human hair which changes length when it comes in contact with moisture. It is an approximate length difference of 2.5% from 0% to 100% humidity.

Psychrometer: which consists of two identical thermometers, one of them is warped into a moistured mull stocking. The "wet" thermometer shows a lower temperature then the other, with this information it is possible to calculate the actual humidity.

Dew point mirror hygrometer: This technique of measurement is used to define the national humidity standards. A mirror is cooled until the humidity will condensate, using a light source and a photoreceptor the moment of condensation will be determined. The dew point is defined by dew point-temperature and pressure, therefore it is possible to directly calculate the relative humidity.

The problem with these methods is that they are just measuring one single point nearby the instrument or that the accuracy is limited. So, a solution is needed to detect water vapor descending from earth in a designated area.

4.2 How to detect water vapor near ground

One possible option would be to use an infrared device that is capable to detect the difference in temperature in a defined area, so it is possible to detect water vapor indirectly over the change of temperature in different areas. So one obtains a vector to walk to for a new measurement. The biggest advance in this method is, that the needed technology is already in use and easy to implement for this new task.

The other possible method is more of a theoretical approach on how water could be detected underneath the earth. In this method, the infrasound produced by underground water flow is the signal to be measured. This task would be performed with special microphones, capable to detect frequencies from 0.001 Hz to 20Hz. The greatest issue is that there needs to be a water current to provide the source for the infra sound. Right now infrasound monitoring stations are used to detect earthquakes and possible nuclear detonations.

5.RESUME

Biological systems provide great inspiration concerning new applications and/or developments of MEMS sensors. Biologists and engineers are encouraged to meet more often at conferences, and to establish a joint scientific language so that biomimetic developments are facilitated.

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