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National MEMS Technology Roadmap – Markets, Applications and Devices

School of Electrical Engineering

Master's Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology, 11.7.2012

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ABSTRACT OF THE
MASTER'S THESIS

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Name of the thesis: National MEMS Technology Roadmap – Markets, Applications and Devices

Date: 11.7.2012 Language: English Number of pages: 7+51

Department of Electronics

Professorship: Electronics integration and reliability Code: S-113

Supervisor: Professor Mervi Paulasto-Kröckel

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MEMS technology has long been applied to the fabrication of various devices from which some have already been in use for several years, whereas others are still under development. In order to find future focus areas in research and development activities in the industry, it is important to know where the development is going. This thesis was conducted as a part of National MEMS technology roadmap, and it aimed for determining the evolution of MEMS devices. The work was conducted as an extensive literature review. In addition, experts from the Finnish MEMS industry were interviewed in order obtain a broader insight to the results.

In this thesis various existing and emerging MEMS devices were reviewed and analyzed from technological and commercial perspectives. The study showed that the MEMS market has long been composed of established devices, such as inkjet printheads, pressure sensors, accelerometers and RF filters. Also gyroscopes, microphones and optical MEMS devices have already been on the market for a long time. Lately, many new devices have started to find their place in the markets. The most recently introduced commercial devices include microfluidic devices, microbolometers, and combo sensors. There are also a few devices including magnetometers, MEMS oscillators, and auto-focus devices that are currently crossing the gap from R&D to commercialization. In addition to the already available devices, many new MEMS devices are under development, and might offer significant opportunities in the future. These emerging devices include various bioMEMS devices, atomic clocks, micro-coolers, micro speakers, power MEMS devices, and RFID devices. All of the emerging devices might not find commercial success, but the constant stream shows, that there are numerous applications, where MEMS devices could be applied in. From a market point of view, the greatest potential in the future lies in consumer electronics market. Other highly potential markets include medical and industrial markets.

The results of the thesis indicate that there are many potential focus areas in the future related to MEMS devices, including improvements of the existing devices in order to gain better utilization, application of the existing devices in new areas, and development work among the emerging devices.

Keywords: MEMS devices, emerging MEMS, MEMS markets, MEMS applications

AALTO-YLIOPISTO
SÄHKÖTEKNIIKAN KORKEAKOULU

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Susanna Lampo
Työn nimi: Kansallinen MEMS teknologioiden tiekartta – markkinat, sovellukset ja laitteet

Päivämäärä: 11.7.2012 Kieli: Englanti Sivumäärä: 7+51

Elektroniikan laitos

Professuuri: Elektroniikan integrointi ja luotettavuus Koodi: S-113

Valvoja: Prof. Mervi Paulasto-Kröckel

Ohjaaja: TkT Toni Mattila

MEMS teknologiaa on jo pitkään käytetty lukuisien eri laitteiden valmistamiseen. Osa näistä laitteista on ollut markkinoilla jo useita vuosia, kun taas osa on vasta kehitysvaiheessa. Jotta tutkimus ja kehitystyötä osattaisiin jatkossa kohdistaa oikeille painopistealueille, on tärkeää tietää mihin suuntaan kehitys on menossa. Tämä työ on osa kansallista MEMS teknologioiden tiekartta -projektia ja sen tavoitteena oli selvittää MEMS laitteiden kehityksen suuntaa. Työ toteutettiin laajana kirjallisuustutkimuksena. Lisäksi tulosten tueksi haastateltiin asiantuntijoita Suomen MEMS teollisuudesta.

Työssä tarkasteltiin lukuisia jo markkinoilta löytyviä ja vasta kehitteillä olevia MEMS laitteita ja analysoitiin niitä sekä teknisestä että kaupallisesta näkökulmasta. Tutkimuksen perusteella kävi ilmi, että MEMS markkinat ovat pitkään muodostuneet vakiintuneista laitteista kuten mustesuihkupäistä, kiihtyvyysantureista, paineantureista sekä RF suotimista. Lisäksi mikrofonit, gyroskoopit ja optiset laitteet ovat olleet kaupallisesti saatavilla jo pitkään. Markkinat ovat hiljattain alkaneet tehdä tilaa myös uusille MEMS laitteille, joita tulee ulos nopeaa vauhtia. Viimeisimpänä markkinoille tulleita laitteita ovat erilaiset mikrofluidistiikka laitteet, mikrobolometrit sekä yhdistelmäanturit. Pian kaupallisesti saatavia laitteita ovat magnetometrit, automaatti-tarkennuslaitteet sekä MEMS oskillaattorit. Näiden laitteiden lisäksi kehitteillä on monia uusia MEMS laitteita, jotka saattavat tarjota merkittäviä mahdollisuuksia tulevaisuudessa. Kehitteillä olevia laitteita ovat erilaiset lääketieteelliset laitteet, atomikellot, mikrojäähdyttimet, mikrokaiuttimet, energiantuottolaitteet sekä RFID – laitteet. Kaikki kehitteillä olevista laitteista eivät välttämättä tule menestymään kaupallisesti, mutta jatkuva tutkimustyö osoittaa, että monilla MEMS laitteilla on potentiaalia useissa eri sovelluksissa. Markkinanäkökulmasta tarkasteltuna suurin potentiaali piilee kuluttajaelektroniikka markkinoilla. Muita tulevaisuuden kannalta potentiaalisia markkinoita ovat lääketieteelliset ja teollisuusmarkkinat.

Tutkimus osoitti että MEMS laitteiden tutkimukseen ja kehitykseen liittyy monia potentiaalisia painopistealueita tulevaisuudessa. Käyttömahdollisuuksien parantamiseksi monet jo vakiintuneet laitteet kaipaavat vielä parannuksia. Toisaalta, jo olemassa olevia laitteita voidaan hyödyntää uusissa sovelluksissa. Lisäksi monet uusista ja kehitteillä olevista MEMS laitteista vaativat vielä kehitystyötä.

Avainsanat: MEMS laitteet, MEMS markkinat, MEMS sovelluskohteet

Preface

This master's thesis was carried out at the department of Electrical Engineering as a part of the National MEMS Technology Roadmap. I would like to thank my supervisor prof. Mervi Paulasto-Kröckel for giving me the opportunity to work on such an interesting topic and for taking an interest in my thesis. I would also like to express my deep gratitude to my instructor Toni Mattila for all the valuable advice and comments on my thesis, as well as for the great effort on helping me to arrange the expert interviews. I also wish to thank the experts who took time off from their busy schedules to participate in the interviews.

Finally, I want to thank my family and friends for all of the encouraging words and support during the completion of this thesis and throughout my studies. Special thanks goes to my boyfriend Morten for his endless support and belief in me in everything I do.

Espoo, 11.7.2012

Susanna Lampo

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List of Abbreviations

AF	Auto-Focus
BAW	Bulk Acoustic Wave
BioMEMS	Biological or Biomedical MEMS
CFHX	Counter-Flow Heat Exchanger
CMOS	Complementary Metal Oxide Semiconductor
CPAP	Continuous Positive Airway Pressure
CSAC	Chip-Scale Atomic Clock
DC	Direct Current
DLP	Digital Light Processing
DOF	Degrees of Freedom
ESC	Electronic Stability Control
FBAR	Thin-film Bulk Acoustic Resonator
GLV	Grating Light Valve
GPS	Global Positioning System
HDTV	High-Definition Television
HVAC	Heating, Ventilation and Air Conditioning
IC	Integrated Circuit
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IR	Infrared
LCD	Liquid Crystal Display
LO	Local Oscillator
LOC	Lab-on-a-Chip
LSD	Laser Scanning Display
LWIR	Long-Wave Infrared
MAC	MEMS Atomic Clock
MEMS	Micro Electro Mechanical System
MOEMS	Micro-Opto Electro Mechanical System
MST	Micro System Technology
NDIR	Non-Dispersive Infrared
POC	Point of Care
PSRR	Power Supply Rejection Ratio
R&D	Research and Development
RF	Radio Frequency
RFID	Radio Frequency Identification
RHFC	Reformed Hydrogen Fuel Cell
RSD	Retinal Scanning Display
SAW	Surface Acoustic Wave
SNR	Signal-to-Noise Ratio
TAS	Total Analysis System
TPMS	Tire Pressure Monitoring System
USD	United States Dollar
VAO	Variable Optical Attenuator
WDM	Wavelength Division Multiplexing
2D	Two Dimensional
3D	Three Dimensional

1 Introduction

Micro Electro Mechanical Systems (MEMS) are miniaturized integrated devices that combine electrical and mechanical components. They are typically the size of few millimeters containing various micrometer scale structures. The term MEMS is most commonly used in USA, whereas in Europe the devices are often referred to as Micro System Technology (MST), and in Japan as Micromachining. MEMS are fabricated using the same type of technologies used in the fabrication of integrated circuits (IC). The two most common fabrication technologies for MEMS are bulk micromachining and surface micromachining. Silicon is by far the most commonly used substrate material in MEMS. However, other materials such as glass can be used as well. (Van Heeren & Salomon 2007) MEMS devices can operate either as sensors or actuators. Sensors obtain information from a detected object and transform it into a signal, which can be measured using various techniques. MEMS sensors can, for instance, be used to measure pressure, motion or sound. Actuators, on the other hand, transform non-mechanical energy into motion, force or torque to change the environment. (Li et al. 2010) Examples of MEMS actuation applications are light projection, microfluidic applications and RF related functions (Yole 2012b).

The history of MEMS starts in the early 1950's and the first commercial products were introduced in the 1970's. Since then the devices have gradually made their way out of research laboratories and into our everyday products. Especially during the last 20 years the development of new MEMS devices has been intense. Today, various MEMS devices can be found in numerous applications across a diversity of industries ranging from consumer electronics to military and aerospace applications. (Van Heeren & Salomon 2007) Even though the first MEMS devices have been on the market for approximately 40 years now, the industry is still considered to be relatively young. However, the MEMS market is still one of the most rapidly growing sectors of the electronics industry (Flament 2011). Especially the introduction of MEMS devices to consumer products, such as cell phones and game consoles has accelerated the growth even further. Plenty of new MEMS devices are being developed and introduced on the market in a fast pace and the MEMS market is expected to achieve further growth in the future. (Yole 2012b)

Finland has had activities in the MEMS industry already for several decades now. The Finnish MEMS industry has remained relatively small with only a few players on the market, although, it is considered to have very strong competence both in research and production. The national MEMS cluster comprises of a few research institutes including Technical Research Center of Finland, also know as VTT and Aalto University of Science and Technology, as well as commercial organizations including VTI Technologies (Murata Electronics since 2012), Okmetic, Vaisala and Scannano. As the MEMS market is constantly developing, it is important for the national industry to keep up with this development in order to maintain its competitiveness and knowhow at the international top level. For this reason, there is currently a need for determining the development trend of the MEMS technology and defining common future focus areas for the research and development activities.

2 Aims of the Study

This master's thesis will be a part of the National MEMS Technology Roadmap, which is conducted by Aalto University School of Electrical Engineering in close co-operation with representatives from the Finnish MEMS industry. The primary objective of the roadmap is to define the future focus areas of research and development activities in research institutes and commercial organizations in Finland. The work is also expected to strengthen the co-operation between organizations in the national MEMS cluster and enhance the opportunities for creating new start-up companies. The first version of the roadmap was published in June 2011. Based on a questionnaire survey and expert meetings three focus areas for the near future national research and development were proposed: next generation 3D integration of MEMS-based systems, functional materials in MEMS based systems, and MEMS based biomedical sensor/actuator systems. The updated version of the roadmap is currently under development and will be published in 2012. The roadmap will be updated in regular time intervals in the future as well.

The purpose of this thesis is to expand the device section of the National MEMS Technology Roadmap by reviewing various existing and emerging MEMS devices and analyzing them from technological and commercial perspectives. The main objective is to determine the development trend of MEMS devices and define potential future focus areas for research and development activities related to MEMS devices. Deeper insights on enabling technologies, materials and packaging are covered elsewhere in the roadmap and are thus not included in this thesis. The work is conducted as an extensive literature review. In addition, experts from the Finnish MEMS industry are interviewed in order to obtain professional opinions to the results of the literature review. As being part of a roadmap, the thesis aims for a compact structure providing information in a summarized form from a large number of different devices.

The literature review starts in chapter 3 with a brief overview of the largest MEMS markets and some important applications for MEMS devices. In chapters 4 and 5 the various MEMS devices are reviewed and analyzed from different perspectives. Chapter 4 reviews the already existing MEMS devices, whereas chapter 5 focuses on the emerging devices not yet available on the market. In these chapters the basic operating principle of the devices is introduced and technological maturity of the devices is analyzed. In addition, the future prospects for the devices and the key challenges related to their further development are determined. In chapter 6 the implementation of the expert interviews is presented. Chapter 7 discusses the results from both the literature review and expert interviews, whereas chapter 8 presents the conclusions.

3 MEMS Markets

The MEMS market is a diverse market with solutions for a wide variety of applications raging from high-volume mass applications to niche applications. Currently the largest markets for MEMS devices are consumer electronics, automotive and medical markets. Other important MEMS markets include industrial, military and aerospace and telecommunication markets. The MEMS market was highly affected by the downturn in the years 2008-2009, but it started gaining growth again in 2010. (iNEMI 2011) According to a market research conducted by Yole Développment the market accounted for 10,2 billion USD in 2011 and is expected to face drastic growth in the following years reaching almost 20 billion USD in 2016 (Manner 2012, Yole 2011e). In figure 1 MEMS market forecast by application in 2010-2015 is presented. From a geographic point of view the largest markets today are Europe, North America and Japan. However, the role of the Asian-Pacific countries, including China, is growing rapidly. (iNEMI 2011) China has already shown great potential in the automotive market where it is considered the fastest growing geographical market (Dixon 2011c). This chapter focuses on reviewing the different MEMS markets. In the chapter the main applications for MEMS devices on the markets are discussed. In addition, future growth opportunities and driving factors for the growth as well as special features and challenges related to the markets are discussed.

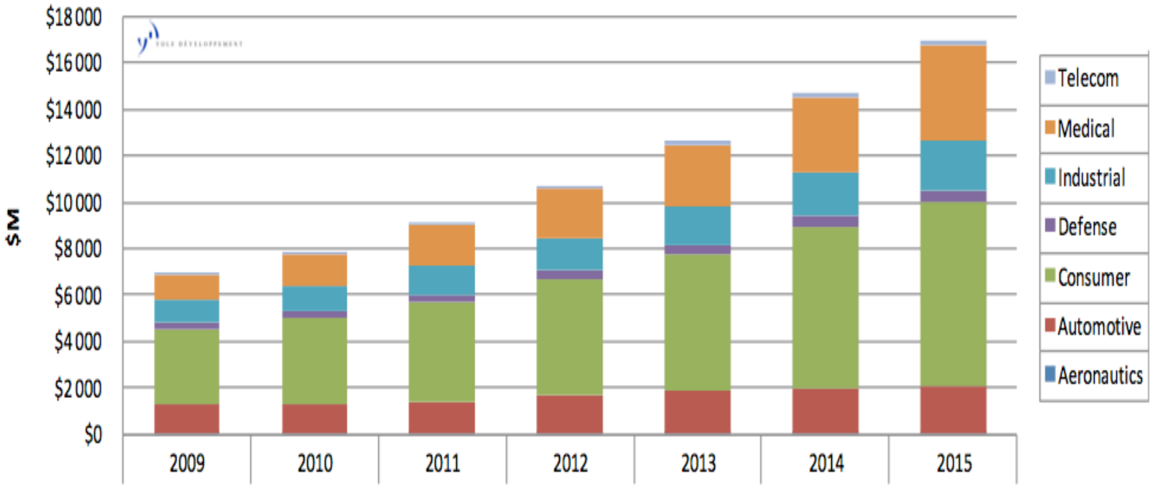

Fig 1. MEMS market forecast ($M) by application 2010-2015 (Yole 2010b)

3.1 Automotive Market

Automotive market was the first mass market for MEMS devices and has been an important growth factor for the MEMS industry for a long time. Many suppliers to the industry are still included in the list of the top worldwide MEMS manufacturers. A wide variety of different MEMS devices, such as accelerometers, gyroscopes and pressure sensors, are used in all modern cars today. The current high-end vehicles feature up to a 100 different sensors of which approximately 30% are MEMS devices. (van Heeren & Salomon 2007) The automotive market is expected to face moderate growth in the coming years due to increasing regulations regarding safety and environmental restrictions. Expected growth areas include MEMS devices for Electronic Stability Control (ESC) and Tire Pressure Monitoring Systems (TPMS). (Dixon 2012) Another factor accelerating the growth of the market is the increased demand for driver and passenger comfort and entertainment. New emerging applications include devices such as integrated microphones and devices for optical signal handling. (iNEMI 2011) In figure 2 the current and emerging MEMS devices and sensors in automotive applications are presented.

