THE FUTURE OF MEMS SENSORS IN OUR CONNECTED WORLD

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ABSTRACT

The MEMS market is year after year growing faster than the average semiconductor industry. Over that time the largest technology driver for MEMS changed from automotive applications to consumer electronics dominated by smartphones. Beyond that, MEMS sensors become the heart of whole classes of new devices like fitness trackers, smart watches, virtual reality glasses and smart sensor nodes for the Internet of Things.

Silicon chips are only one part of the MEMS story, you need as well special mixed signal circuitry, low power data processing, smart algorithms and connectivity to transform raw signals into meaningful information. Multi-sensor applications & modules are playing an increasingly important role.

INTRODUCTION

Technological Background

The following 6 key technologies developed by Bosch are the basic micromachining processes used for most of today's sensor products:

- Growth of very thick layers of polysilicon, so-called "Epipoly" [1]
- High-precision and fast deep trench etching (the "Bosch DRIE-process") [2]
- Vapor phase etching for release of structures [3]
- Encapsulation for hermetical sealing [4], [5]
- APSM process – exact vacuum cavities in silicon (Advanced Porous Silicon Micromachining) [6]
- FlipCore geomagnetic field sensing in a thin-film semiconductor process

Bosch holds more than 1000 patent families on a large variety of MEMS technologies and sensor applications. With these technologies acceleration sensors, gyroscopes, pressure sensors, magnetometers and others were fabricated at Bosch with a cumulated volume of more than 4 000 000 000 parts until 2014.

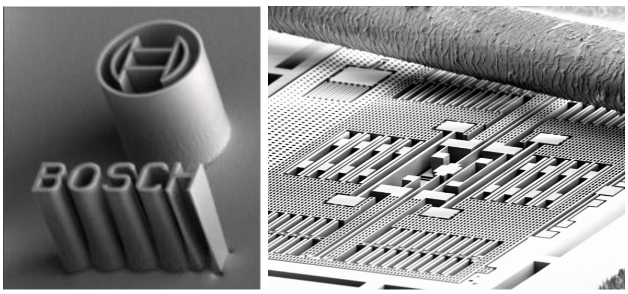

Figure 1: Silicon structures created by the Bosch process for deep trenching. For size comparison, a hair with 90 µm diameter is shown on top of an acceleration sensor structure on the right.

THE THREE WAVES OF MEMS PROLIFERATION

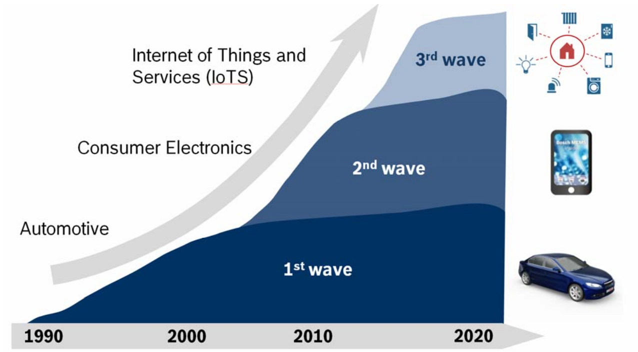

Figure 2: The three waves of MEMS proliferation

The first wave: Automotive

In the mid 90ies automotive MEMS started with airbag, yaw-rate and pressure sensors in high volume. In a typical car of today you find more than 50 MEMS sensors, which are used for [7]:

Engine Management
- Barometric Air Pressure (BAP)
- Diesel particulate filter
- Mass flow sensor…

Vehicle Dynamics Control
- Yaw rate sensor
- High pressure sensor
- IMU and low g sensors…

Safety Systems
- Rollover sensor
- Occupant weight sensor iBolt
- Pedestrian Contact Sensor (PCS)
- Upfront Sensor (UFS)
- Peripheral Pressure Sensor (PPS) …

Figure 2: MEMS sensor applications in a car of today.

