MEMS Technology & Its Application for Miniaturized Space System

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Abstract— MEMS- Micro electro mechanical system. Over the last decade Micro-Electro-Mechanical System (MEMS) have evoked great interest in the scientific and engineering communities. They are formed by integration of electronic and mechanical components at micron level. MEMS has gained acceptance as viable products for many commercial and government applications. This paper will give an introduction to these exciting developments of MEMS, the fabrication technology used and application in various fields. Future applications of miniaturized space systems will have special needs on MEMS components. This paper addresses the needs, status and perspectives of the MEMS Technology for miniaturized space system from the perspectives of a spacecraft developer. First, the needs of the future space missions on MEMS components are discussed. Then, the state-of-the-art MEMS technologies are reviewed based upon these needs. Finally, perspectives of space-based MEMS technology will be addressed based on the analysis of both future mission needs and technological trends. Lastly, it concludes saying that MEMS have enough potential to establish a second technological revolution of miniaturization.

Key words: MEMS, Space Systems, Miniaturization, Micro-Propulsion, Satellite

I. INTRODUCTION

Micro-Electro-Mechanical System (MEMS) technology promises to improve performance of future spacecraft components while reducing mass, cost and manufacture time. In the past two decades, MEMS technology has significantly been advanced. The progress of MEMS offers potentials and opportunities for miniaturized space system, especially micro and nano satellites. By using this technology, also small countries can play a strong role in future space exploration and applications. On the other side, future applications of miniaturized space systems have demanding needs, which may call for MEMS components, thus further boosting the developments of MEMS technology.

This paper addresses the needs, status and perspectives of the MEMS technology for miniaturized space systems as seen by a spacecraft developer. Here, 'miniaturized space systems' denotes spacecraft with a mass of less than 100kg, i.e. micro-, nano-, pico-, and even femto-satellites. It is noted that this paper will not cover MEMS for other space systems, e.g. for large spacecraft or planetary missions. This paper intends to answer three (3) questions:

- What are the needs of developing MEMS components for miniaturized space systems?
- What is the state-of-the-art of MEMS components in miniaturized space systems?
- What are the perspectives of MEMS components for future miniaturized space systems?

The paper is organized in three main parts. First, past and expected future missions utilizing miniaturized space systems are discussed, followed by an analysis of mission needs on various aspects, such as performance, reliability, cost and unique functionality of MEMS components. Specific developments for sensors and actuators will be presented.

The domain of MEMS, encompasses the process-based technologies which are used to fabricate tiny integrated devices and/or systems that integrate functionalities from various physical domains into one devices. Such devices are fabricated using a wide range of technologies, having in common the ability to create structures with micro- and even nanometer accuracies. The critical physical dimensions of MEMS products can vary from a few micrometers to several millimeters. These devices or systems have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move. The term used to define MEMS varies in different parts of the world. In the USA they are predominantly called MEMS, while in some other parts of the world they are called 'Microsystems Technology' or 'Micro Machined Devices'. While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable elements are the micro sensors and micro actuators. Micro sensor and micro actuators are appropriately categorized as 'transducers', which are defined as devices that convert energy from one form to another. In the case of micro sensors, the device typically converts a measured mechanical signal into an electrical signal.

II. HOW MEMS WORK

The sensors gather information by measuring mechanical, thermal, biological, chemical, magnetic and optical signals from the environment.

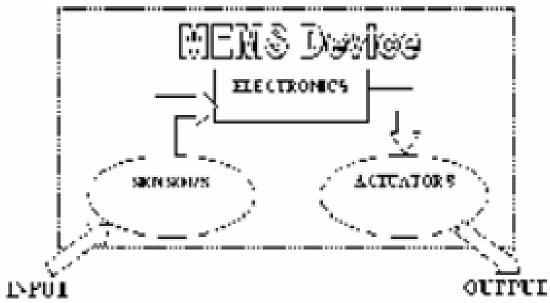

Fig. 1: MEMS Functional View

The microelectronic ICs act as the decision-making of the system, by processing the information given by the sensors. Finally, the actuators help the systems respond by moving, pumping, filtering or somehow controlling the surrounding environment to achieve its purpose.