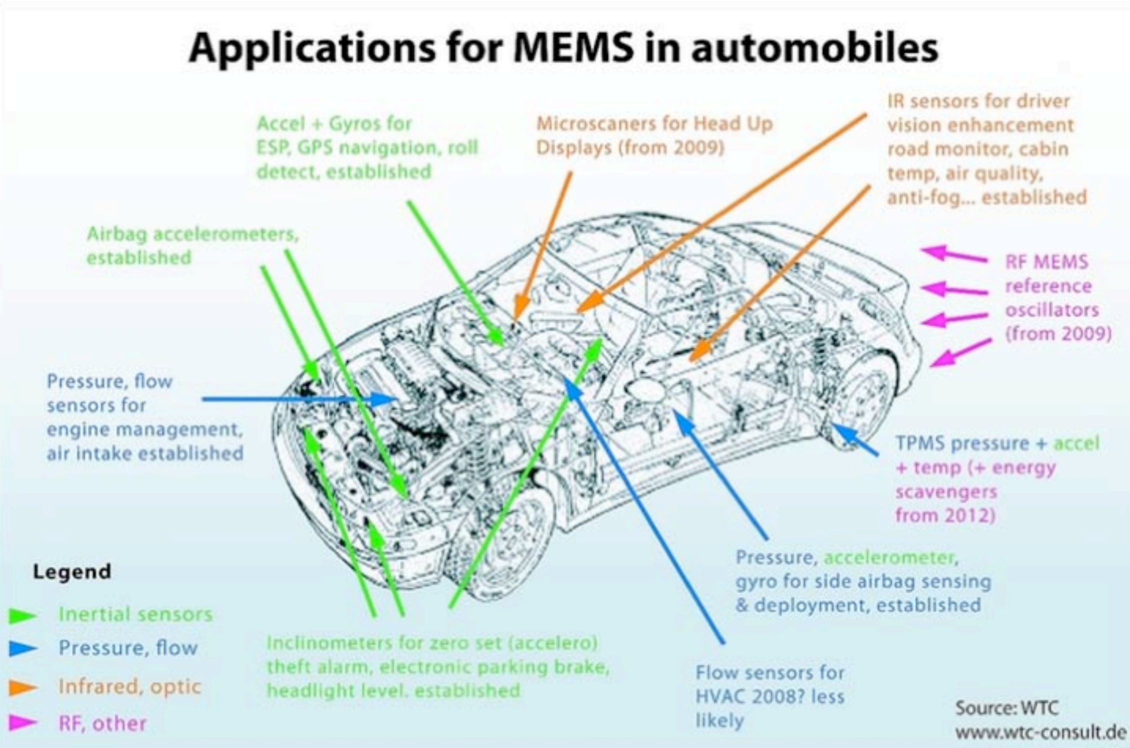

Fig. 2. MEMS devices in automotive applications (Dixon & Bouchaud 2007)

In automotive applications MEMS devices are exposed to exceptionally harsh operating environment. One of the major challenges for the devices is the extreme temperature range. The temperature range is from -40°C to 85°C for in-vehicle and from -40°C to 125°C for underhood applications. Another major challenge for the devices is the quality and reliability requirements. The devices are expected to last up to decades without failure, which is far longer than in many other applications. (iNEMI 2011) These requirements pose challenges to the development of the devices and need to be taken into consideration in the early design phase.

3.2 Consumer Electronics Market

Consumer electronics market is currently the fastest growing MEMS market. The increasing demand for new functionalities and smaller feature size are the main driving factors for the use of various MEMS-based devices in consumer applications. (Yole 2012c) Among consumer products, cell phones account for the largest share of MEMS use including devices such as RF filters, inertial sensors, optical devices and microphones. The second largest application for consumer MEMS is game consoles, which mainly employs motions sensors. An application with high growth prospects in the near future is tablets integrating a wide variety of different MEMS devices. Other important applications for MEMS devices in consumer electronics include products such as cameras, projectors, laptops, MP3 players and televisions. The consumer electronics market is expected to face further growth in the following years. A factor accelerating the growth is the various emerging devices hitting the commercial markets in the near future. (Bouchaud 2011c) These devices include electronic compasses, RF switches and varactors, auto-focus and timing devices (iNEMI 2011). As an example in figure 3 the current and emerging MEMS devices used in modern cell phones are presented.

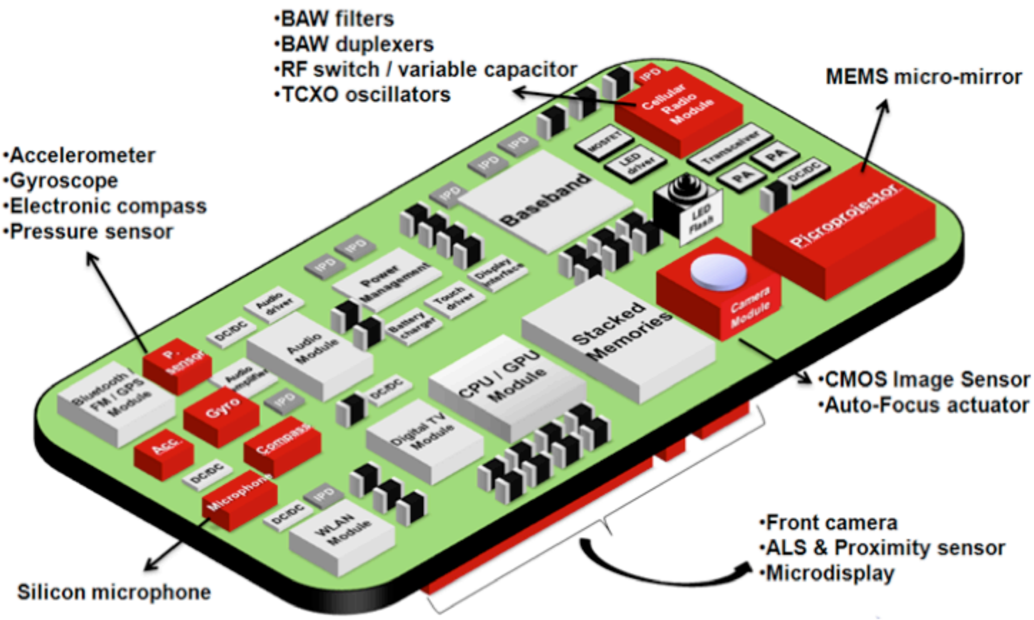

Fig. 3. Current and emerging MEMS devices in cell phones (Yole 2021b)

The consumer market poses several requirements for the MEMS devices. The devices need to be small in size and light in weight in order to be integrated in the small, typically portable products. Moreover, the power consumption of the devices needs to be low. Most importantly, the market demands for high volume production in order to achieve low-cost devices. The high volume requirements have had a high impact on changing the MEMS production infrastructure. However, this still remains a challenge for a large number of MEMS manufacturers. (iNEMI 2011)

3.3 Medical Market

Medical market is one of the newer MEMS markets with very high growth potential in the future. The market is driven by the increasing demand for miniaturized, low cost devices with high operating speed for diagnostics and individualized treatment. (Thusu 2011) One of the largest application areas for MEMS devices is life science and diagnostic applications, where the devices enable dramatic new possibilities for detecting, analyzing and manipulating biological materials ranging from proteins to bacteria and blood. (iNEMI 2011) Another large application area consists of medical sensors, such as pressure sensors used for patient monitoring. MEMS devices are also used in electrical stimulation devices and medical imaging. The medical devices have gradually evolved from large bench top devices used in hospitals and laboratories into small portable devices through miniaturization and integration. In the future there will be an increasing trend towards autonomous wireless systems used on wearable and implantable applications. Emerging MEMS devices such as energy harvesting systems and RFID may play an important role in powering these wireless systems. Other important emerging applications include delivery systems for therapeutic treatment for diseases. (Yole 2011d) In figure 4 the evolution of medical devices is presented.

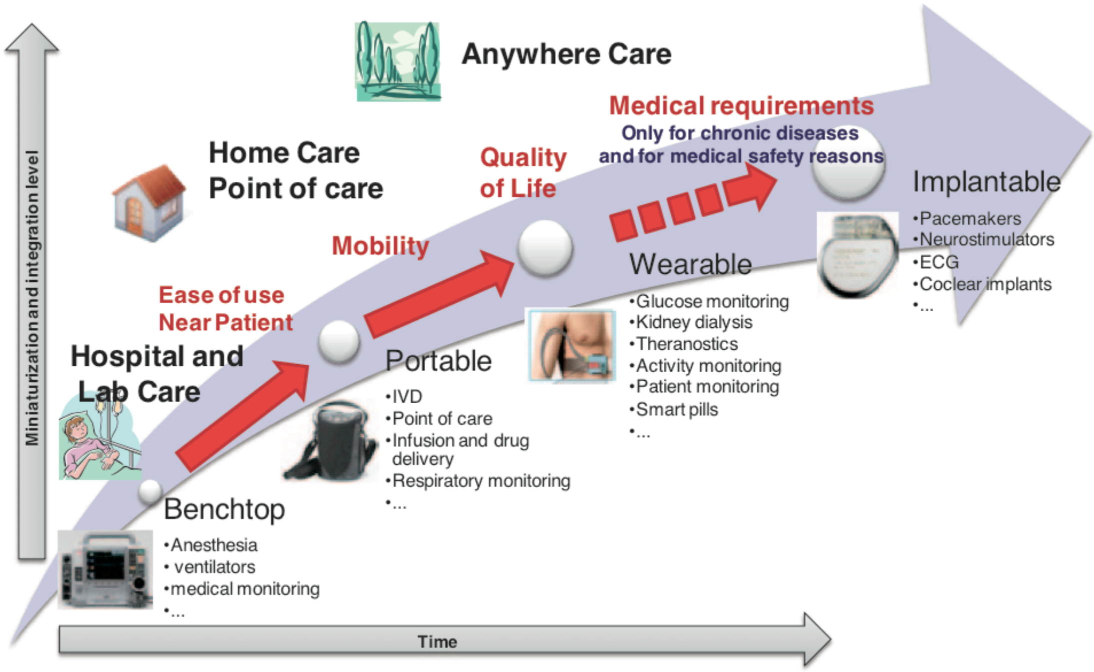

Fig. 4. Evolution of medical devices (Yole 2011d)

Major challenges for the growth of the medical market include strict regulations and huge investment requirements. Before being allowed on the commercial markets, the devices have to go through intense approval processes, which are both time-consuming and costly. (Pyzowski 2011) Moreover, due to the high investment costs, the devices are typically more expensive when compared to conventional devices. This hinders the adaptation of the new technologies to the market. (iNEMI 2011)

3.4 Military and Aerospace Market

Military and aerospace market is one of the earliest markets for MEMS devices. However, it has remained a low volume market particularly when compared to other MEMS markets, such as consumer electronics and automotive. (van Heeren & Salomon 2007) A wide variety of MEMS devices are used in military and aerospace applications including pressure sensors for fuel and hydraulic pressure monitoring, inertial sensors for missile and projectile guidance, uncooled bolometers for night vision goggles and micromirrors for head-up displays. The greatest growth opportunity for MEMS devices in the market include MEMS-based inertial measurement units (IMU) and combo sensors for guidance, and stabilization applications. The devices have particularly high potential in personal navigation systems, typically referred to as inertial navigation systems (INS), which become highly useful in areas not served by reliable GPS. (iNEMI 2011)

The military and aerospace market is highly driven by performance. The devices used in the market must meet the high performance requirements and satisfy the strict specifications and environmental conditions. In general, operational and environmental requirements include resilience to radiation, high temperatures, vibration and shock, as well as electromagnetic compatibility. (WTC 2006) For this reason, it is typically difficult for devices that have been developed for low-end application to be applied in military and aerospace application. Usually, improvements in the performance of several orders of magnitude are required. (iNEMI 2011)

3.5 Industrial Market

Industrial market is a relatively large MEMS market with high growth prospects in the future. MEMS devices can be used in a wide variety of industrial applications ranging from process control and industrial automation to energy applications. (Bouchaud 2010a) Process control and industrial automation is a prominent business, which is taking strides toward intelligent, distributed, and wireless monitoring and control. In these applications, MEMS sensors, such as pressure sensors, flow sensors and accelerometers are already widely applied. Also RF MEMS devices are making inroads for wireless sensing applications. (Cairns 2007) MEMS devices are also applied in energy finding applications such as oil and gas exploration and extracting. In these applications MEMS-based accelerometers and gyroscopes play an important role. In addition, low power MEMS devices can be used for energy conservation purposes in many industrial processes and transportation. An emerging application area is energy production MEMS-based energy harvesting systems. (Bouchaud 2011b) With regards to costs, the industrial market is less price-sensitive than higher volume markets for more commodity-type devices. On the other hand, the performance requirements are much higher in these applications as the devices are typically used under harsh conditions. (Cairns 2007)

3.6 Telecommunication Market

Telecommunication market is a low volume MEMS market with moderate growth prospects. The largest application area for MEMS devices in the market is optical communication. The optical telecommunication market has only recently started to recover from the telecom burst experienced in the turn of the millennium. At that time there were high hopes of the optical MEMS technology to be applicable in the high volume telecom market. However, the burst resulted in the crash of many new start-up companies, from which only a few survived. Over the years many optical MEMS-based devices have been developed but adoption of the industry has been slow due to their reluctance to introduce unproven technology. (Van Heeren & Salomon 2007) Today, the situation looks a little brighter. Steady growth of optical MEMS devices in telecom is expected during the next couple of years as the demand for broadband Internet services continues to increase. A key driver to the growth is the increasing deployment of fiber-to-the-home technologies to accommodate faster data traffic in networks. (Bouchaud 2011b) In addition to optical communication, the wireless market is becoming an interesting sector with many new functionalities on offer by various RF MEMS components. Currently, this market is also growing rather slowly although high potential can be seen in the future. (Van Heeren & Salomon 2007) RF MEMS devices can be employed both in RF front-ends in mobile devices and in telecommunication infrastructure (Bouchaud 2010b).

3.7 Summary of the MEMS Markets

Chapter 3 has reviewed various different markets and applications where MEMS devices are currently employed. The key features related to these markets and applications covered in this chapter are summarized in table 1.

Table 1. Summary of MEMS markets, largest application for MEMS devices, growth opportunities and driving factors for future growth

MEMS Market	Largest Applications	Growth Opportunities	Driving Factors
Automotive	Safety applications	Moderate	Increasing safety regulations
Consumer Electronics	Cell phones, game consoles, tablets	Very high	New features and applications
Medical	Life science and diagnostics, medical sensors	High	Personal health monitoring devices
Industrial	Process control and automation, energy applications	High	Wireless sensing and monitoring
Telecommunication	Optical and wireless communication	Moderate	Faster data traffic
Military and aerospace	Pressure monitoring, vision enhancement, missile guidance	Moderate	Navigation systems

4 Existing MEMS Devices

Since the introduction of the first MEMS devices, many new devices have gradually made their way into the commercial markets. Today, various different MEMS devices can be found in the market used in various applications. The largest share of the market is still covered by the most established devices such as inkjet printheads, accelerometers and pressure sensor, although, many new devices have started to conquer the market. Figure 5 presents the market value breakdown of MEMS devices in 2011. This chapter focuses on reviewing the already existing MEMS devices. In the chapter the basic operations principle of the devices is introduced, the current development stage is analyzed and the main functional limits are presented. In addition, the possible future prospects of the devices are discussed in the chapter. The emerging MEMS devices will be reviewed in chapter 5 and are thus not covered in this chapter.

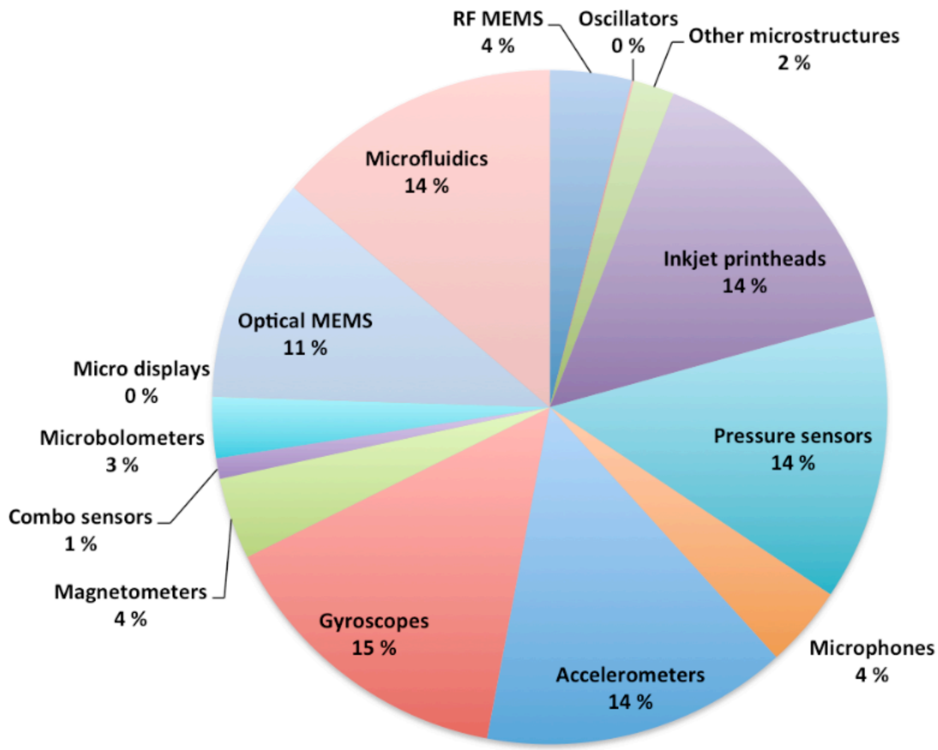

Fig. 5. MEMS market value breakdown in 2011 (total $10,2B) (modified from Yole 2012b)

4.1 Pressure Sensors

A pressure sensor is a sensor that measures pressure of gas or fluid. MEMS pressure sensors are based on a diaphragm, which deforms as pressure is applied. The pressure is determined by measuring the amount of deflection on the diaphragm. The different pressure sensors can be classified by the transduction mechanism. (Eaton & Smith 1997) The most commonly used transduction mechanism is piezoresistive method (Fragiacomo et al. 2010). Piezoresistive pressure sensors are based on a piezoresistors mounted on the diaphragm. As the diaphragm deflects in response to applied pressure, the resistance of the piezoresistor changes and the change can be measured. There are also other transduction mechanisms such as capacitive, optical and resonant methods. (Eaton & Smith 1997)

The first MEMS pressure sensors were introduced in the 1970's for automotive applications. In fact, pressure sensors are considered to be the first commercial successes of micromachined devices (Bogue 2009). Since their introduction they have been deployed in various different automotive applications, such as manifold air pressure measurement and safety applications (iNEMI 2011). To this day automotive applications remain the largest market for MEMS pressure sensors covering over 70% in revenue. The automotive sector is followed by medical and industrial applications with approximately 10% in revenue each. In medical applications pressure sensors are used mostly as disposable devices for catheters during surgery, whereas in industrial applications they are employed in the heating, ventilation and air conditioning (HVAC) sector as well as in various industrial process control applications. The remaining percentage of revenue is split between military and aerospace application and consumer electronics applications. (Dixon 2011a)

Since the introduction of the first MEMS pressure sensors, the devices have gone through significant development. They have decreased in size, their cost has dropped and their performance has improved. Today, the devices are mostly used in high-end application, where the harsh operation environment poses challenging requirements for the devices. For instance, in automotive applications pressure sensors are exposed to high temperature changes. In addition, they are typically used in safety applications, where high-performance and reliability are required. (Dixon 2011a) In medical applications sensitivity and reliability are also highly required. In addition, biocompatibility and low power consumption are necessary features especially in implantable applications. Even though piezoresistive pressure sensors are the most commonly used sensors today, their temperature sensitivity and limited pressure range, among other features, can in many case limit their use. As a result, there is currently an increased interest in alternative methods (Fragiacomo ym. 2010).