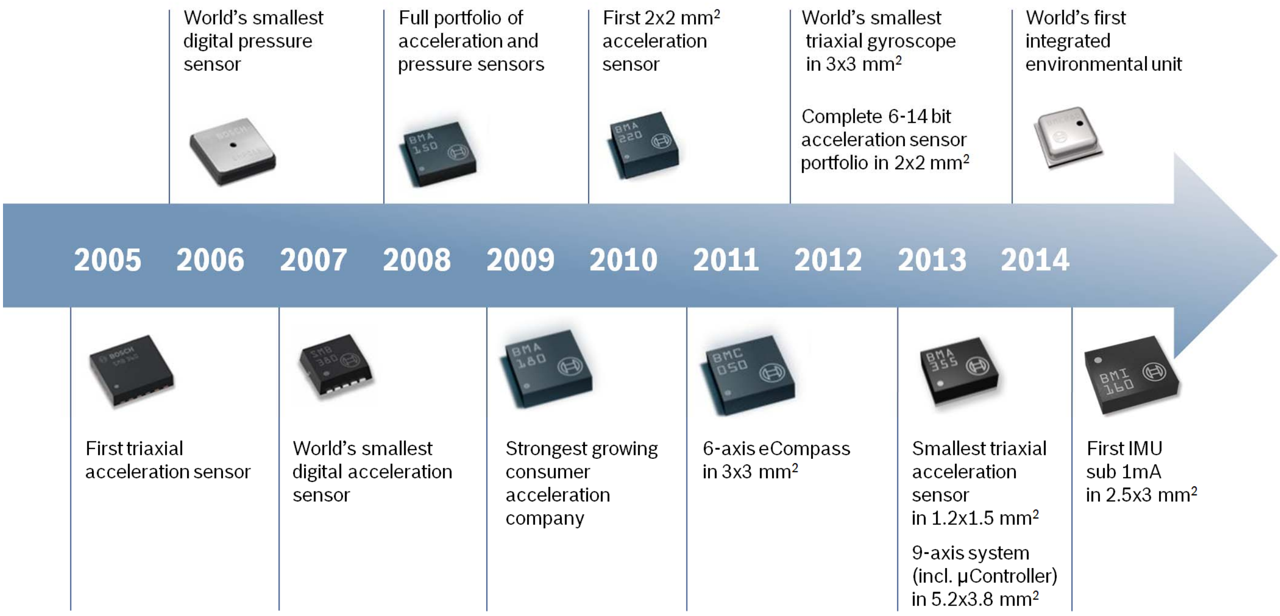

Figure 3: Consumer MEMS products shrink path.

With MEMS sensors the cars became safer, more fuel efficient and cleaner, which benefits our environment.

The second wave: Consumer electronics

In the mid of the last decade mobile phones started using MEMS sensors. Meanwhile they became the strongest driver of new MEMS developments, shrinking size and cost at a high pace while increasing the performance, see Fig. 3. Today's applications of MEMS sensors in smart phones are:

Orientation detection

- Portrait / landscape
- Upside down
- Free speech profile

User interface

- Gaming input
- Menu navigation
- Gesture recognition

Motion analysis

- Step counting
- Activity monitoring
- Power management

Pedestrian navigation

- Dead reckoning
- Floor level tracking
- Location based services

The third wave: Internet of Things and Services (IoTS)

If you want to increase comfort, security, health and productivity you have to create smart, interactive and sensitive systems. Beyond smartphones new classes of wearable devices emerge, like fitness trackers, smart watches and virtual reality glasses that are all loaded with MEMS sensor. They target the following applications:

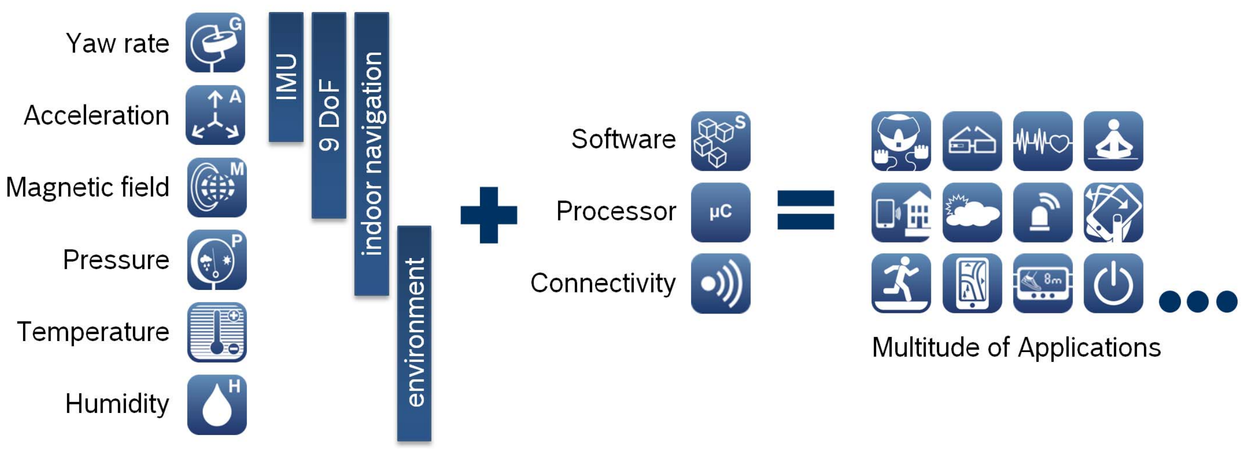

Figure 4: From measurands to sensor data fusion

Wellbeing

- Sleep monitoring
- Activity classification
- Stress level detection

Fitness

- Speed and performance
- Fitness level
- Calorie monitoring
- Sports trainer

The Internet of Things also targets home automation and smart cities. Today we see that stand-alone devices like home appliances, heating, venting and air conditioning (HVAC) get connected by proprietary solutions within distributed networks. The future will shift from monitoring towards control of intelligently connected household devices and HVAC systems in function of persons present, their individual behavior, weather forecast, electricity price etc.

These sensor applications have in common that the sensor modules measure multiple physical quantities, are always on, have a processing unit with software and are connected to a communication network, see Fig. 4. The impacts on sensor requirements are:

- Reducing power consumption
- Reducing footprint
- Smart data fusion software
- Integration with micro controller and RF

FROM SENSOR SIGNALS TO USER EXPERIENCE

The cause-and-effect dependencies between use-case and technology are usually passing several steps. Three of these chains shall be shown here to explain the processing of different signals for their respective application.

From pressure sensors to faster navigation

An atmospheric pressure sensor can be used to measure the altitude above sea level. The measurement gets more precise if the weather dependent sea level pressure (average value 1013.25 hPa) is taken into account, which can be obtained online by service providers, e.g. from the closest airport.

A GPS can take up to several minutes from cold start to output the first position, also known as TTFF (time-to-first-fix). This time can be shortened by using the almanac data from mobile cell towers (A-GPS, Assisted GPS). The waiting time can be further decreased when the altitude above sea level is available in the system [8]. The reason is that the 3D location solution space for locking the satellite codes and pseudoranges is reduced. This feature was first used in high volume in the 2011 Google Nexus phone [9].

Sensor data fusion: more than the sum of its parts

A compass and a gyroscope both suffer from fundamental imperfections for finding the true north heading. The compass is distorted by steel constructions in buildings, electrical power lines and transformers, electrical motors in printers, elevators etc., as well as by other components in the mobile device itself like loudspeakers and NFC antennas. The gyroscope has a temperature dependent yaw rate offset (bias) that leads to a heading drift when integrated.

With the help of Kalman filters [10], the errors of both sensors can be estimated continuously and cancelled mutually using the overdetermined properties of the equation systems. The computation power is considerable, since matrix inversion is needed. Additionally, the algorithms need to be optimized according to the sensors' characteristics.

This so called sensor data fusion to obtain the true orientation vector (roll, pitch, heading) in world coordinates has been successfully integrated in one component BNO055 (see Fig. 5). It contains acceleration sensor, gyroscope and magnetometer, each 3-axis, in total 9 DoF (degrees of freedom), together with a micro-processor and software to output the self-calibrated orientation in real time.

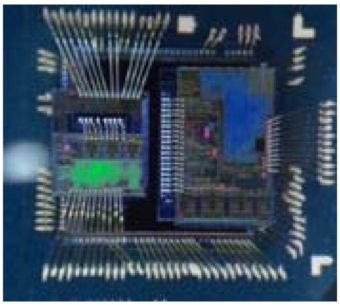

Figure 5: Multi chip package for true orientation sensor BNO055.