A. Interdisciplinary Nature of MEMS

The interdisciplinary nature of MEMS relies on design, engineering and manufacturing expertise from a wide and diverse range of technical areas including integrated circuit fabrication technology, mechanical engineering, material science, electrical engineering, chemistry and chemical engineering, as well as fluid engineering, optics, instrumentation and packaging. The complexity of MEMS is also seen in the extensive range of markets and applications that incorporate such devices. MEMS can be found in systems ranging from consumer electronics, automotive, medical, communication to defense applications as well as satellites. Current examples of MEMS devices include accelerometers for airbag sensors, microphones, projection display chips, blood and tire pressure sensor, optical switches, and analytical components such as lab-on-chip, biosensors and many other products.

More recently, the MEMS research and development communities have demonstrated a number of micro actuators including: micro valves for control of gas and liquid flows, optical switches and mirrors to redirect or modulate light beams, independently controlled micro mirror arrays for displays, micro resonators for a number of different applications, micro pumps to develop positive fluid pressures, micro flaps to modulate airstreams on airfoils, as well as many others. Surprisingly, even though these micro actuators are extremely small, they frequently can cause effects at macro scale level; i.e. these tiny actuators can perform mechanical feats far larger than their size would imply.

B. Fabrication of MEMS Technology

MEMS, an acronym that originated in the USA, is also referred to as Micro System Technology (MST) in Europe and Micromachining in Japan. Regardless of terminology, the uniting factor of a MEMS device is in the way it is made. While the device electronics are fabricated using 'computer chip' IC technology, the micromechanical components are fabricated by sophisticated manipulations of silicon and other substrates using micromachining process. MEMS fabrication is an extremely exciting endeavor due to the customized nature of process technology and the diversity of processing capabilities. MEMS fabrication uses many of the same techniques that are used in the integrated circuit domain such as oxidation, diffusion, ion implantation etc. and combines these capabilities with highly specialized micromachining processes. Processes such as bulk and surface micromachining as well as high-aspect-ratio micromachining (HARM) selectively remove parts of the silicon or add structural layers to form the mechanical and electromechanical components. While integrated circuits are designed to exploit the electrical properties of silicon, MEMS takes advantage of other material properties like optical, mechanical etc. Within the wider field of MST we also see processes like micro molding, laser ablation etc. used to create Microsystems components.

III. OVERVIEW OF MISSIONS UTILIZING MINIATURIZED SPACE SYSTEMS

There are already more than 200 modern miniaturized space systems launched into orbit since 1980s. In addition to existing systems, a significant number of miniaturized space systems are under development worldwide and many missions are expected to be launched in the following ten years. Table 1 exhibits typical miniaturized space systems that utilize or will utilize MEMS components.

Mission name	Mission type	Developer	# of s/c	Mass [kg]	Miniaturized components	Launch year
MEMS Picosat[2]	Demonstration	DARPA	2	0.4	MEMS RF switch	2000
THNS-1[3]	Demonstration	Tsinghua University	1	25	MIMU, Miniature magnetometer, μ-propulsion	2004
ST-5[4]	Demonstration	NASA	3	25	Thermal louvers, μ-thruster, Miniature magnetometer, Miniature spinning sun sensor	2006
MEPSI[5]	Demonstration	DARPA	2	1.4 and 1.1	Miniaturized imager, MEMS gyros, μ-propulsion	2006
PRISMA[6]	Demonstration	Swedish Space Corporation	2	150 (Mango), 40 (Tango)	μ-Pressure sensors and MEMS μ-propulsion	2010
NEOMEx[7]	Demonstration	ESA	1	20	μ-propulsion, μ-sun sensor, modular μ-systems interface, etc.	2018
PAM[8]	Science	NASA	1000	1	Carbon nanotubules structure, etc.	2020-2025
OLFAR[9]	Science	Dutch institutes	50	10	Extensively using MEMS technology (μ-propulsion, MEMS star tracker, etc.)	TBD
APIES[10]	Science	ESA	19	45	Arcjet thruster	TBD

Table 1: Typical Miniaturized Space Systems utilizing MEMS

A. Needs for MEMS

The needs of miniaturized space systems on MEMS technology can be obtained by analyzing 'Table1'.