MEMS pressure sensors have been on the market for approximately 40 years now and are considered to have reached a mature stage of development. However, growth in some application areas can still be expected. In automotive applications, the key growth factor continues to be the use of MEMS pressure sensors in safety systems that are becoming government mandated. Currently topical safety regulations are those relating to electronic stability control (ESC) and tire pressure-monitoring system (TPMS). On the other hand, the devices used in consumer electronics and military and aerospace applications might face rapid growth in the near future as they are integrated with inertial sensors to form so called multi degrees of freedom (DOF) sensors. Multi-DOF sensors can, for instance, be applied in navigational purposes where pressure sensors are used to determine the altitude of an object. (Dixon 2011a) Multi-DOF sensors are discussed more closely in chapter 4.3.3. The key issues covered in this chapter are summarized in table 2.

Table 2. Summary of the development stage, largest markets and current challenges of MEMS pressure sensors

Development status	Largest Markets	Current Challenges
Mature	Automotive, medical, industrial	Temperature sensitivity, limited pressure range

4.2 Inkjet Printheads

Inkjet printhead is the element of an inkjet printer that applies ink onto a substrate (Yole 2006). The device comprises three components: a chamber for storing the ink, nozzles for delivering the ink and an electrode for the actuation of the inkjet. The most common actuation mechanisms used in the devices are thermal based actuation and pietzoelectric actuation. Thermal based actuation system consists of an integrated micro-heating element in the ink chamber. When a current is applied to the system, the heating element heats up resulting in rapid vaporization of the ink to eject a droplet from the nozzle. Piezoelectric actuation, in turn, uses a pietzoelectric material integrated into the chamber. When voltage is applied, the pietzoelectric material rapidly changes shape, which increases the pressure in the chamber and ejects the ink droplet. (iNEMI 2011)

The first inkjet printheads were developed in the early 1980's by Hewlett Packard and were among the first MEMS devices. They are by far the most commercially successful MEMS-based microfluidic devices. (iNEMI 2011) Since their introduction, the devices have been employed both in consumer and industrial application, from which the consumer market accounts for the largest share (Yole 2006). In the consumer market, the key driver at the moment is digital imaging. Digital devices, such as cameras, camera phones, and other digital imaging devices are pushing an increased need for printing digital photos. (GIA 2011) Inkjet printheads are still a very important part of the market today and many printer manufacturers, such as Hewlett Packard, Canon and Lexmark, are in the list of the top worldwide MEMS manufacturers (iNEMI 2011).

Inkjet printheads have already reached a mature market and only limited growth is expected in the future. However, there are still some new and emerging industrial applications, which are expected to affect the growth of the inkjet printhead market. One major growing application area is the use of inkjet printheads in printed electronics (GIA 2011). In fact, Konica Minolta has recently introduced the first commercial inkjet printhead device for printed electronics applications (Konica Minolta 2012). The sector could evolve into producing electronics at a fraction of the cost for the conventional technologies (GIA 2011). Other potential future applications for inkjet printheads include three dimensional printing, conductive traces for LCD and plasma displays and biomedical applications, such as bioprinting for artificially constructing living tissue (iNEMI 2011).

Inkjet printheads have gone through substantial development during their lifetime. Major improvements have been made in resolution, reliability, speed and cost. (Hudd 2009, p. 12-16) However, improvements are still needed in order to further improve the performance and utilization of inkjet printheads. Particularly, print quality and speed improvements at low cost are required in many applications, such as digital printing (GIA 2011). This could, for instance, be achieved by developing new ink materials, using more nozzles or improving drop placement accuracy. Another development area relates to the miniaturization of the devices, which is required in emerging applications, such as printed electronics. (Hudd 2009, p. 16-18) The key issues covered in this chapter are summarized in table 3.

Table 3. Summary of the development stage, largest markets and current challenges of inkjet printer heads

Development status	Largest Markets	Current Challenges
Mature	Industrial and commercial inkjet printers	Printing quality, speed, miniaturization

4.3 Inertial Sensors

Inertial sensors are sensors, which sense change in an object's state of motion and convert the produced inertial force into a measurable signal. There are two types of inertial sensors: accelerometers and gyroscopes. Both devices measure a change in velocity of an object but accelerometers are typically used to measure changes in linear motion whereas gyroscopes are used to measure changes in angular velocity. (Gad-el-Hak 2002, s. 887-888) In addition, inertial sensors can be combined to form inertial measurement units (IMU) to enable complete motion sensing (Zotov et al. 2010). In this chapter the basic principles of accelerometers, gyroscopes and inertial measurement units are introduced. In addition, the development stage of the devices is reviewed and their future challenges are discussed.

4.3.1 Accelerometers

An accelerometer is a sensor that measures a change in an object's velocity with respect to time. It can be used to measure the direction and acceleration of an object and to sense orientation, vibration and shock. (Analog Devices 2012) MEMS accelerometers generally consist of a suspension system and a proof mass which deflection provides a measure of the acceleration (Kraft 2000). Conceptually an accelerometer behaves as a damped mass on a spring. When the system experiences acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to define the acceleration. (Yazdi et al. 1998) There are several different transduction methods, which can be used to convert the mechanical deflection into an electrical signal. The two most commonly used transduction methods are piezoresistive and capacitive sensing. Alternatives are piezoelectric sensing, magnetic sensing, tunnelling current sensing, and optical methods. (Yazdi et al. 1998, Kraft 2000) The first commercial MEMS accelerometers were based on piezoresistive detection. Piezoresistive detection is still used in some commercial devices, but most of the commercial MEMS accelerometers today are based on capacitive detection. Capacitive accelerometers offer several benefits when compared to the piezoresistive type accelerometers, with their good DC response and noise performance, high sensitivity, low drift and low temperature sensitivity. (Acar & Shkel 2003)

MEMS accelerometers were developed in the 1970's and the first commercial devices were introduced in the early 1990's. Since then they have been widely employed in various automotive applications such as airbag crash sensors, rollover detection and electronic stability control, among other functions. In the late 2000's accelerometers were applied in consumer electronics applications as well. However, their adoption was slow due to high price of the accelerometers. Today MEMS accelerometers are used in various consumer electronics devices and the interest in them is constantly increasing. (ITRS 2011) To this day the largest markets for MEMS accelerometers are automotive and consumer electronics applications. Other minor applications areas are military and aerospace applications and medical and industry applications. (Yole 2009a) According to the latest market research conducted by Yole Développment, the largest manufacturers of MEMS accelerometers are STMicroelectronics, Bosch Sensortec and Kionix (Yole 2011f).

During the last decade MEMS accelerometers have seen significant development. Their size has been even further reduced, their performance and functionality has improved and their price has dropped considerably. (iNEMI 2011) In addition, motion sensing along multiple axes has been enabled by the development of 2- and 3-axis accelerometers. Comprehensive motion detection is highly desired, for example, by consumer applications and inertial navigation systems. (Hollocher et al. 2009) Several companies have launched their 3-axis accelerometer during the last decade and they are widely applied in different applications today. (Qu et al. 2008) The first multi-axis accelerometers were formed as hybrid structures where individual devices were integrated together. This resulted in increased size and cost as well as complicated packaging. (Chae et al. 2005, Qu et al. 2008) Today, there are already some single-chip structures available on the market with high performance and at low cost (Ayazi 2011).

According to a market research conducted by Yole Développment it can be expected that the demand for accelerometers continues to increase in consumer electronics in the future (Yole 2009a). For these low-end applications, low cost, small size and low power consumption are the driving factors (Hollocher et al. 2009). On the other hand, demand for accelerometers in automotive applications as well as in high-end applications, such as industrial, healthcare and military and aerospace applications, can be expected to remain stable (Yole 2009a). For these applications, accuracy and reliability are the main considerations and incremental improvements in these areas can be expected. (iNEMI 2011) Besides the high growth in low-end applications, one of the main future trends seems to be the integration of accelerometers together with gyroscopes to form so called inertial measurement units (Yole 2009a). They enable complete motion sensing in consumer electronics applications as well as high-end inertial navigation systems (Ayazi 2011). Inertial measurement units are discussed more closely in chapter 4.4.3. The key issues discussed in this chapter are summarized in table 4.

Table 4. Summary of the development stage, largest markets and current challenges of MEMS accelerometers

Application	Development status	Largest Markets	Current Challenges
Low-end Applications	Developing	Automotive, Consumer electronics	Size, cost and power consumption
High-end Applications	Mature	Military and Aerospace, Medical, Industrial	Accuracy, reliability

4.3.2 Gyroscopes

A gyroscope is a sensor that measures angular rate of rotation. It can be used to measure rotation of an object. MEMS gyroscopes are fabricated from quartz or silicon and they typically employ vibrating mechanical elements instead of spinning masses used in conventional gyroscopes. (Yazdi et al. 1998) Sensing is based on the Coriolis effect, which is used to determine the rate of the rotation. When the system is rotated the vibrating element experiences the Coriolis acceleration effect, which causes a secondary vibration orthogonal to the primary vibration that can be sensed by different methods. (Woodman 2007) Most available devices employ the tuning fork configuration (Esafandyari et al. 2010). The tuning fork configuration is composed of a pair of masses that are driven to oscillation with equal amplitude but in opposite directions. When rotated, the Coriolis force creates an orthogonal vibration that can be sensed by capacitive, piezoresistive or pietzoelectric detection methods. The oscillation of the masses, in turn, is caused electrostatically, electromagnetically or piezoelectrically. (Yazdi et al. 1998)

In the past ten years the largest market for MEMS gyroscopes has been the automotive industry. The first MEMS gyroscopes were used in luxury cars during the late 1990's. Since then they have been widely employed in different automotive applications such as electronic stability control, rollover prevention and navigation. During the last couple of years, MEMS gyroscopes have entered the consumer electronics market. The adoption was significantly slower than with MEMS accelerometers due to the high price of the devices. Today they are used in various consumer electronics devices such as cell phones, video game controllers and cameras. (iNEMI 2011) After the market penetration the growth has been extremely rapid. In fact, MEMS gyroscopes have been reported to be the top revenue generator in consumer electronics market in 2011. (Bouchaud 2012a) In addition to automotive and consumer electronics applications, MEMS gyroscopes are also employed in different military and aerospace applications and in small quantities in industrial and healthcare applications (Yole 2009a). According to the latest market research conducted by Yole Développment, the largest manufacturers of MEMS gyroscopes are STMicroelectrinics, InvenSense and Epson Toyocom (Yole 2011f).

As in the case of accelerometers, MEMS gyroscopes have drastically developed during the last decade. Their price has been incrementally reduced, the size has decreased and their performance has improved. MEMS gyroscopes have also moved from single-axis sensing to 3-axis sensing. However, their commercialization has been slow due to high price and technical challenges with packaging. (ITRS 2011) The first commercial 3-axis gyroscopes were introduced in 2009 (Fraux 2011) and most of the devices available on the market are formed as hybrid structures containing individual sensors combined together. Recently, a few single-chip 3-axis devices have become commercially available. The size and price of current MEMS gyroscopes are still relatively high and their performance lacks behind that of accelerometers. Especially in low-end applications, further reduction in size, price and power consumption are still required. Currently, MEMS gyroscopes do not match the accuracy of conventional gyroscopes, which prevent their use in high-end applications, such as military and aerospace applications. There are some major challenges to overcome regarding the resolution and bias stability of the devices. (Ayazi 2011)

Unlike MEMS accelerometers, which have been on the market for a longer time and have reached a more mature stage in the development, MEMS gyroscopes can be expected to face high growth in both low-end and high-end applications especially once the technological issues have been resolved. According to a market research conducted by Yole Développment, MEMS gyroscopes for consumer electronics applications can even be expected to overtake automotive applications. As mentioned in the previous chapter, one of the main future trends appears to be the integration of inertial sensors into inertial measurement units to enable more accurate motion sensing. In particular, the use of gyroscopes in high-end inertial navigation systems will increase once the required accuracy has been achieved (Yole 2009a). Inertial measurement units are discussed more closely in the following chapter. In table 5 the key issues discussed in this chapter are summarized.

Table 5. Summary of the development stage, largest markets and current challenges of MEMS gyroscopes

Application	**Development status**	**Largest Markets**	**Current Challenges**
Low-end Applications	Developing	Automotive, Consumer electronics	Size, cost and power consumption
High-end Applications	Emerging	Military and Aerospace, Medical, Industrial	Accuracy, resolution, bias stability

4.3.3 Inertial Measurement Units

An inertial measurement unit (IMU) is a device, which combines accelerometers and gyroscopes for complete motion detection. It enables the measurement of linear acceleration as well as angular velocity. (Geiger et al. 2008) To achieve more accurate motion and position mapping inertial sensors can be integrated with magnetometers and pressure sensors to form so called combo sensors. (Ayazi 2011)

Inertial measurement units can vary in configuration, depending on the components contained in the package. IMUs typically contain a 3-axis accelerometer and a 3-axis gyroscope to cover all six degrees of freedom (Yole 2011g). Accelerometers measure linear motion along x-, y- and z-axes, while gyroscopes measure rotation around these axes. In figure 6 motion sensing in six degrees of freedom is illustrated. For navigation applications inertial sensors can be integrated with magnetometers and pressure sensors to provide necessary information about the initial heading value and altitude of the object. There are already some commercial combo sensors available that cover nine to ten degrees of freedom. In these devices, 3-axis magnetometers are used to provide heading information by measuring the earth's magnetic field and pressure sensors to measure atmospheric pressure to determine relative altitude of an object. (Ayazi 2011)

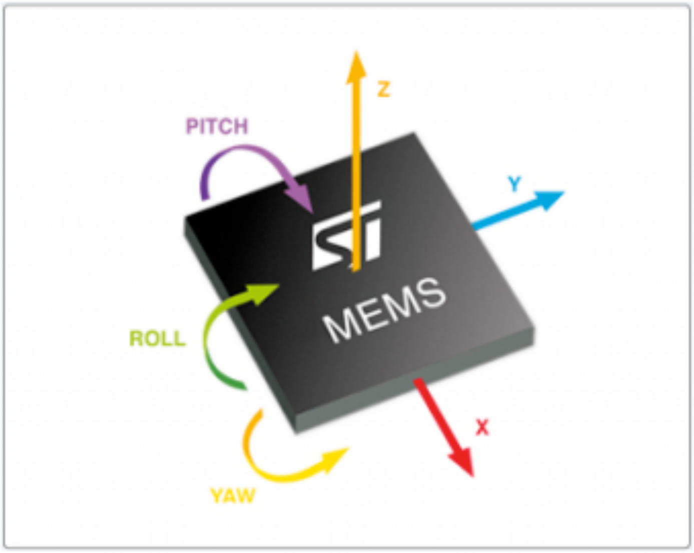

Fig. 6. Motion detection in six degrees of freedom (ST 2012)

IMUs and combo sensors have been on the market for a relatively short time and there are still many challenges to overcome. Besides the development of high precision inertial sensors, one major challenge in development of compact IMUs is the integration of different sensors. (Zotov et al. 2011) Current methods of creating IMUs typically rely on hybrid structures where individual sensors are first manufactured in dedicated technology and then assembled as complex structures (Alandry et al. 2010). While the hybrid structure allows for the use of high performance sensors, its further miniaturization is limited. In contrast, integration of multi-axis sensors on the same chip provides small size of the device but suffers from more complex fabrication, compromises in sensor design and performance as well as reduction in cross-axis sensitivity. (Zotov et al. 2010) Due to small size and higher level of integration single-chip designs are preferred. In fact, a lot of research has been conducted to improve the performance of the devices and simplify fabrication. (Zotov et al. 2011, Alandry et al. 2010, Xie et al. 2010, Ayazi 2011, Mertz et al. 2010). Single-chip 6-DOF IMUs have recently entered the market, but single-chip 9- and 10-DOF sensors are still under development (Ayazi 2011).