- Package size: 5.2mm x 3.8mm x 1.1mm
- Accuracy: 2° … 3° (static)
- Latency: 20 ms
- Robust to magnetic distortions
- Optimized HW/SW Codesign

This orientation vector can be combined with a step counter for dead reckoning, which is the extrapolation of the location from the last or to the first known fix from GPS or WiFi localization. The merging of MEMS sensor data with other sources improves the accuracy of localization especially indoors, e.g. in shopping malls and other public buildings.

As the power consumption of sensors decreases (e.g. less than 1 mA for Bosch Sensortec's BMI160 inertial measurement unit with a 3-axis gyroscope and 3-axis acceleration sensor) it is important not to waste power in signal processing. Therefore integrated sensor functions enable always-on applications, e.g. a step counter with less than 50 µA consumption for computation. This is orders of magnitudes less than the application processor of a smartphone would consume on average, even if it is woken up only for a very short time.

Beyond motion sensors, the pressure sensor used as altimeter can track indoor floor levels, which is not possible with GPS.

Environmental sensors

We call the combination of pressure, humidity and ambient temperature sensor an environmental sensor, see Fig. 6. Such sensors are usually integrated in HVAC control systems, where the response time is not critical. Bosch Sensortec's BME280 shows a very fast response time of $\tau = 1$ sec. This enables completely new applications like detecting the proximity of human skin (which always evaporates some humidity) in contrast to other surfaces. Unlike optical proximity sensors, this environmental sensor can distinguish between a user and another object close to the device, which is helpful to save power by a more specific wake-up feature.

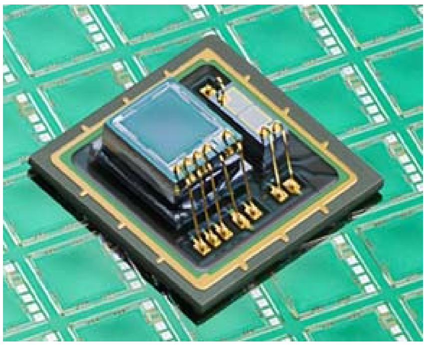

Figure 6: Environmental sensor BME280, 2.5 x 2.5 mm², here shown without metal cap on top.

CONCLUSION

Bosch sensors can be found in every second smartphone worldwide today.

Modules with a multitude of sensors, integrated low power signal processing e.g. for context awareness and specific applications, will change MEMS from the provision of raw data to meaningful data fusion output from sensor nodes for our connected world, see Fig 7.

ACKNOWLEDGEMENTS

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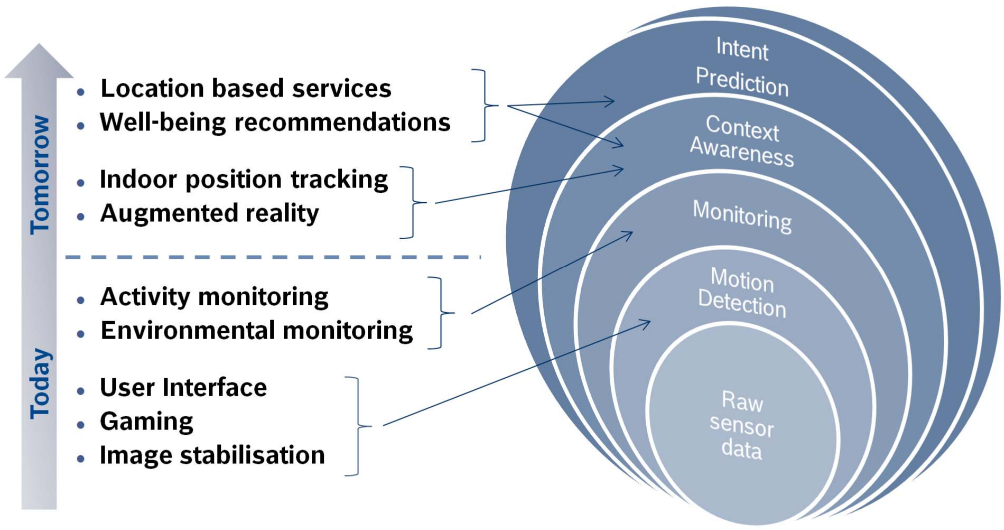

Figure 7: More advanced use-cases will drive systems.

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