First, it can be found from 'Table1' that so far MEMS components have been used for technology demonstration only, although future science missions plan to extensively utilize MEMS components. This is due to the low technology readiness level (TRL) of space components. On the other side, although there is a strong demand on using mature Commercial-Off-the-Shelf (COTS) terrestrial MEMS products, e.g. accelerometer, in space, the suitability of these products in space environment is still doubtful. Therefore, it is necessary to extensively validate the reliability and performance of COTS MEMS components before using them in operational missions. Furthermore, space MEMS components developers must be aware of the difference between terrestrial and space environments, especially in relation to radiation and thermal aspects.

Second, there is an obvious trend that future operational missions will utilize a cluster of miniaturized spacecraft, which implies that cost will be a key driver. Mass production could possibly reduce the manufacturing cost of, e.g., the PAM mission. However, for most other missions, the number of spacecraft will not be very high and the benefit of mass production will not be significant. In this case, a dedicated development of a MEMS component for a mission might not be optimal. The need will be, in contrast, developing low-cost and modular MEMS components that can be utilized by a large range of space missions. Modifying terrestrial MEMS components for a better reliability and performance in space environment could be a promising solution here.

Third, the strongest demand on MEMS components is from the Attitude and Orbit Control System (AOCS). This is due to two reasons: [1] The AOCS is one of the bottlenecks of utilizing miniaturized space systems for operational mission. Future mission typically require high precision attitude control and orbit maintenance capability within very limited mass. Power and volume budgets, which cannot be realized by traditional technology [2] The AOCS is the most typical system in a spacecraft bus that combines mechanical system with electronics, where MEMS can play a very important role. Therefore high-precision, low-cost and modular AOCS MEMS components will still be the primary need of miniaturized spacecraft.

B. MEMS Sun Sensor

Different types of MEMS sun sensors have been developed in Europe. The left side of Fig 2 shows the 2-axis sun sensor originally developed for DTUsat-1. The sensor has the size of 7mm 8mm and can achieve the resolution on the order of 1degree in the 40 degree range and 2.5 degree – 5 degree from +40 degree - +70 degree and -40 degree to -70 degree. Another interesting development is the digital sun sensor on a chip (right side of Fig 2), which was developed by a consortium led by Selex Galileo. The imager sensor, processor, and interface electronics are placed on the same chip. This sensor and interface 'on a chip' results in low mass (60 grams), low powering consumption (0.21W) and small volume (30mm 30mm 25mm) with good performance (resolution 0.02 deg, field of view 128 deg).

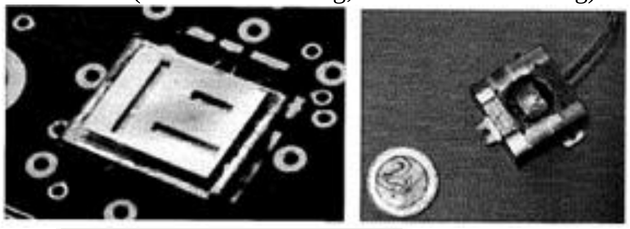

Fig. 2: The MEMS 2-axis Sun Sensor of DTU (left) & digital Sun Sensor on a chip of Selex Galileo (right)

C. Miniaturized Star Tracker

Under the ESA NEOMEx programme, a miniaturized star tracker is under development by Selex Galileo. The casing of the star tracker is shown in Fig 3. The star tracker also utilizes the 'System-on-chip' concept by placing imager sensor, processor and interface electronics on the same chip. It is expected that the star tracker could provide the accuracy of 15 arcsec with the mass of 175 grams,power consumption of 0.72W and the volume of 42mm 37mm 83mm.