During that last couple of years inertial measurement units have been deployed in number of consumer electronics, automotive and industrial applications such as gaming, image stabilization in cameras, electronic stability control in automotive applications and robotics. As the devices are relatively new to the market, no accessible information about the market leaders is yet available. However, at least InvenSense, STMicroelectronics and Analog Devices have brought their IMUs and combo sensors on the market specially aimed for consumer electronics applications (InvenSense 2012, ST 2012, Analog Devices 2012) The performance of the current devices is sufficient for these low to medium performance applications and significant growth in these areas can be expected. However, improvements in size, price and power consumption are still required. There is also a high interest in high-end applications such as military and aerospace applications. In particular, combo sensors have great potential in inertial navigation systems. However, the current sensors do not yet meet the performance requirements. This is mostly due to the lack of stable high-precision 3-axis gyroscopes and problems in integrating the different sensors. (Ayazi 2011) Once the performance requirements have been met, a high growth in the high-end applications particularly in inertial navigation systems can be expected (Yole 2009a). In table 6 the key issues discussed in this chapter are summarized.

Table 6. Summary of the development stage, potential markets and current challenges of MEMS IMUs and combo sensors

Application	**Development stage**	**Potential Markets**	**Current Challenges**
Low-end Applications	Developing	Consumer electronics	Size, cost and power consumption
High-end Applications	Emerging	Military and Aerospace	Integration of the sensors, improvements in gyroscopes

4.4 Microphones

MEMS microphones are miniaturized acoustic devices that are produced using micromachining technology. They offer several benefits when compared to conventional microphones. Firstly, they are smaller in size, which is a desired feature in many applications today. Secondly, they can be integrated with other electronics in one process, which leads to improved manufacturing and cost reductions. Finally, MEMS microphones have improved acoustic performance. (iNEMI 2012)

MEMS microphones operate similarly to capacitive pressure sensors. They contain a deformable diaphragm, which deflects in response to sound waves. Most of the MEMS microphones use capacitive transduction mechanism. ((Dixon-Warren 2011) In these devices the flexible diaphragm serves as one electrode of a capacitor, whereas the other electrode is located right next to it. As the diaphragm deflects, the average gap between the electrodes changes. (Park et al. 2002) This results in variation of the capacitance that is then amplified by an associated integrated circuit (IC) to produce either an analog or digital output signal (Dixon-Warren 2011). Other transduction mechanisms, such as optical and piezoresistive mechanisms can also be used, although, they are less common (Yole 2011a).

During the recent decades, extensive research works have been carried out to develop microphones based on MEMS technology (Yew et al. 2009). However, the first commercial devices were first introduced in the early 2000s. The first devices were analog-output microphones intended for cell phones. Not long after, in 2006, came digital-output microphones, which were quickly deployed in laptops. (iNEMI) To this day consumer electronics remain the largest market for MEMS microphones. The devices are employed in various portable applications, such as cell phones, laptops, tablets, headsets and cameras. (Bouchaud 2012b) MEMS microphones are also used in automotive and medical applications, such as hands frees, voice recognition and hearing aids. (Zinserling 2007, Elko et al. 2005) In 2011 the largest suppliers of MEMS microphones were Knowles Electronics, ACC and Analog Devices (Bouchaud 2012b).

Since the introduction of the first MEMS microphones, the devices have improved in performance and decreased in size. At the same time the cost of the devices has dropped as volumes have increased. In addition, improvements in packaging have been made which has improved the signal-to-noise ratio of the devices. (iNEMI 2011) Recently, devices using a single-chip microphone technology called CMOS MEMS have been introduced. This type of technology has the advantage of requiring less overall silicon area than its two-chip counterparts, leading to smaller, lower cost microphones. (Dixon-Warren 2011, Huang et al. 2011) However, most of the current microphones still utilize two-chip technology containing a separate MEMS transducer chip and IC chip. This may be explained by the fact that only few of the MEMS microphone suppliers actually manufacture their own MEMS or IC dies. (Yole 2011a, ITRS 2011) Currently, both analog and digital microphones are commercially available, although, at the moment there seems to be an increasing interest in digital microphones. While analog microphones are less expensive and widely used in many applications, digital microphones are gaining better utilization because of their design flexibility, lower sensitivity to electromagnetic interference, and their increased power supply rejection ratio (PSRR). In addition, in the case of the noise suppression with multiple microphones the signal from digital microphones is easier to process than from analog.

Thus, digital microphones can be expected to overtake analog microphones in the near future. (IHS 2012)

In the future there will be an increasing demand for even smaller microphones for consumer electronics applications, where multiple microphones are adopted in a single device. Multiple microphones are required for instance for noise cancelling and stereo recording. On the other hand, there is a growing request for higher performance microphones. Especially improvements in signal-to-noise ratio (SNR), frequency response and sensitivity are required. (ITRS 2011) According to a market research conducted by IHS iSupply, growth in consumer electronics sector can be expected in the following years (Bouchaud 2012b). Growth can be also expected in other application areas as well (Mathas 2011). In table 7 the key issues discussed in this chapter are summarized.

Table 7. Summary of the development stage, largest markets and current challenges of MEMS microphones

Development stage	Largest Markets	Current Challenges
Developing	Consumer electronics	SNR, frequency response, sensitivity

4.5 Optical MEMS

Optical MEMS devices often referred to as Micro-Opto Electro Mechanical Systems (MOEMS) combine micro-optics and MEMS technology. The devices involve sensing and manipulating optical signals on a very small scale using integrated optical, electrical and mechanical systems. (Motamedi 2005, p. 11-13) A number of different techniques can be used to scan, steer or modulate light using various optical elements such as micromirrors, microlenses or gratings. Many available optical MEMS devices employ mechanical micromirrors, which are used to redirect light by controlling the position and tilt of the mirrors. The micromirrors can be used either as a single device or large arrays depending on the application. (Motamedi 2005, p. 369) The mechanical movement of the mirrors can be caused by various actuating methods such as thermal, piezoelectric, electromagnetic and electrostatic actuation, although, the electrostatic method appears to be growing in popularity (iNEMI 2011). Besides using MEMS micromirrors, which are reflective-type devices, diffractive, refraction, interference and polarization type optical components can also perform light modulation (Toshiyoshi 2005).

The first optical MEMS devices were introduced on the market in the late 1990's. Since then they have been used in various different applications ranging from optical communication to image displays and other optical systems. (Motamedi 2005, p. 11-17) In **optical communication** MEMS devices are used to direct and modulate light in fiber optic systems. They are used, for instance, as variable optical attenuators (VAO), optical 2D and 3D switches, tunable filters and wavelength division multiplexing (WDM) systems. (Motamedi 2005, p. 13-15) The advantage of optical MEMS devices compared to conventional optical communication technologies is that they enable all-optical communication. Instead of having to convert optical signals to electrical signals and vice versa, optical MEMS devices require no O/E conversion. This enables lower cost, immunity from electromagnetic interference, increased density and wavelength independence. (iNEMI 2011) However, their adoption to the market has been rather slow due to the telecom downturn in the turn of the millennium. During the recent years the devices have started to make a new comeback on the market (Motamedi 2007). Steady growth of optical MEMS devices in telecom is expected during the next couple of years as the demand for broadband Internet services continues to increase. A key driver to the growth is the increasing deployment of fiber-to-the-home technologies to accommodate greater data traffic in networks. (Bouchaud 2011a)

Another large application area for optical MEMS devices is **image display systems**, such as direct view displays and projection displays. The first and probably the most known display technology referred to as Digital Light Processing (DLP) was developed by Texas Instruments. The device comprise of millions of individually addressable micromirrors, which allow for redirecting light to form displays. The mirrors are only capable of two positions, either illuminating or not illuminating the display at each pixel location. (iNEMI 2011) There are also several other technologies to form displays, such as Laser Scanning Display (LSD), which uses a single micromirror to scan color laser beams on the screen. Other technologies are Grating Light Valve (GLV) technology and Retinal Scanning Display (RSD) technology. (Liao & Tsai 2009) Unlike optical MEMS devices used in telecommunication, image displays have gained great commercial success and are now widely employed in various applications ranging from digital cinemas, projectors and HDTVs to head-mounted displays and head up displays mainly used in military and aerospace applications (Bogue 2009). Recently the devices have also been deployed in portable consumer devices such as cell phones and tablets where they are used as picoprojectors and microdisplays (Johnson 2010a, Qualcomm 2012). In the future the application area is expected to expand even further and high growth especially in consumer applications is expected. The emerging devices include micromirror-based zoom lenses and auto-focus devices for mobile cameras and high definition holographic displays for 3D projection (Jayapala 2011, Gutierrez 2010). MEMS-based auto-focus devices are discussed in more detail in chapter 5.8.

In addition to optical communication and image displays, optical MEMS devices can also be used in a wide variety of other applications such as spectrometers, optical imaging systems, and infrared (IR) detectors and imagers (Motamedi 2005, p. 369-370). Many MEMS-based **visible light and IR spectrometers**, such as Fabry Perot interferometers and IR spectrometers have been developed. The devices are employed in various industrial and research application for detecting and analyzing different substances. (Wolffenbuttel 2005) **Optical imaging systems** can in turn be used in medical applications for *in vivo*- diagnostics for instance in endoscopic devices (Xie 2009). **IR detectors and imagers** exploit infrared radiation in applications like thermal imaging, temperature measurement and gas detection (Yole 2011c). MEMS-based IR detectors and imagers will be discussed in more detail in chapter 4.6.2.

Optical MEMS devices have come a long way and as described above today some of the applications are more mature than others. Over the past years there have been some major challenges regarding the process development for MOEMS chips, the integration of optical devices with CMOS and cost-effective packaging to obtain optical transparency. (Motamedi 2007) Cost is an important factor especially in consumer electronics applications. It has also a high impact in telecommunication applications, although, the main limiting factor is perhaps the reluctance to adopt a new technology. In table 8 the key issues covered in this chapter are summarized.

Table 8. Summary of the development stage, largest markets and current challenges of optical MEMS devices

Type of MOEMS	Development stage	Largest Markets	Current Challenges
Optical communication	Developing	Telecommunication	Integration, cost-effective packaging
Image Displays	Developing	Consumer electronics	

4.6 MEMS IR Detectors

Infrared (IR) detectors are sensors that detect IR radiation and convert it to an electrical signal (Yole 2011c). There are two types of IR detectors: photonic and thermal. Photonic detectors require cooling in order to obtain a signal whereas thermal detectors work without cooling and are thus called uncooled IR detectors. MEMS technology can be used in the fabrication of thermal detectors, such as microbolometers and thermopiles. (Jain 2007) In this chapter, the basic principle of MEMS based microbolometers and thermopiles is introduced. In addition, the development state of the devices is reviewed and the current challenges are discussed.

4.6.1 Microbolometers

A microbolometer is an infrared detector used in thermal imaging cameras, which convert IR radiation into a visible image. Unlike many other types of infrared detecting equipment, microbolometers do not require cooling. The devices operate at long-wave infrared (LWIR) wavelengths ranging from 8 to 14 µm, meaning that they do not use any visible light for image creation. (Yole 2010a) Microbolometers consist of an array of thermally sensitive pixels, which absorb IR radiation. On receiving the radiation, the temperature of the pixel increases resulting in a change in the resistance of the thermally sensitive material on the pixel. These changes are processed by separate electronics to create a thermal image. (Jones et al. 2009) The most commonly used materials in the sensor layer are vanadium oxide (VOx) and amorphous silicon (α-Si) (Niklaus et al. 2007).

Microbolometer technology was developed in the late 1980's for military application, such as weapon sight, night vision goggles and vehicle vision enhancement (Nikalus et al. 2007, Yole 2011b). Today the military applications still form a large part of the market however the devices are also employed in various commercial applications ranging from industrial applications to automotive and medical applications. (Yole 2011b) In industrial applications microbolometers can be used for instance in process monitoring, predictive maintenance and building inspection. In automotive applications the devices can in turn be used as vision enhancement systems and in medical applications in diagnostics. In addition, microbolometers are also used in law enforcement and fire fighting equipment and security and surveillance applications

(Yole 2010a, Sofradir 2011). At the moment the largest manufacturer of microbolometers is FLIR (Yole 2011b).

Microbolometer market has grown dramatically over the past decade primarily due to significant improvements in sensor performance, manufacturability and cost reductions (Li et al. 2011). Particularly, great improvements in sensitivity and resolution have been made. Microbolometers with various pixel sizes have also become available further increasing the amount of new applications. (Sofradir 2011) In the future the focus will be mainly on further cost reductions and higher level of integration with camera electronics (Yole 2010a). One way of reducing costs is the use of wafer level packaging (WLP), which has already been applied by at least one manufacturer (Yole 2011b). Another way of reducing costs is using smaller pixel size and larger wafer in order to increase the number of die per wafer (Li et al. 2011). In addition, the use of α-Si as the sensor layer material is expected to increase in the near future, because it enables easier manufacturing that enables low-cost volume production (Sofradir 2011). They key issues covered in this chapter are summarized in table 9.

Table 9. Summary of the development stage, largest markets and current challenges of microbolometers

Development stage	Largest Markets	Current Challenges
Developing	Military, various commercial applications, security and surveillance	Cost, integration

4.6.2 MEMS Thermopiles

Thermopiles are electronic devices that convert thermal energy directly into electrical energy. They are composed of multiple thermocouples connected typically in series. (Xu et al. 2010b) The thermocouples exploit the Seebeck effect consisting of two dissimilar conductors joined together in one end. When a temperature difference is applied between the junction and the open end, a voltage proportional to the temperature difference arises and can be measured. Thermopiles are self-powered devices and do not require any external form of excitation. They are capable of generating an output voltage of some μV/K from the applied temperature difference. Thermopiles are typically fabricated using microfabrication technologies, although they do not contain any electromechanical functions. Traditionally used materials in the conductors are metals such as Bi-Sb, although the use of various semiconductor materials is increasing in popularity. (Graf et al. 2007)

Thermopiles are used in a wide variety of applications ranging from remote temperature measurement to gas detection and spectroscopy (Xu et al. 2011). The devices work in a similar way in all of the applications measuring the amount of infrared radiation. **Remote temperature measurement** is the largest application area of thermopiles. The devices measure the heat flow emitted by an object trying to reach thermal equilibrium with its surroundings. The temperature sensors can be used for instance in automobiles, various household appliances and medical instruments, such as thermometers. (Graf et al. 2007) In addition to remote temperature measurement applications, thermopiles are widely applied in **non-dispersive infrared (NDIR) gas detection applications**. The gas detectors exploit the Lambert-Beer law for absorption measuring the amount of radiation absorbed by the gas. When the gas is exposed to IR radiation it absorbs light in a specific wavelength range. By covering the IR detector with a wavelength selective filter, the radiation absorption due to a specific gas can be measured. The gas detectors can be used in various industrial applications to detect gases or fire. (Graf et al. 2007, Yoo et al. 2011) Thermopiles are also used in **spectroscopy** for analyzing substances in many industrial and research applications, such as chemical and food industry. The spectroscopic devices work in a similar way to gas detectors. (Wu et al. 2010)

In addition to the existing application areas, thermopiles have been studied in many new applications. One of the most promising new application areas is temperature measurement in portable electronic devices, such as cell phones and tablets (Keränen et al. 2010). In fact, in 2011 Texas Instruments introduced a MEMS thermopile for non-contact temperature measurement in portable consumer applications (Texas Instruments 2012). Another extensively studied application area for thermopiles is energy harvesting systems. In these systems thermopiles are used to capture thermal energy from the ambient environment and convert it to an electrical signal. The devices have a very high potential in the future to power up a wide variety of wireless devices. (Vullers et al. 2009) Thermal energy harvesting systems are discussed more closely in chapter 5.2.1.

Over past decades thermopiles have gone through significant development. First of all, the introduction of MEMS technologies to the fabrication of thermopiles has made the devices to decrease in size, which is a highly desired feature in many applications today. (Graf et al. 2007) Moreover, the development of CMOS-compatible devices has enabled cost-effective fabrication and the integration of the detector and read-out circuitry (Xu et al. 2010a). A major advantage in thermopiles is that they do not require cooling in order to work, which allows simple and compact sensor structure. Further advantages include insensitivity to vibrations and the lack of self-heating. Lately, in addition to single element detectors, thermopile arrays have also begun to enter the market perhaps allowing for new applications. However, despite the many improvements in thermopiles, the current devices do not yet reach the performance level of other IR detectors, such as microbolometers and pyrometers. They lack behind in sensitivity and responsivity and are relatively expensive compared to the other devices. (Graf et al. 2007) In table 10 the issues discussed in this chapter are summarized.

Table 10. Summary of the development stage, largest markets and current challenges of MEMS thermopiles

Development stage	Largest Markets	Current Challenges
Developing	Consumer electronics, Medical, Industrial	Cost, sensitivity, responsivity

4.7 RF MEMS

Radio Frequency (RF) MEMS devices are microsystems that provide RF functionality covering frequency spectrum from direct current (DC) to sub-millimeter wavelengths (Lucyszyn 2010, p. 1-2). RF MEMS devices offer a range of advantages compared to conventional technologies. They enable miniaturization of the devices as well as component integration. In addition, they offer lower power consumption, lower losses, higher linearity, and higher Q factors than conventional devices. (Singh & Nagachenchiah 2008) Various RF MEMS have been developed ranging from lumped components to more complex networks based on a combination of the basic components. (Iannacci 2011) The RF functionality is provided by vibrating mechanical structures, which are actuated using various different actuation mechanisms. However, some devices classified as RF MEMS do not necessarily contain electromechanical functions. (Lucyszyn 2010, p.1-4) In table 11 the most common RF MEMS actuation mechanisms, components and networks are listed.