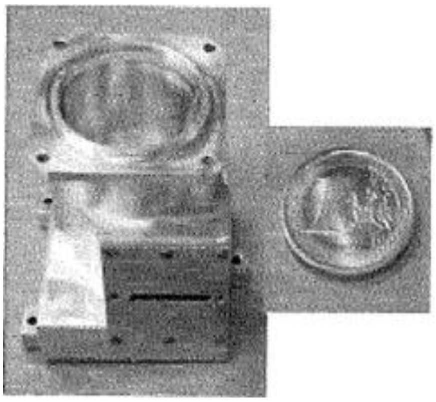

Fig. 3: The Miniaturized Star Tracker by Selex Galileo

D. MEMS Gyro

A space MEMS Gyro has been developed by a group of British companies led by Systems Engineering & Assessment Ltd (SEA). This MEMS Gyro uses a silicon ring which is with a number of plates on the silicon structures around its circumference that are capacitively coupled to the ring (drive and sense plates). The physical implementation of the silicon detector is shown in Fig 4, which clearly shows the silicon ring and the associated balance plates, as well as the external wires. The flight experiment unit (most right in Fig 4) has been flight on Cyrosat-2 and exhibited moderate performance (bias stability < 10 deg/hour).

Fig. 4: The silicon detector (left three) and the flight experiment unit (most right) of the MEMS Gyro by SEA

E. MEMS Earth Sensor

Engineers from EPFL are developing a MEMS-based Earth sensor that directly measures the gravity gradient vector instead of optical information to provide the attitude knowledge. As shown in Fig 5, the MEMS Earth sensor measures the gravity gradient vector by measuring the gravity gradient torque on a Si-pendulum. This approach eliminates the need for multiple external access ports, allowing a compact sensor to be situated anywhere inside the spacecraft. It is expected that this MEMS Earth sensor could achieve the accuracy of better than 5 degree.

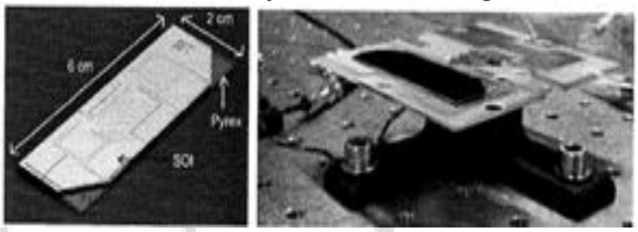

Fig. 5: The MEMS-based Earth sensor of EPFL

F. Micro-Propulsion

Micro-propulsion is the most active area of space MEMS developments in Europe. The first micro-propulsion system to be introduced here is a cold-gas one developed by NanoSpace and has been demonstrated on board the PRISMA mission in 2010. The system is capable of delivering accurate thrust ranging from tenths of micro-Newtons up to milli-Newtons. As shown in Fig 6, the system consists of three types of MEMS components: MEMS thruster module, MEMS pressure sensor and MEMS isolation valve. The key component is the golf-ball sized thruster module containing a silicon wafer stack with four complete rocket engines with integrated flow controlled valves, filters and heaters. Extremely small internal heaters inside the thrust chamber increase the performance of the system in terms of specific impulse. The propellant is Nitrogen. The four thrusters are orthogonally distributed in the equator plane of the golf-ball sized thruster module.

Fig. 6: The cold-gas micro-propulsion system of NanoSpace. (most left- System; second left- MEMS thruster module; second right- MEMS pressure sensor; most right- MEMS isolation valve)

Another micro-propulsion system is a plasma-arcjet micro-rocket (Fig 7) developed by Micro-Space in Italy. This system ignites plasma inside the micro-nozzle for low thrust range and microrocket for larger thrust range.

Propellant consumption is reduced by 10 times; therefore it is suitable for much longer nanosatellite missions.