Table 11. Most common RF MEMS actuation mechanisms, components and networks (modified from Lycyszyn 2004)

Electromechanical Actuation	RF MEMS Components	RF MEMS Networks
Electrostatic Thermal Magnetic Pietzoelectric	Switch BAW, SAW, FBAR Variable capacitor Variable inductor Resonator	Antenna Filter, Duplexer Phase shifter Impedance tuner Power divider

Surface and bulk acoustic wave (SAW, BAW) resonators are currently the most mature RF MEMS components and they represent the major part of RF MEMS (Yole 2009b). The devices are based on piezoelectric materials that resonate with surface and bulk acoustic waves (iNEMI 2011). They are used for frequency selection in filters and duplexers in RF front-ends in replacement of conventional technologies, which are too bulky for modern portable devices. Recently, also **thin-film bulk acoustic resonators (FBAR)** have been deployed due to higher frequency capability. (Yole 2009b) The devices are based on the resonation of piezoelectric material sandwiched between two electrodes. The filters and duplexers used today are fixed devices, where tuning is accomplished by switching between the different components. In order to achieve flexible devices with improved robustness and the possibility of implementation of more modes, tunability is required. Hence, at the moment the main focus is on developing tunable devices. (iNEMI 2011)

Extensive research works have also been carried out to develop **MEMS oscillators** to replace conventional quartz oscillators used in frequency reference and timing applications. Si-based MEMS oscillators consist of resonating mechanical structures that oscillate at given frequencies when exited with an energy source. Oscillation can be driven by many actuation mechanisms, such as electrostatic and piezoelectric methods. (iNEMI 2011) The devices offer several advantages compared to conventional quartz oscillators including smaller size, better shock resistance, smaller form factor and better suitability for mass production. Most of all they enable high level of integration with CMOS. (Van Peek & Puers 2012) Despite the fact that the MEMS oscillators have already been under development for several decades now, they have not yet reached high commercialization rates due to major challenges regarding cost, packaging and temperature sensitivity of the devices. Some commercial devices already exist, although, the high-volume production is not expected to start until the following years. (iNEMI 2011)

In addition to different kinds of resonators, **capacitive and ohmic switches** have long attracted much attention among RF MEMS products. The excellent performance of MEMS switches has demonstrated great potential for replacing conventional switches in numerous applications, including T/R switches, phase shifters, switchable filters and tunable antennas. (Singh & Nagachenchiah 2008) Despite the high level of interest to RF MEMS switches, the commercialization of the devices has been rather slow. This is due to challenges regarding packaging, cost, reliability, self-heating and high controlling voltages (Iannacci 2011, ITRS 2011). Not until recently the devices have found their way into commercial products. Also **variable capacitors** often referred to as varactors and **variable inductors** have recently started to emerge in to the market. (Bouchaud 2010b) The devices have faced the same kind of challenges in their development as switches (Iannacci 2011).

The aforementioned RF MEMS components are used as building blocks in complex **RF MEMS networks**, such as filters, impedance tuners, RF power dividers and phase shifters. Due to the slow development of RF MEMS components, the RF MEMS networks have also lacked behind in commercialization. (Iannacci 2011) In 2011 Wispry introduced the first commercial product. The device is an impedance tuner containing various components such as variable capacitors and inductors. So far the device has been applied in smartphones for antenna tunning purposes. (Bouschaud 2012c, Wispry 2012) RF MEMS networks, especially tunable devices are highly desired and expected to face rapid growth in the future as soon as the performance issues regarding reliability, stability and packaging have been solved (Iannacci 2011).

Even though RF MEMS have been under extensive research for the last three decades, the devices have been relatively slow to move out of the laboratories and into commercial products. The first commercial RF MEMS devices were introduced on the market in turn of the millennium and yet today they have not reached a massive market adoption. (Singh & Nagachenchiah 2008) So far RF MEMS devices have been used for research purposes in test equipment and instrumentation. The devices have also been deployed in mobile and wireless communication as well as military and aerospace applications. (Johnson 2010b) The fastest growing application area for RF MEMS devices is expected to be mobile communication, where the devices can offer reduction of signal interruptions and dropped calls, faster data transmission rates and improved design and power efficiency. (Bouchaud 2012c) The key issues discussed in this chapter are summarized in table 12.

Table 12. Summary of the development stage, largest markets and current challenges of RF MEMS

Development Stage	Largest Markets	Currents Challenges
Developing	Test equipment, telecommunication, military and aerospace	Packaging, stability, reliability, cost

5 Emerging MEMS Devices

For a long time, the MEMS market has been composed of established MEMS devices such as inkjet printheads, pressure sensors and accelerometers. However, new MEMS devices are coming out in a fast pace. Not all of the new devices find commercial success, but the constant research work shows there are a large amount of applications where MEMS devices have potential. Currently, there are plenty of new MEMS devices that are crossing the gap from R&D to commercialization. According to a market research conducted by Yole Développment the emerging MEMS devices of today are expected to account for more than 10% of the total MEMS market by 2015. (Yole 2010d) In figure 7 a forecast of the emerging MEMS market compared to the forecast of total MEMS market is presented. This chapter focuses on reviewing the emerging MEMS devices found in the literature. Here, the basic operation principle of the emerging MEMS devices is introduced, the current development stage is analyzed and the main technical challenges are presented. In addition, the potential of commercialization of the devices is discussed in the chapter.

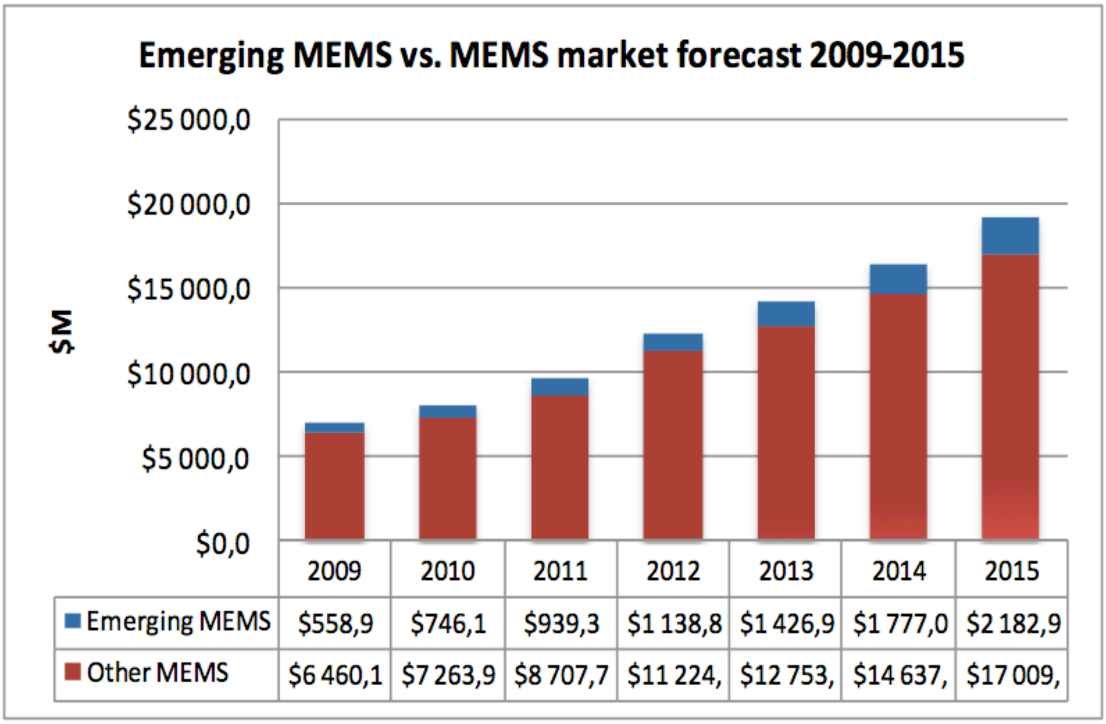

Fig. 7. Emerging MEMS market vs. the total MEMS market forecast in 2009-2015 (Yole 2010b)

5.1 Magnetometers

A magnetometer is a sensor that measures strength or direction of magnetic fields. There are several different approaches to the implementation of the magnetic field measurement. The most common approaches are based on the Hall-effect, magneto-resistance and magnetic tunnel junction. (Yole 2012a; Kyynäräinen et al. 2008) These sensors are typically classified as MEMS magnetometers even though they do not necessarily contain electromechanical functions (Manner 2012). In addition, there is an increasing interest in MEMS based resonant magnetic field sensors, which exploit the Lorentz force principle. These magnetometers are based on the displacement of mechanical structures when exposed to an external magnetic field. The interaction between the magnetic field and an applied electrical current results in a Lorentz force causing the displacement of the mechanical structures. The displacement can be measured by using optical, capacitive, and piezoresistive sensing techniques. (Herrera-May et al. 2009) Lorentz force magnetometers can be considered superior to the aforementioned types of magnetometers due to their easier fabrication, low power consumption as well as better sensitivity and resolution (Kyynäräinen et al. 2008; Herrera-May et al. 2009).

Miniaturized magnetometers are relatively new to the market and most of the commercial devices today do not contain electromechanical functions. The largest manufacturer of silicon magnetometers in 2010 was Asahi Kasei Microdevices. Their sensor is based on the Hall-effect produced with CMOS technology. (Dixon 2011b) In table 13 the most common operating principles of available magnetometers and their manufacturers are listed. The first commercial Lorentz force magnetometer based on MEMS technology was introduced in 2011 by Baolab Microsystems (Baolab 2012). Several MEMS magnetometers based on the same principle are currently under development (Bahreyni et al. 2007; Kyynäräinen et al. 2008; Ren et al. 2009; Herrera-May et al. 2009; Thompson et al. 2011).

Table 13. The most common operating principles of available magnetometers and their manufacturers (modified from Yole 2012a)

Operating Principle	Manufacturer
Hall-effect	Asahi Kasei Microdevices
Magneto-resistance	ST, MEMSIC, Honeywell
Magnetic tunnel junction	Freescale
Lorentz force	Baolab, VTT

Miniaturized magnetometers are already used as electronic compasses in portable consumer electronic devices, such as mobile phones and tablets, to provide orientation information. In the near future they are most likely going to be deployed in numerous other handheld electronic devices and high growth in the market can be expected (Dixon 2011b). Magnetometers are specifically used in combo sensors, together with inertial sensors. These combo sensors combining different functions were discussed in detail in chapter 4.3.3. Consumer electronics is one of the most attractive future trends for magnetometers. Other possible markets for magnetometers are military and aerospace, industrial automotive and health care applications, although they require much higher accuracy and resolution than what can be achieved with current devices (Herrera-May et al. 2009).

Even though MEMS magnetometers have only recently entered the market, there is an increasing interest in them due to the advantages they offer compared to the conventional technologies. As the most promising market for magnetometers is portable electronic devices, the sensors need to be produced in high volumes at a low cost. Other essential requirements for the sensors are small size, light weight, low power consumption and high sensitivity and resolution. In principle these requirements could be met by using MEMS technology. In addition, the technology enables the integration of individual sensors to form more compact multi-axis structures and combo sensors (Herrera-May et al. 2009). However, in order to reach a full commercialization of Lorentz force magnetometers there are still some challenges to overcome regarding noise and packaging, among other functions (Kyynäräinen et al. 2008; Herrera-May et al 2009; Thompson et al. 2011). The key points discussed in this chapter are summarized in table 14.

Table 14. Summary of the development stage, most potential markets and current challenges of MEMS magnetometers

Development stage	Potential Markets	Current Challenges
Emerging	Consumer electronics	Noise, packaging

5.2 Power MEMS

Power MEMS devices are miniaturized MEMS-based power generators. These miniaturized power supplies, such as energy harvesting systems and micro full cells, are intended for replacing conventional powering systems, such as batteries in various wireless and portable devices. (Bogue 2009) In this chapter the basic principle of energy harvesting systems and micro fuel cells is introduced. In addition, the development stage and main challenges of the devices are discussed.

5.2.1 Energy Harvesting Systems

Energy harvesting also known as power scavenging is a process by which energy of the ambient environment is captured and converted into an electrical signal. There are several different sources of energy that can be exploited, such as vibrational, thermal, solar and RF energy. Various different technologies can be used for the energy conversion, MEMS technology being one of them. (Harb 2011) At the moment, **vibrating energy harvesters** are the most established MEMS-based harvesting systems. In these devices mechanical vibrations are converted into electrical signals by using transduction mechanisms, such as piezoelectric, electrostatic or electromagnetic mechanisms. Electrostatic transduction is based on a polarized capacitor, where the distance of the electrodes changes due to the vibration of one movable electrode. This motion causes a voltage change across the capacitor and results in a current flow in an external circuit. In piezoelectric transducers the vibrations cause deformation of a piezoelectric material sandwiched between two electrodes consequently generating a voltage. In electromagnetic transducers, in turn, the relative motion of a magnetic mass with respect to a coil causes a change in the magnetic flux. This generates a voltage across the coil. (Vullers et al. 2009) Pietzoelectric energy harvesting systems have been most intensely studied and present many advantages compared to the two other mechanisms mostly due to simple configuration, high converting efficiency and precise control (Beeby et al. 2006).

During the recent years there has also been an increasing interest in developing **thermal energy harvesters**. The devices are based on the Seebeck effect i.e. the direct conversion of a temperature difference in thermopiles into electricity. These devices do not, however, contain any electromechanical functions. (Vullers et al. 2009) Some research has also been conducted on **solar energy harvesting systems**. For the development of solar energy harvesters different approaches have been presented, such as using mechanical structures and RF MEMS components. (Nielson et al. 2007, Huang et al. 2010) However, compared to the aforementioned energy harvesters the research of these devices is still at initial stage.

Energy harvesting systems have been under extensive research during the last decade (Harb 2011). This is due to the many advantages they offer compared to conventional power systems such as batteries. First of all the devices are significantly smaller in size and much lighter, which are highly desired features in most of the modern wireless devices. Secondly, they enable increased lifetime of the wireless devices by using renewable energy sources. Finally, due to fact that the power devices do not have to be frequently replaced, energy harvesting systems offer an environmental friendly solution for power generation. (Chalasani & Conrad 2008, Yole 2012b)

Despite the advantages energy harvesting systems offer compared to the conventional powering devices, there are still many challenges that hinder the commercialization of the devices. One of the main challenges is the inadequate power produced by the devices. The power harvested by the devices is generally quite low ranging from 1 to 300 $\mu W/cm^3$. Higher energy densities can be achieved with solar energy harvesters. However, they need sunlight in order to function. In addition to insufficient power densities, there are still some technical challenges regarding the implementation and performance of the devices. (Yole 2012b) The current technical challenges and energy densities of different types of vibrating and thermal energy harvesting systems are listed in table 15. Another factor slowing down the commercialization is the high cost of the devices compared to low-cost batteries. Moreover, there is a need for ultra low power electronics in order to minimize the power consumption of the wireless devices. In addition, to balance a mismatch between power generation and consumption a small energy storage system is required for continuous operation. (Vullers et al. 2010)

Table 15. Current technical challenges and typical energy densities of different types of vibrating and thermal energy harvesters (modified from Yole 2012b)

Type of Energy Harvester	**Transduction Mechanism**	**Technical Challenges**	**Energy Density ($\mu W/cm^3$)**
Vibrating	Electrostatic	Low energy density	1-300
	Pietzoelectric	Pietzoelectric films are difficult to deposit	
	Electromagnetic	Too bulky	
Thermal	Seebeck effect	Costly	10-100

MEMS-based energy harvesting systems are still mostly at development stage and no commercial devices are yet available. However, the devices have high potential in powering up wireless devices in various markets in the future such as automotive, industrial, military and aerospace, medical and consumer electronics applications. The most promising applications for the energy harvesters are wireless devices, in which the replacement of conventional batteries is complicated and highly undesired. In automotive applications energy harvesters have high potential in tire pressure monitoring systems (TPMS), whereas in industrial applications the devices could be employed in various sensors and metering systems. In medical applications energy harvesters could in turn be used in implantable devices and home health monitoring devices. In consumer electronics applications energy harvesters would probably not replace batteries, but could in turn be used as secondary power sources for various portable devices, such as cell phones and laptops. (Yole 2012b)

Improvements in energy harvesting systems are expected in the upcoming years, which will most likely lead to gradual transition of the devices to commercial markets. At the moment the most advanced MEMS-based energy harvesting systems are vibrating energy harvesters. In addition, thermal energy harvesters are starting to be viable devices. (Vullers et al. 2010, Yole 2012b) On the other hand, the development of MEMS-based solar energy harvesters is still at initial stage and the devices do not seem to have much potential in replacing conventional solar cells. In table 16 the key issues discussed in this chapter are summarized.

Table 16. Summary of the development stage, potential markets and current challenges of MEMS energy harvesting systems

Development stage	**Potential Markets**	**Current Challenges**
Emerging	Automotive, industrial, military and aerospace, medical, consumer electronics	Cost, low power density, need for low power electronics and small energy storage devices

5.2.2 Micro Fuel Cells

Micro fuel cells are devices that convert chemical energy from a fuel into usable electrical energy through an electrochemical reaction. The devices are comprised of an anode and cathode separated by an electrolyte. At the anode a catalyst oxidizes the fuel, typically hydrogen or methanol, turning it into positively charged ions and negatively charged electrons. The created ions travel through the electrolyte to the cathode, whereas the electrons travel in the external circuit from anode to cathode creating an electrical current. At the cathode an oxidant, typically air, is reduced creating water and carbon dioxide as reaction products. (La O et al. 2007) In the recent years there has been a growing interest in using microfabrication technologies to develop micro fuel cells. The micromachined parts of the micro fuel cell are generally the electrode plates and the fuel delivery system. The latter is often achieved through microchannels or flow fields. Also micropumps and valves may be applied for the transportation of fluid and gases. However, the energy conversion itself does not contain any electromechanical functions. Most commonly used material in the microfabrication of MEMS-based micro fuel cells is silicon, although other materials, such as various metals and polymers have been studied as well. (Pichonat 2009)

Micro fuel cells have been under extensive research over the last decade due to the many advantages they offer compared to conventional powering systems. First of all, micro fuel cells are much lighter and significantly smaller in size than batteries, which is a highly desired feature in many portable devices. In addition, the energy densities they are capable of producing are 3-5 times higher than with conventional devices. Moreover, contrary to batteries, which require frequent long-time recharging, micro fuel cells only require an occasional change of the fuel tank depending on the size of the tank. Lastly, they provide a more environmental friendly solution for power generation. (Pichonat 2009)

Despite the many advantages micro fuel cells offer compared to conventional devices, there are still many challenges to overcome. One of the main challenges is the storage and effective management of the fuel to maximize the energy density and provide for safe devices. Moreover, packaging of the devices remains a challenge, as oxygen from the air is needed in the chemical reaction occurring in the fuel cells. The packaging also has a major impact on the safety of the devices. There are also other issues related to heat and water management that have not yet been fully solved. In addition, the cost of the devices is still significantly higher than with batteries. (Pichonat 2009)

At the moment hydrogen fed fuel cells and direct methanol fuel cells are the most studied types of micro fuel cells. **Hydrogen fed fuel cells** are the simplest and most effective type of fuel cells with high efficiency. However, there are some major issues concerning storing of the fuel. (Kundu et al. 2007) Hydrogen is far too dangerous to be stored as compressed gas and too complicated to be stored as liquid. To avoid this problem, **reformed hydrogen fuel cells** (RHFC), which use intermediate storages, such as hydrides or methanol as a supply for hydrogen, have been developed. However, the use of an intermediate storage adds complexity to the overall fuel cell and might require high temperatures especially when methanol is used. (Pichonat 2009) **Direct methanol fuel cells**, in turn, are an attractive choice because methanol, its fuel, is a low-cost liquid, which is much easier to store and transport than hydrogen. However, direct methanol fuel cells have lower efficiency than hydrogen fed fuel cells and the devices are quite expensive due to large amount of catalyst needed. Moreover, methanol crossover is one of the major challenges to overcome. (Yao et al. 2006) In table 17 the advantages and drawbacks of hydrogen fed fuel cells, reformed hydrogen fuel cells and direct methanol fuel cells are compared. In addition to the aforementioned fuel cells, also devices using ethanol and formic acid are currently being considered as interesting alternatives (Pichonat 2009). There is also an increasing interest in so-called biofuel cells, which use biological metabolite products, such as glucose, as fuel (Davis & Higson 2007, Lueke & Moussa 2011).

Table 17. Comparison of the advantages and drawbacks between hydrogen fed fuel cells, reformed hydrogen fuel cells and direct methanol fuel cells

Type of Micro Fuel Cell	**Advantages**	**Drawbacks**
Hydrogen fed fuel cells	Simple, high efficiency	Difficult to store
Reformed hydrogen fuel cells	Easy to store	Complex structure, needs high temperatures
Direct methanol fuel cell	Low cost, high energy density, easy to store	Costly, low efficiency, methanol crossover

Despite years of research, micro fuel cells are currently still under development. However, the research in the area is growing rapidly and some companies have already produced prototypes of the devices. (Pichonat 2009) Micro fuel cells are highly desired in applications where long-time operation and light weight power devices are required. The most potential markets for micro fuel cells are consumer electronics, military and medical applications. In consumer electronics the devices could be employed in various portable devices such as cell phones, tablets, music players and laptops, which currently require long-time recharging. The same applies to military applications, where the devices could be used in various portable products that require long operating times. In medical applications the fuel cells could for instance be used in implantable devices, such as pacemakers and glucose sensors. (Kundu et al. 2007) However, it will probably take up to several years until micro fuel cells become commercially available. The issues covered in this chapter are summarized in table 18.

Table 18. Summary of the development stage, potential markets and current challenges of micro fuel cells

Development stage	**Potential Markets**	**Current Challenges**
Emerging	Consumer electronics, military, medical	Cost, safety, packaging, heat and water management

5.3 BioMEMS

MEMS devices used in biological or biomedical applications are typically referred to as bioMEMS (biological or biomedical micro electro mechanical system) devices (Bashir 2004). BioMEMS devices can be used in various different applications and some of them have already been reviewed in the previous chapters. In this chapter, bioMEMS devices including microfluidic devices and medical sensors are reviewed. The basic principle of the devices is introduced and the development stage and main challenges are discussed. A more in-depth review of various bioMEMS devices can be found in (Lampo 2011).

5.3.1 Microfluidics

Microfluidics refers to the control of fluid flow in very small amounts, typically a few microliters in a miniaturized system. The main functions performed by these devices include transporting, mixing, separating or otherwise processing the used fluids. (Ashraf et al. 2011) Microfluidic devices are comprised of various microfluidic components, which allow precise control and manipulation of the fluids. Examples of such components are micro chambers, channels, valves, pumps and mixers. The components can be either passive or active in nature and several different actuation methods can be used for the actuation of the active components. (Addae-Mensah et al. 2010) MEMS technology is commonly used for the fabrication of microfluidic devices, although not all of the devices include any electromechanical functions. The main materials used for the fabrication of the devices are silicon, glass and polymer, although polymer-based devices are increasing in popularity due to their low-cost and better biocompatibility. (Bashir 2004) Microfluidic devices can be used in wide variety of applications, the most important being diagnostics, pharmaceutical and life science research as well as drug delivery applications (Yole 2010c). There are also other MEMS devices, such as inkjet printer heads and micro fuel cells that contain microfluidic components. These devices have already been reviewed in earlier chapters (4.2 and 5.2.2) and will not be covered in this chapter.

In many applications microfluidic devices can be used for the detection and analysis of wide variety of different substances. In **diagnostic applications** the devices are typically used for the detection of various pathogens, such as cells, viruses, protein and microorganisms. (Bashir 2004) In **life science applications** the devices are in turn used as analytic devices to analyze various chemical and biochemical molecules compounds. These devices are typically referred to as Lab-on-a-Chip (LOC) devices or micro Total Analysis Systems (µTAS). The devices contain one or several miniaturized laboratory functions integrated on the same chip enabling a whole analysis or detection process. (James et al. 2008) In addition to the various microfluidic components used in the Lab-on-a-Chip devices, different detection methods are needed for the recognition of the wanted substances. For instance various different mechanical, electrical or optical detection methods can be used. (Bashir 2004) An extensive review of the different detection methods can be found in (Bashir 2004). On the other hand, in **drug delivery systems**, which are used for storing and dosing of drugs, microfluidic components, such as micro pumps and needles play a major role (Ashraf et al. 2011). An extensive review of different microfluidic components used in drug delivery can be found in (Ashraf et al. 2011).

The research on microfluidic devices started in the early 1990's and experienced high growth in the turn of the millennium. However, the commercialization of the devices has been rather slow and so far no revolutionizing applications have been presented. One of the most researched areas for microfluidic devices is **medical diagnostics**. The main driving factors for the use of miniaturized diagnostic devices are smaller sample sizes and faster measurement times. In addition, it enables the diagnostic testing near the patient site instead of remote laboratories. This is typically referred to as point of care (POC) diagnostics. (iNEMI 2011) Another large application area for microfluidic devices is **pharmaceutical and life science research applications**, such as drug discovery and genomics (Yole 2010c). The same kind of devices can also be applied in various other application areas, such as environmental screening, food control and homeland security (iNEMI 2011). In addition to the aforementioned applications, extensive research has been conducted on microfluidics-based **drug delivery applications**. The main driving factor for the use of the devices in drug delivery is more accurate and localized dosing of drugs. (Ashraf et al. 2011) Various different devices, including inhalers and transdermal and implantable devices, are currently under development (Bouchaud & Dixon 2009).

Today there are already some commercial **diagnostic and analytic microfluidic devices** available on the market and rapid growth in the commercialization is expected in the coming years (Breussin 2012). However, there are still some challenges to overcome in the future. First of all, the current microfluidic devices are more Chip-in-a-Lab type of devices rather than Lab-on-a-Chip devices. That is to say that the current devices are used together with bulky conventional devices instead of having all of the functions integrated on the single chip. Thus, improvements in miniaturization of various functions as well as high-level integration are required in the future. (iNEMI 2011) Moreover, the cost of the devices still needs to drop in order to reach high volume markets. Other challenges include lack of collaboration between technology providers and medical experts, high investment costs and medical companies not willing to invest in risky new technologies (Yole 2010c). In addition to microfluidics, the role of nanofluidics is expected to grow in the future. Reducing the dimensions of the devices to nanoscale offers new potential application and has already brought some new analysis techniques available. (van der Berg et al. 2010)

The commercialization of **drug delivery systems** lacks behind from other microfluidic systems and in fact the devices are still mainly at development stage. This is mostly due to some major challenges regarding biocompatibility, integration, packaging and reliability (Ashraf et al. 2011). Another factor hindering the commercialization of the devices are the time-consuming and strict clinical testings and approvals required in the medical industry. In addition, the high cost of the devices compared to conventional systems hinders the adaptation to the market. Many research institutes and commercial companies are currently developing various drug delivery systems. Among the different drug delivery systems, inhalers seem to be the most mature devices followed by micro needles and pumps intended for transdermal drug delivery. In terms of volume, micro needles have the largest potential, since they are suitable for the replacement of large amount of vaccinations performed every year. Implantable drug delivery systems, in turn, are far behind in the development and the commercialization can be expected to take a lot longer time. Particularly, responsive drug delivery systems capable of on-demand drug delivery are still far in the future. (Bouchaud & Dixon 2009) In table 19 the issues discussed in the chapter are summarized.

Table 19. Summary of the development stage, largest markets and current challenges of microfluidics

Application area	Development stage	Largest Markets	Current Challenges
Diagnostics, Analytic Devices	Developing	Medical, Pharmaceutical, Life Science	Cost, miniaturization and integration of laboratory functions on the same chip
Drug delivery systems	Emerging	Medical	Cost, reliability, biocompatibility, integration, packaging

5.3.2 Medical Sensors

Medical sensors are used to measure a wide variety of physiological properties such as temperature, pressure, pH and the concentration of biological compounds. Currently, there is an increasing trend towards portable medical sensors that can be worn or implanted in the body. MEMS technology has been applied to the development of many miniaturized medical sensors ranging from pressure sensors to biosensors. It offers several advantages, such as small size, low power consumption and high-level of integration, when compared to other technologies. (Thusu 2010)

Currently, the most established MEMS-based medical sensor is the **pressure sensor** (Bouchaud 2011b). The medical pressure sensor works in the similar fashion as pressure sensors used in other applications. The operating principle of the device was described in chapter 4.1. Currently, medical pressure sensors are mostly used as low-cost disposable blood pressure sensors for catheters employed in surgical operations. However, they can also be found in more expensive devices used for pressure and differential flow monitoring in continuous positive airway pressure (CPAP) machines for treating sleep apnea. (Dixon 2011a) Other potential applications for medical pressure sensors include implantable sensors for cardiac measurements and glaucoma monitoring in the eye (CardioMEMS 2012, Sensimed 2012). In addition to pressure sensors various other MEMS-based medical sensors have been developed. For instance, MEMS-based **flow sensors** can already be used to measure air and gas flow in oxygen concentration, inhaled anesthetics and ventilator application. The flow sensors employ thermopiles to convert thermal energy into electrical energy to measure the mass flow rate. (Omron 2012) In addition, MEMS **accelerometers** are used in medical devices such as pacemakers and defibrillators. New potential applications for accelerometers and gyroscopes include patient monitoring. They could for instance be used for fall detection of the elderly. (Thusu 2011) Other potential applications of MEMS sensors in the medical market include sensors used in medical instruments for minimally invasive surgery. For instance, pressure and strain sensors can be incorporated in surgical tools to distinguish between different types of tissue. (Khoshnoud & de Silva 2012, Yole 2011d)

Another widely researched area for MEMS medical sensors is the detection of biological molecules. These devices are typically referred to as **biosensors**. The most extensively studied biosensor is glucose sensor for monitoring the blood sugar level on diabetic patients. Most of the researched glucose sensors are affinity type sensors that are based on binding the glucose molecules to a specific glucose binding material. The glucose concentration is measured by using a vibrating membrane or a cantilever, which measures the change in the material viscosity. The viscosity change is caused by the binding of glucose to the material. (Khoshnoud & de Silva 2012) MEMS-based glucose sensors have been under development for several years now. However, they have not yet made their way into the commercial markets.

Medical sensors experience the same kind of functional limits as their analogues in other applications. In addition, the biological environment sets its own challenges to the devices regarding reliability, biocompatibility and packaging. A major issue related particularly to implantable devices is how to power the devices. The most common method to power MEMS-based *in-vivo* devices is a conventional or thin film battery. Normally, the battery system becomes a limiting factor to the lifespan and applicability of medical sensors, as the battery will eventually require replacement or recharging. Extensive research work has been conducted on finding alternative wireless power sources for implantable bioMEMS devices. (Lueke & Moussa 2011) One widely researched alternative is radio frequency identification (RFID) type systems, which use RF telemetry for information and power transfer (Sauer et al. 2005). Another powering method, which has gained interest in the recent years, is MEMS-based energy harvesting systems (see chapter 5.2.1). (Lueke & Moussa 2011) A major challenge related to the commercialization of the medical sensors is the long development cycles. Before being allowed on the commercial markets, the devices have to go through intense approval processes, which are both time-consuming and costly. (Pyzowski 2011) Moreover, due to the high investment costs, the devices are typically more expensive when compared to conventional devices. This hinders the adaptation of the devices to the market. (iNEMI 2011) The issues discussed in this chapter are summarized in table 20.

Table 20. Summary of the development stage, largest markets and current challenges of MEMS-based medical sensors

Development stage	**Largest Markets**	**Current Challenges**
Emerging	Medical	Packaging, reliability, biocompatibility, cost, power source, long approval processes

5.4 MEMS Atomic Clocks

Atomic clocks are devices used for frequency reference in timing applications. They are by far the most accurate and stable devices available. (Nguyen 2007) Currently, there is an increasing demand for small and low-power clocks, as more and more applications become mobile. The conventional quartz-based clocks currently used in these devices face limitations in their operation, which is why scientists focus their effort on the miniaturized version of the atomic clock, better known as chip-scale atomic clock (CSAC) or MEMS atomic clock (MAC). (Chutani et al. 2012)

In contrast to quartz –based clocks, in which the reference frequency is determined by a mechanical vibration, the reference frequency in atomic clocks is in turn determined by the energy transition of atoms (Knappe et al. 2006). Among the existing approaches to realizing an atomic clock, the alkali vapor cell method seems to be the most amenable to miniaturization (Nguyen 2007). In fact, many MEMS-based alkali vapor cells are currently under development (Knappe et al. 2006, Nieradko et al. 2007, Hasegawa et al. 2011). MEMS technology is used for the fabrication of the alkali vapor cells, although the devices do not include electromechanical functions. The heart of the device consists of a vapor cell containing an alkali metal, such as Cesium or Rubidium, in dense vapor state. The vapor is illuminated by high-frequency modulated laser beam and collected by a photodiode. The output signal is then used to lock the frequency of a local oscillator (LO), which produces the clock signal. (Hasegawa et al. 2011) In order to operate the atomic clock the alkali metal atoms must be maintained at a sufficient density in a vapor state, which means that the vapor cell must be heated. Thus, a heating element must be incorporated in the device as well. In addition to the optical method used to excite the energy transition of the atoms, a microwave cavity producing a RF signal can also be used. (Nguyen 2007) However, the microwave cavity requires a larger volume and has higher power consumption, which is why the optical method is often a more desired option (Hesegawa et al. 2011).

Over the last decade there has been an increasing interest in developing MEMS-based atomic clocks. The development is driven by the demand for more accurate and stable devices for frequency references. (Chutani et al. 2012) The devices have potential in many applications, such as telecommunication networks, military navigation systems and industrial applications, such as seismic sensors (Hasegawa et al. 2011, Symmetricom 2011). The MEMS-based atomic clocks offer several advantages compared to conventional quartz-based clocks. Not being subjected to mechanical wear the devices are capable of providing enhanced long-term frequency stability and precision. In addition, improvement in power consumption can be achieved. Other advantages include high-volume wafer-based production, which can substantially reduce costs. Such improvements would make atomic clocks useful in a variety of applications where quartz-based oscillators are currently used. (Knappe et al. 2006)

Currently, MEMS-based atomic clocks are mainly at development stage, although extensive research work is being conducted in various research groups in order to bring the devices into commercial markets. Among the commercial companies at least Symmetricom has recently introduced their MEMS-based atomic clock on the market (Frenzel 2011). However, there are still some challenges to overcome before high-volume production can be entered. One of the main challenges in realizing a miniaturized atomic clock is maintaining the temperature of the vapor cell constant in order to operate the atomic clock. Moreover, the thermal management must be implemented using as little power as possible. Another major challenge is the collision between the atoms and cell walls, which can dephase the atoms, disrupting their coherent state. Buffer gases have been applied in order to prevent the collisions, although the interaction between the atoms and buffer gas still remains a challenge. (Nguyen 2007, Chutani et al. 2012) The key issues discussed in this chapter are summarized in table 21.