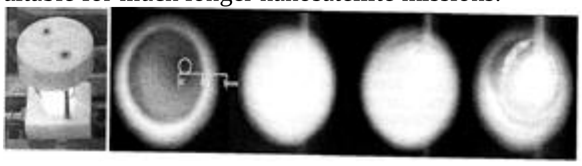

Fig. 7: Plasma-arcjet micro-rocket of Micro-Space

With the support of the European and ESA, a consortium led by EPFL is developing a micro Electric propulsion (EP) system. The concept for this micro EP system is a colloid thruster using electrostatic acceleration of charged species for propulsion. In addition, this EP system uses voltage-driven fluid handling with arrays of individually addressed MEMS capillary emitters with integrated extraction electrodes. This approach allows for a simple architecture, since no pumps are required; all fluid handling is done by capillary and electrostatic forces. Hence, the complexity of the complete propulsion system is radically reduced, leading to lighter, more compact, and reliable design, as shown in Fig 8. The baseline propellant is the ionic liquid, though other propellants are under investigation.

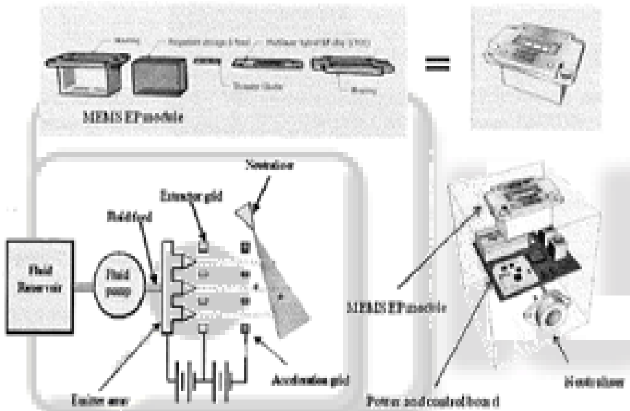

Fig 8: The micro EP system. (top- MEMS EP module; bottom left- The Principle; bottom right- The complete system)

IV. Perspective of MEMS in Space

From aforementioned existing or ongoing developments of space MEMS components, it is apparent that the MEMS technology allows developers to rescale traditional space systems down to the microsystem level and, therefore, provides tremendous opportunities for future missions utilizing miniaturized space systems. However, this downscaling is only a small part of the benefits that can be brought by MEMS technology.

The first perspective is the role of MEMS as an enabling technology for future miniaturized space systems. 'Enabling' means the MEMS technology will provide the presently unavailable capabilities that are vital for long-term missions. There are many unique physical phenomenon that only happen in the micro world. For example, the electrostatic force is not strong in the macro world but could act as the actuator in a MEMS switch. An array of fine pointing micromirrors or membrane mirrors can enable inter-satellite optical communication or optical observation with a nano-satellite or even a cubesat.

As the enhancement of the role as an enabling technology, it is expected by spacecraft developers that the MEMS components could provide multiple functionalities. For example, the nano-material could provide multifunctional substrate and coating that combines the functionalities of radiation shielding with Electrical-Magnetic (EM) transparent. The MEMS processing technology also allows the realization of photovoltaic solar cell in planner 'antenna' structures. These multi-functional capabilities could significantly reduce the required resources of the components to the miniaturized spacecraft.

The final perspective is a system integrated approach making use of space MEMS technology. Currently, space MEMS products are developed as standalone components to be integrated into miniaturized spacecraft. Typically, the interconnection and coherence between the MEMS components are not known at all. This may lead to an extensive test and therefore loose the benefits of utilizing MEMS technology. In order to solve this problem, the 'system-of-systems' approach shall be used. An expected output of the system-of-systems approach is the concepts of 'satellite-on-chip' or 'satellite-in-package', which integrate the functionalities of different spacecraft subsystems on a same chip or a same Printed Circuit Board (PCB). The involvement of space craft systems engineers in the development of space MEMS technology will be done of the best solutions here.

V. Conclusion

The reduction of mission costs requires substantial reduction in mass, volume and power consumption. At the same time, ever-more ambitious science objectives require miniaturization without loss of performance. MEMS enable this exploration of space by producing miniature science and engineering devices that are potentially integral with radiation-hardened electronics. Reliability, packaging and flight qualification of MEMS and their related systems are critical in fast insertion of these breakthrough EMS technologies into space applications. The international space and MEMS communities recognize this, and large efforts are being created to produce an exciting new era in space exploration.

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