Table 21. Summary of the development stage, potential markets and current challenges of MEMS atomic clock

Development stage	Potential Markets	Current Challenges
Emerging	Telecommunication, industrial, military	Low power thermal management, interaction between the atoms and a buffer gas

5.5 Micro-Coolers

Micro-coolers are miniaturized cooling devices intended for cooling down electronic components and small instruments, such as miniaturized sensors and MEMS devices. In these devices the operating temperature is lowered to reduce thermal noise and increase the speed of the system. (ter Brake et al. 2008) The need for new cooling techniques is driven by the continuing increases in power dissipation of electronic parts and systems. In many cases conventional techniques cannot achieve the required cooling performance due to physical limitations in heat transfer capabilities. (Lasance & Simons 2005)

MEMS technology has been applied to the development of various micro scale coolers. The most researched technologies are thermoelectric coolers and cryogenic coolers. Microfabrication technologies are used for the fabrication of these devices, although the devices do not include electromechanical functions. **Thermoelectric coolers** use the Peltier effect to create a heat flow between a junction of two different types of materials when an electric current is applied. Heat absorbed from the hot object flows from the one side of the device to the other cooling down the object. Commonly used materials in the devices are metals and n- and p- type semiconductors. (Huang et al. 2008) **Cryogenic micro-coolers**, also referred to as cryocoolers, are in turn based on a whole range of different cooling principles. However, the research has mainly focused on cooling obtained by using a so-called Joule-Thompson cooling cycle. (Lerou et al. 2006) A high-pressure gas flows through a counter-flow heat exchanger (CFHX) exchanging heat with a colder low-pressure gas flowing in opposite direction. The high-pressure fluid consequently cools down, expands adiabatically and partly liquefies. A heat load, resulting from the object being cooled down, evaporates the liquid and the vapor flows back through the CFHX. (Derking et al. 2012) In open-cycle systems, the low-pressure gas leaving the CFHX is vented to air, whereas in a closed-cycle system the fluid is re-compressed. Cryocoolers are used to cool down objects to cryogenic temperatures typically lower than 120 K. (Lerou et al. 2006) Also other MEMS-based micro-coolers, such as liquid cooling systems and Stirling-type coolers, are under development (Deng et al. 2007, Moran 2001).

Micro-coolers have been under active research for many years now. However, the devices are still mostly at development stage. (ter Brake et al. 2008) The devices hold great potential to be used for thermal management in wide variety of applications ranging from consumer electronics to military and aerospace applications in the future (Kirkconnel 2008). MEMS-based micro-coolers offer several advantages compared to conventional technologies. The devices are smaller in size, which is a highly desired feature in the current miniaturized products. Moreover, they can easily be integrated with electronic circuitry and allow low-cost production by using batch processing. (Lerou et al 2006) In addition, the miniaturized coolers enable cooling of localized regions of higher temperature commonly known as hot spots. Particularly, thermoelectric coolers are developed for this purpose. (Huang et al. 2008)

Despite the advantages MEMS-based micro-coolers can offer, there are still several challenges to overcome before the devices become commonly applied in commercial products. With **thermoelectric coolers** challenges arise in how to ensure that the devices achieve a high efficiency of energy conversion into cooling. This is mostly due to challenges in obtaining efficient thermoelectric materials with low thermal conductivity and high electrical conductivity. (Lasance & Simons 2005) However, at least one company has already introduced a commercial MEMS-based thermoelectric micro-cooler on the market (Micropelt 2012). **Cryogenic micro-coolers** are in turn still on development stage and no commercial devices yet exist. There are some major challenges related to the miniaturization of the compressor and clogging of the system (Kirkconnel 2008). The clogging occurs when small amounts of water in the micro-cooler freezes resulting in a decrease in mass-flow rate and hence in cooling power (Lerou et al. 2006). Moreover, information of the long-term reliability of the devices is still needed (Mahajan et al. 2006). The key issues discussed in this chapter are summarized in table 22.

Table 22. Summary of the development stage, potential markets and current challenges of MEMS micro-coolers

Type of a Micro-Cooler	Development stage	Potential Markets	Current Challenges
Thermoelectric cooler	Emerging	e.g. Military & aerospace, consumer electronics	Efficiency, material performance
Cryogenic cooler	Emerging	e.g. Military & aerospace, consumer electronics	Miniaturization of the compressor, clogging, long-term reliability

5.6 Micro Speakers

Micro speakers are miniaturized electroacoustic transducers that convert electrical signals into sound (Yole 2010b). MEMS-based micro speakers offer several benefits compared to conventional loudspeakers that are currently used in various electronic devices. First of all they are smaller in size and lighter in weight, which are highly desired features in many portable electronic devices today. Moreover, the MEMS-based micro speakers enable better sound quality and higher efficiency. In addition, the devices offer reduced power consumption, higher level of integration and improved manufacturability. (Shahosseini et al. 2012)

MEMS-based micro speakers are based on a mechanical membrane, which displacement produces a change in the atmospheric pressure generating a sound in audio frequency range. Various actuation mechanisms, such as electrostatic, pietzoelectric and electrodynamic can be used for the actuation of the membrane. (Shahosseini et al. 2010) In electrostatic actuation an electrostatic force causes the displacement of the membrane when a voltage is applied to the system, whereas in pietzoelectric actuation the displacement is caused by deformation of the piezoelectric material on the membrane when voltage is applied (Roberts et al. 2007, Ko et al. 2003). Electrodynamic actuation in turn exploits the Lorentz force, which produces a displacement of the membrane when a magnetic field is applied (Cheng et al. 2004). The current technical challenges of different actuation mechanisms are listed in table 23. Judging by the increasing number of publications, electrodynamic actuation seems to be growing in popularity (Cheng et al. 2004, Je et al. 2009, Shahosseini et al. 2012, Lemarquand et al. 2012). This is due to the many advantages it offers compared to other actuation methods. It enables the production of high sound pressure level while having a linear response and reaching a high fidelity sound reproduction (Shahosseini et al. 2010).

Table 23. Technical challenges of different types of MEMS-based micro speakers (combined from Shahosseini et al. 2012, ITRS 2011)

Actuation Type	Technical Challenges
Piezoelectric	Nonlinearity, integration of piezoelectric material
Electrostatic	High bias voltage, low power density
Electrodynamic	Integration of permanent magnet, low power efficiency

During the recent decades extensive research work has been conducted to develop MEMS-based acoustic devices. However, the development of micro speakers has lacked far behind from MEMS-based microphones, which are already commonly used devices. Currently, micro speakers are still at development stage and no commercial devices are yet available on the market. (ITRS 2011) From commercial companies so far at least Audio Pixels have announced that they have MEMS-based micro speakers under development (Audio Pixels 2012). One of the most potential application areas for micro speakers is portable consumer electronics devices, such as music players, cell phones, earphones and tablets (iNEMI 2011). In these applications there is a high demand for micro speakers with small size, light weight and improved audio performance (ITRS 2011). Another potential application area for micro speakers is medical applications, such as hearing aids. In these applications small size, low cost and improved performance are highly desired features that could be reached with the MEMS-based devices. (Je et al. 2009)

Despite the many advantages MEMS-based micro speakers can offer, there are still many challenges that hinder the commercialization of the devices. One of the main challenges to overcome is how to achieve sufficient output pressures at relatively low actuation voltages. Another, even more fundamental challenge for MEMS-based micro speakers is how to achieve sufficient sound pressures with a device of such a small area. As the speakers generate sound by moving air, large area membranes or membranes capable of large displacements are required for sufficient output pressure. This becomes problematic particularly for the low frequencies as the radiation impedance, which determines the pressure generated for a given membrane displacement, decreases with decreasing frequency. (ITRS 2011) Using a combination of individual micro speakers in large arrays has been proposed as one possible solution for the problem (Roberts et al. 2007). The current micro speakers are clearly facing some major challenges in their development and in order to enter the commercial markets great improvements are still required. The issues covered in this chapter are summarized in table 24.

Table 24. Summary of the development stage, potential markets and current challenges of micro speakers

Development stage	Potential Markets	Current Challenges
Emerging	Consumer electronics, medical	High actuation voltage, small size, insufficient sound pressures

5.7 Auto-Focus Devices

Auto-focus (AF) is a common feature in digital cameras to ensure that the object being photographed is in focus. Auto-focus devices have only recently been applied to small portable consumer products, such as cell phone cameras where the image quality, as well as feature size and low cost, are critical requirements. The conventional technologies have failed to meet these requirements, which is why new technologies have emerged to fill these needs, MEMS technology being one of them. (Gutierrez 2010)

The auto-focus devices can either be lens-motion-type devices or lens-modification-type devices. **Lens-motion-type devices** are based on moving the optical lens of the camera in order to achieve focus. (Gutierrez 2010) Tessera Technologies is currently developing a MEMS-based actuator that uses comb drives for the creation of movement. Comb drives are capacitive actuators that utilize electrostatic forces that act between two electrically active combs. When a voltage is applied an attractive electrostatic force is created drawing the combs together and causing the movement of the lens. (Tessera 2010) The **lens-modification-type devices** are in turn based on varying the optical power also known as focal length by using refractive or reflective optics (Wei et al. 2011). A start-up company poLight is currently developing a MEMS-based device, which uses a refractive deformable glass membrane to alter the focal length of the device. The deformation of the membrane is achieved by using a piezo actuator embedded on the glass membrane. When a voltage is applied the piezo actuator forces the membrane to deform generating focal length variation and enabling focusing. (Vieillard 2011) Another lens-modification-type device being developed uses the deformation of a reflective MEMS micromirror to vary the focal length. The deformation of the micromirror is achieved by using electrostatic actuation. (Wei et al. 2011) The same type of operating principle is also used in micro zooms, which are currently under development (Jayapala 2011).

There has been an increasing interest in the use of MEMS technology to the development of auto-focus devices during the last couple of years. The development is driven by the increasing demand for new technologies to replace the conventional auto-focus devices in portable consumer electronics applications, such as cell phones and tablets. MEMS technology is currently one of the leading technologies, which offers several advantages compared to other technologies. It has the greatest potential to miniaturization and cost reduction because it integrates all of the actuator components on a single chip. (Gutierrez 2010) Other advantages include lower power consumption and higher speed of autofocus. In addition, due to low power consumption and silent operation the devices are also capable of continuous video recording, which has been a challenge with other new technologies. (Gutierrez 2010, Vieillard 2011) Among the lens-motion-type devices MEMS-based auto-focus devices are currently the only technology capable of moving a single lens instead of a whole lens train. This brings several benefits, such as smaller size, higher speed and better precision. (Tessera 2010)

Despite the many advantages the MEMS-based auto-focus devices offer, there are still some challenges to overcome. For instance, Wei et al. (2011) reported limitations in optical system design and correction of high-order aberrations. However, no information about the current development challenges in the commercial products is available. There are already some commercial products on the market, although, the high volume productions is expected to start in the next couple of years. (Courtemanche 2011,Vieillard 2011) In case the devices will gain great success in consumer electronics, they might have potential in other markets as well in the future. The issues covered in this chapter are summarized in table 25.

Table 25. Summary of the development stage, potential markets and current challenges of MEMS auto-focus devices

Development stage	Potential Markets	Current Challenges
Emerging	Consumer electronics	Optical system design, correction of high-order aberrations

5.8 MEMS RFID

Radio frequency identification (RFID) devices are wireless communication systems that allow storage and extraction of information using radio waves (Bluechiip 2012). RFID devices are commonly used for identification and localization of objects in applications such as product tagging, inventory, security and transportation (Pereyma et al. 2007).

Recently MEMS technology has been applied to the development of RFID devices in order to enable the devices to be applied in new applications.

RFID devices comprise of two components: a transponder commonly referred to as a tag for storing the information and a receiver for reading the information. The devices can be either passive or active systems. Active systems include an embedded power source, whereas passive systems use energy produced by the receiver and do not contain any inner power source. (Pereyma et al. 2007) In contrast to the conventional IC –based RFID devices, most of the MEMS-based devices are passive systems based on mechanical resonators. In these devices the information transfer is accomplished by measuring the resonance frequencies of the MEMS resonators embedded in the tag using an external reader. (Veratag 2012, Bluechiip 2012, Viikari & Seppä 2009) Also active systems using vibrational energy harvesting to power the device have been studied (Kaya 2007).

The interest in MEMS-based RFID devices has increased during the recent years. There are many attractive application areas for the devices ranging from medical and life science applications to authentication and security applications. In medical and life science market the devices could be employed in various different applications, such as patient identification, drug and biological specimen tagging and surgical instruments (iNEMI 2011, Yole 2011d). In addition, the MEMS RFID devices have potential in various authentication and security applications, such as access control, identification cards and lock-and-key devices (Veritag 2012). Other potential application areas include powering wireless sensors for instance in industrial applications (Kaya 2007). MEMS technology offers several advantages compared to conventional RFID technologies. It enables lower manufacturing costs and compact tag size as well as high-level of integration with various sensors, such as temperature sensors and pressure sensors. (Pereyma et al. 2007, Viikari & Seppä 2009) In addition, the mechanical structures enables the devices to be used in harsh environments, such as very high and low temperatures and under ionizing radiation, which is not currently possible with the conventional devices (Bluechiip 2012).

Currently, several university groups and start-up companies have contributed to developing MEMS RFID devices. Among the commercial companies, at least Bluechiip is soon approaching commercial launch for their MEMS RFID devices particularly aimed for medical and life science applications (Swedberg 2011). Also Veratag is currently developing MEMS-based RFID systems for authentication and security purposes (Veratag 2012). In addition, the Finnish Research Center VTT has been studying MEMS-based RFID systems for passive wireless sensors (Viikari & Seppä 2009). No public information about the current challenges in developing MEMS-based RFID devices was found. The issues covered in this chapter are summarized in table 26.

Table 26. Summary of the development stage, potential markets and current challenges of MEMS RFID devices

Development stage	Potential Markets	Current Challenges
Emerging	Medical and life science, industrial, authentication and security	Information not available

6 Expert Interviews

In this thesis expert interviews were conducted to obtain professional opinions to the results of the literature review. All of the companies and research institutes part of the Finnish MEMS industry were contacted. However, not all of the contacted experts were able or willing to participate in the interview. In total four experts from Vaisala Oyj, VTT (Technical Research Center of Finland), Okmetic Oyj and VTI Technologies (Murata Electronics Oy since 2012) were interviewed. All of the interviewed experts currently work in close contact with MEMS technologies and have a long working history in the MEMS industry. In table 27 the list of the interviewed experts is presented.

Table 27. Interviewed experts from the Finnish MEMS industry

Name	Title	Company	Date of the Interview
Tomi Salo	Principal Scientist	Vaisala Oyj	11.6.2012
Vladimir Ermolov	Principal Scientist	VTT	14.6.2012
Markku Tilli	Senior Vice President	Okmetic Oyj	20.6.2012
Sami Nurmi	Senior Manager	VTI Technologies (Murata Electronics Oy since 2012)	20.6.2012

The purpose of the interviews was to obtain professional opinions about MEMS markets, applications and devices. The experts were asked questions about the current development stage and functional limits of the various existing MEMS devices. In addition, questions about emerging MEMS devices, their development challenges and potential in the commercial markets were presented. To determine the role of MEMS from a national perspective in the future, questions about development possibilities of the Finnish MEMS industry were asked. Finally, the role of MEMS devices in the long run was discussed. The content of the interviews was shaped according to the field of expertise of the interviewed experts and was consequently more focused on the specific devices and applications the most familiar to the experts. The results of the interviews were used to shape the conclusions made based on the literature review and are presented and discussed in the next chapter.

7 Discussion

In this thesis various existing and emerging MEMS devices were reviewed and analyzed from different perspectives. The results of the literature review are presented in chapters 3-5. After conducting the literature review, experts from the Finnish MEMS industry were interviewed in order to obtain professional opinions to the result of the literature review. The implementation method and the list of the interviewed experts are presented in chapter 6. In this chapter the results based on the literature review and expert interviews are discussed. In addition, suggestions for possible future focus areas for research and development activities are made based on the results.

7.1 Evolution of Commercial MEMS Devices

The conducted literature review showed that MEMS technology has been applied to the development of various devices, from which some have already been in use for many years now, whereas some are still under development. In figure 8 the various MEMS devices are presented on a product life-cycle curve. The graph presents the evolution of the devices in terms of time and sales volume and categorizes them in different stages including development, introduction, growth, maturity and decline stages. The graph was constructed on the basis of the literature review and experts interviews. However, it should be noted that the purpose of the graph is to suggest a general view of the evolution of MEMS devices rather than trying to determine the exact status of individual devices. Even among the interviewed experts there were differing opinions about the status of some of the devices. For instance, some of the experts saw that gyroscopes and microphones still have not reached their peak sales, whereas some considered them already as mature devices.

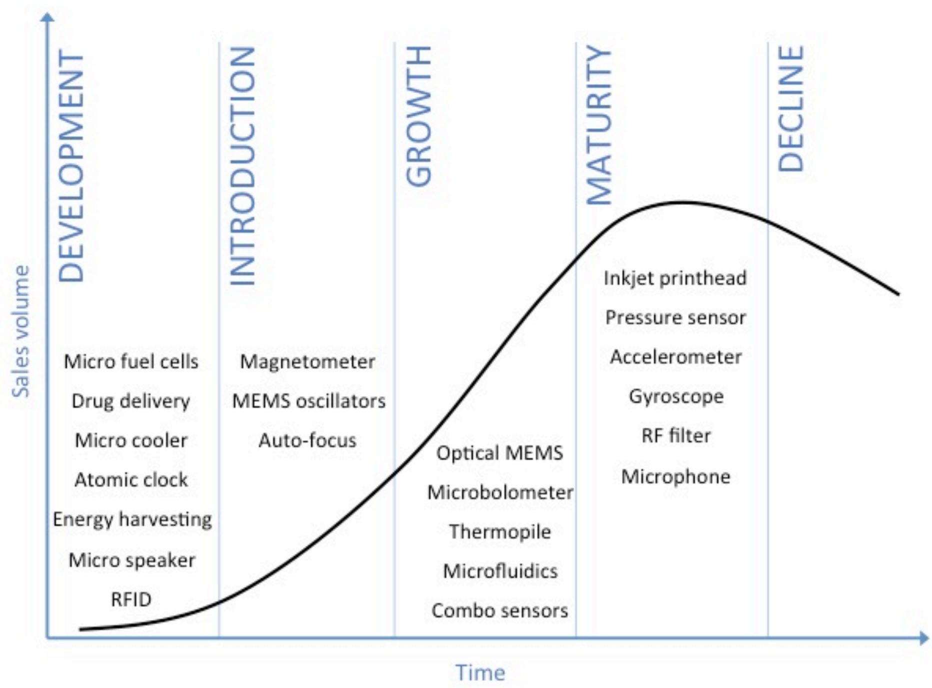

Fig. 8. MEMS device evolution on a product life-cycle curve

The differing opinions about the status of some of the devices presented in figure 8 may be explained by the different development stage of the devices. In the case of microphones and gyroscope, technological improvements could gain better utilization of the devices and thus further increase the sales. For this reason, one of the focus areas in the future might as well concentrate on improving the existing devices and perhaps applying them in new applications.

When looking at the graph in figure 8, it should also be noted that the shape of the curve and the rate at which the devices are moving along it are not necessarily the same for all of the devices. Some of the devices evolve faster than the others reaching the mature stage earlier, whereas some of them remain at the growth stage a lot longer and some might not even progress at all. An important factor affecting this, which was raised in the expert interviews, is the different functions for MEMS devices. Some of the MEMS devices are developed to replace an already existing technology, whereas some are developed to offer a completely new function. For instance, MEMS microphone technology has already existed for several decades now but the devices were first deployed in commercial products little more than a decade ago. This is due to highly conservative companies, which are unwilling to invest in new technologies. The new devices need to offer significant improvements in performance or reductions in cost in order to displace conventional technologies. It should also be noted that the competing technologies are also constantly developing. On the other hand, devices offering completely new functions might gain rapid growth in the sales in case a killer application for the devices is found. For instance, for MEMS gyroscopes the killer application was their use in Electrical Stability Control (ESP) systems first applied in Mercedes Benz cars. Without such an application, the adaptation of the new devices to the market might be rather slow. Recently, also a third function type for MEMS devices has been introduced: combination of different functions in one device. These combo sensors have somewhat different requirements than stand-alone devices and consequently the adoption rate to the market can differ as well. For instance, MEMS-based magnetometers may not have potential in replacing conventional technologies in stand-alone devices, but are highly desired in combo sensors since they can easily be integrated with other MEMS sensors. These are important factors that affect the evolution of the new devices and need to be taken into account when considering their potential in the future. In figure 9 the different functions for MEMS devices and examples of such devices are presented.

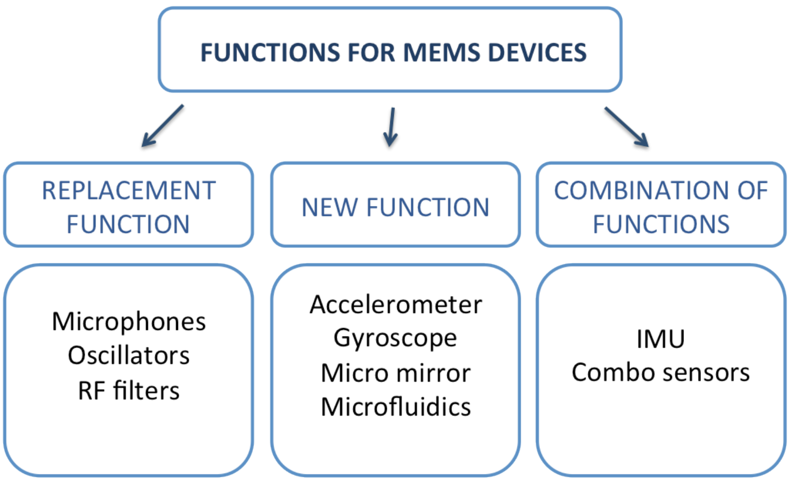

Fig. 9. Different functions for MEMS devices (modified from Yole 2011e)

7.2 Commercialization Potential of Emerging MEMS Devices

An important part of this thesis was to review the emerging MEMS devices not yet available on the commercial markets. As was shown in the literature review a wide variety of new MEMS-based devices are currently under development. In figure 10 the commercial potential of these emerging MEMS devices is presented on a timeline, which represents the expected time for commercial introduction of the devices. The devices were placed on the timeline by using information about their development stage gained by the literature review, whereas in determining the commercial potential of the devices greater emphasis was placed on the opinions of the interviewed experts. Again it should be noted that the purpose of the graph is only to present the overall picture of the commercial potential of the emerging MEMS devices rather than trying to determine the exact status of individual devices. Even among the interviewed experts there were some differing opinions about the potential of some of the devices and not all of them even had an in-depth knowledge of all of the presented devices.

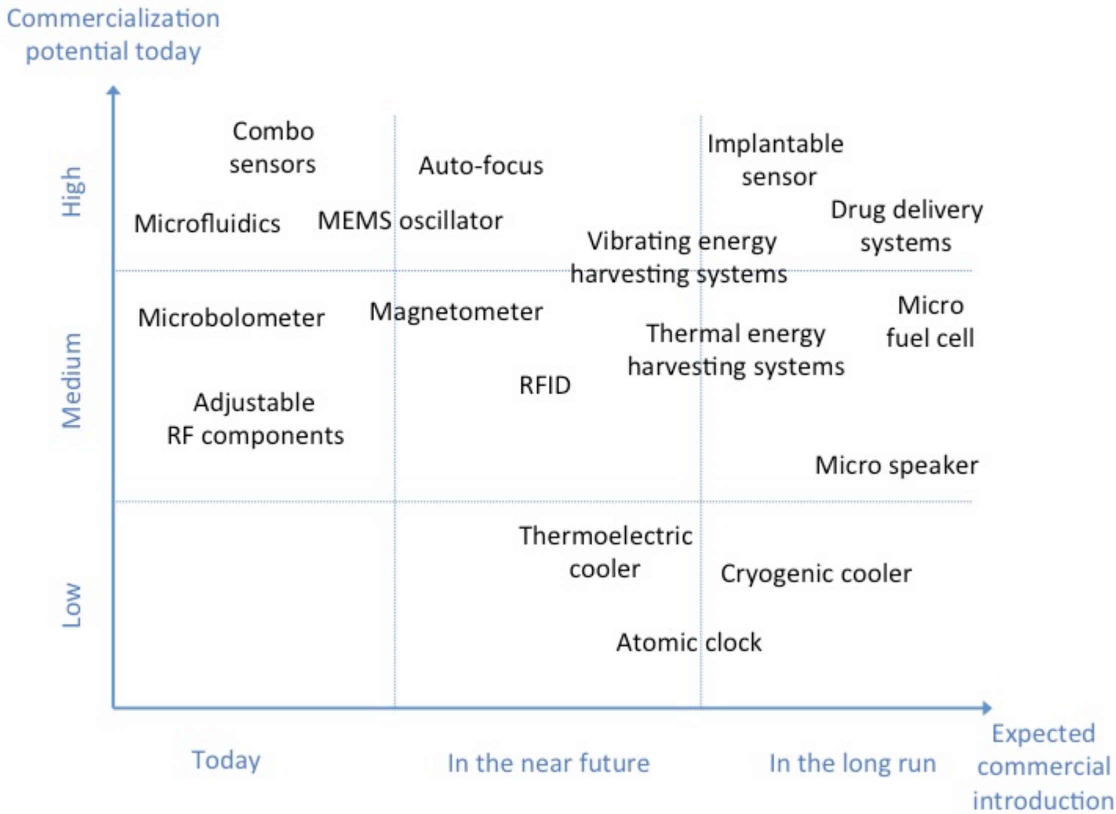

Fig. 10. Commercial potential of the emerging MEMS devices

Despite some differing opinions among the interviewed experts, some of the emerging devices were still considered to have significantly less potential on the commercial markets than the others. This is mostly due to some major technological challenges and lack of highly potential applications. Among the emerging devices, micro-coolers, micro speakers and atomic clocks were not seen as highly potential devices. The main limiting factor for micro speakers was considered to be the physical challenges related to producing sufficient sound pressure levels. This was also confirmed by the literature review. Therefore, not much potential in replacing conventional technologies at least in the near future was seen. In the case of atomic clocks and micro-coolers the main challenge was in turn considered to be finding appropriate applications for the devices. Based on the literature review some potential applications were listed, although, according to the experts the need for them at the moment was considered to be rather low.

On the other hand, many MEMS devices that have recently been introduced on the market or are on the verge of commercialization were considered highly promising. Especially combo sensors gained a lot of support particularly in consumer applications, such as personal navigation systems. Also microfluidics devices were considered to have plenty of unused potential left. In the case of magnetometers the greatest potential was seen in combo sensors where the integration of the different components is essential. MEMS oscillators and auto-focus device were also included in the most potential devices in the near future. Other MEMS devices that were considered to have commercial potential included microbolometers, RFID devices and adjustable RF components. Among the devices that are still under development, power MEMS devices including energy harvesting systems and micro fuel cells were considered promising by most of the experts. However, in the case of energy harvesting systems, concerns about the inadequate power level rose. Fuel cells were considered to be further behind in the development and major concerns about their implementation were presented. In the long run, the most potential was seen in bioMEMS devices, such as drug delivery systems and implantable sensors. All of the experts were unanimous about that bioMEMS devices will have a major role in the future. Long approval processes were considered to be the major limiting factor in their commercialization.

When the MEMS devices are viewed from a market perspective, the greatest potential in the future lies in consumer electronics market where various emerging MEMS devices such as combo sensors, magnetometers, RF oscillators and auto-focus devices will have an important role. Other highly potential markets in the future include medical and industrial markets. In the medical market the focus will be on personal health monitoring applications, which offer opportunities for various medical and microfluidic devices. In the industrial market, in turn, the trend is towards wireless sensing and monitoring. Here, alternative energy sources, such as energy harvesting systems might have an important role in the future. According to the interviewed experts, high potential is also seen in environmental monitoring applications, such as weather monitoring and seismic monitoring. Automotive market will keep exploiting the existing MEMS devices such as motion sensors and pressure sensors. The increasing safety regulation will drive the market in the future as well. Telecommunication market will benefit from increases in telecommunication and wireless communication applications, whereas military and aerospace market will have a minor role in MEMS development in the future.

7.3 Potential Future Focus Areas

The results of this thesis indicate that there are many potential focus areas in the future related to MEMS devices. Many of the existing devices, such as gyroscopes and microphones, still require improvements in order to gain better utilization. On the other hand, new applications are needed for recently introduced devices, such as microfluidic devices and microbolometers in order to enhance their growth opportunities. In addition, the emerging MEMS devices currently under development and on the verge of commercialization offer numerous possibilities for future research and development activities. When viewing this from a national point of view, Finland already has high expertise in established MEMS devices such as motion sensors, pressure sensors and gas sensors. Research and development work in the area of optical MEMS devices, microphones, magnetometers and RF MEMS is also conducted. A viable option for future research and development activities could be utilizing this competence to improve the existing devices and/or apply the devices in new applications. Strong emphasis is, however, suggested to be placed on the more recent devices, which have high growth opportunities in the near future. These devices include for instance magnetometers and RF oscillators, in whose development Finland is already involved with. However, in order to maintain the competitiveness on the international market in the long run, the Finnish MEMS industry should also focus on the emerging devices. One possible focus area could be on finding alternative energy source solutions for wireless sensors used in many applications. Another possible focus area could be the various bioMEMS devices, such as sensors and microfluidic devices. In fact, bioMEMS devices were already listed as a focus area in the previous version of the National MEMS Technology Roadmap. The suggested future focus areas for research development activities are summarized in table 28. In addition, new opportunities could be brought to the Finnish MEMS industry by start-up companies. All of the interviewed experts saw that there was high potential for fabless application-based companies in Finland. Most of the suggestions related to industrial instrumentation applications. For instance, online monitoring of machine operations with various sensors in the Finnish technology companies was suggested as a possible alternative. Another suggested possibility was the development of software for various MEMS devices.

Table 28. Potential future focus areas for research and development activities related to existing and emerging MEMS devices

Potential Focus Areas for Research and Development Activities
1. Performance improvements of the existing MEMS devices in order to improve their utilization. Special emphasis on the most recent devices, such as MEMS oscillators and magnetometers. 2. Finding new applications for the existing MEMS devices, such as microfluidic devices, to enhance their growth opportunities. 3. Research and development of emerging MEMS devices, particularly bioMEMS devices and MEMS for powering wireless sensors.

8 Conclusions

This thesis was conducted as a part of National MEMS technology roadmap and it reviewed various existing and emerging MEMS devices and analyzed them from technological and commercial perspectives. The results were used for determining the evolution of the MEMS devices, and defining some potential research and development activities related to MEMS devices in the future. The work was conducted as an extensive literature review. In addition, experts from the Finnish MEMS industry were interviewed in order to obtain professional opinions to the results of the literature review.

MEMS technology has been applied to the production of various devices, from which some have already been in use for many years now, whereas some are still under development. For a long time, the MEMS market has been composed of established MEMS devices such as inkjet printheads, pressure sensors, accelerometers and RF filters. These devices are also technologically considered to be the most mature devices. Also gyroscopes, microphones and optical MEMS devices have already been on the market for a long time now. However, technological improvements could still improve their utilization. The most recently introduced devices to market include microfluidic devices, microbolometers and combo sensors. They can already be found in many applications, although, with technological improvements new applications could be found and sales would start growing. There are also a few devices that are currently crossing the gap from R&D to commercialization. These devices include magnetometers, MEMS oscillators and auto-focus devices. Some devices have already been introduced to the market, although, high-volume production is first expected to begin in the following years. These devices are still facing some challenges, which are hindering the commercialization.

In addition to the already available devices, many new MEMS devices are currently under development. These emerging devices include various bioMEMS devices, atomic clocks, micro-coolers, micro speakers, power MEMS devices and RFID devices. The devices are in different development stages, although all of them still involve some major technological challenges, which prevent them from commercialization. Due to these challenges or lack of potential applications, some of the emerging MEMS devices are currently expected to have less commercial potential than the others. These devices include micro-coolers, atomic clocks and micro speakers. On the other hand, other emerging devices such as energy harvesting systems and bioMEMS devices, such as sensors and drug delivery systems are considered to have high commercial potential. This may be explained by the whole new opportunities these devices are offering. In addition, many of the MEMS devices that have recently been introduced on the market or are on the verge of commercialization are considered as promising devices. Most of these devices, such as magnetometers, MEMS oscillators and auto-focus devices, are developed to replace an existing technology. The potential is seen in the improvements the technologies bring, although, it should be kept in mind that the adaptation to the market can be rather hard due to conservative companies and developing competing technologies. Other recent devices, such as microfluidics devices offer, in turn, completely new functions. No killer application for these devices have yet been found, which is why they may be considered to have unused potential left. Combo sensors, on the other hand, bring out a completely new function by combining different sensors.

This offers many opportunities and applications, which is why they are probably considered to have so much potential.

The MEMS devices reviewed in this thesis are used in many different applications ranging from mass applications to niche applications. The MEMS market with highest growth potential in the future is the consumer electronics market. It offers plenty of opportunities for many new MEMS devices. Other highly potential markets in the future include medical and industrial markets. In the medical market the growth is driven by personal health monitoring applications, which offer opportunities for various medical and microfluidic devices. However, long approval processes needed to accept the devices on the market are hindering the growth. In the industrial market, in turn, the trend is towards wireless sensing and monitoring. Here, finding new energy sources for powering the sensors will likely have an important role in the future. Automotive market is still an important MEMS market and will be driven by the increasing safety regulation in the future. The market will, however, mainly keep exploiting the existing MEMS devices such as motions sensors and pressure sensors. Other minor but important MEMS markets include telecommunication and military and aerospace markets.

The results of this thesis indicate that there are many potential focus areas in the future related to MEMS devices. Many of the existing devices, such as gyroscopes and microphones, still require improvements in order to gain better utilization. On the other hand, new applications are needed for recently introduced devices, such as microfluidic devices and microbolometers in order to enhance their growth opportunities. In addition, the emerging MEMS devices currently under development and on the verge of commercialization, such as power MEMS and bioMEMS devices, offer numerous possibilities for future research and development activities. When these opportunities are considered from a national point of view alternatives, which exploit the existing competence of the Finnish MEMS industry are suggested. These suggestions include improving and/or applying the existing devices in new applications. Focus should, however, be place on the more recent devices rather than the most established ones, which may no longer offer high growth opportunities in the future. In addition, to maintain the international competitiveness in the future, emphasis on the emerging devices should be placed as well. Among the emerging devices, finding new energy sources for wireless sensors and bioMEMS devices are considered to be the most potential ones for future research and development activities. New kind of opportunities for the industry could also be brought by start-up companies. Suggested alternatives include online monitoring of machine operations with various sensors and software development for different MEMS devices.

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