MEMS Reliability Assessment Program – Progress to Date

J. L. Zunino III*, A. Coscia Jr*, D.R. Skelton*
U.S. Army RDE Command,
Picatinny, NJ 07806-5000
james.zunino@us.army.mil ; alfred.coscia@us.army.mil ; donald.skelton@us.army.mil

ABSTRACT

As the Army transforms into a more lethal, lighter and agile force, the technologies that support these systems must decrease in size while increasing in intelligence. Micro-electromechanical systems (MEMS) are one such technology that the Army and DOD will rely on heavily to achieve these objectives.

The MEMS devices within these systems will be required to last as long as the lifetime of the weapon systems in which they are embedded which may be decades. MEMS devices are also required to function properly after extended periods of inactivity while in storage. Even though the reliance on MEMS devices has been increasing, there have been limited studies performed to determine their reliability and failure mechanisms. Accordingly, the US Army Corrosion Office at Picatinny Arsenal, NJ manages the MEMS Reliability Assessment Program to address this issue.

The goals of the MEMS Reliability Assessment Program are to 1) Establish the reliability of MEMS devices including the impact of transportation, long term storage, operating environment, packaging & interconnection issues; 2) Analyze the compatibility of MEMS devices with energetic and other hazardous materials found in military items; 3) Identify failure mechanisms and failure rates; 4) Develop accelerated test protocols for assessing the reliability of MEMS; 5) Develop reliability models for these devices; 6) Identify a standardizing body, standard terminology, definitions, and categories for MEMS devices; 7) Determine potential test methodologies for assessing these mechanisms.

Current ongoing efforts in support of the program include: 1) an assessment of the Long-term storage performance and standards requirements, 2) initiation of ESS testing for the identification of failure mechanisms of selected devices, 3) drafting of a joint test protocol for assessment of the corrosion potential of MEMS devices, 4) assessment of applicability of reliability software packages for use with MEMs devices and 5) development of test guidelines and test capabilities for the assessment of MEMS reliability.

Recent accomplishments of the program include an assessment of the MEMS & NEMS technologies currently of interest to the Department of Defense, Test Guidelines for Environmental Stress Screening (ESS) of MEMS devices and components, Long-Term Storage Test Guidelines, Assessment of the Barriers to Implementation, and other tools and methodologies to facilitate the transition of MEMS & NEMS to the Department of Defense.

The MEMS assessment generated under this program will benefit the MEMS user community by filling the information gap that currently exists for reliability. With the rapid growth of the MEMS industry it is crucial to consider the reliability of this emerging technology and its applications in the early stages of its development

Keywords: MEMS, Reliability, Characterization, Testing, Military

1 INTRODUCTION

Recent conflicts abroad have brought numerous issues to the forefront. The need to rapidly respond and adapt to varying missions and operational environments is one such issue. The U.S. Army is transforming into a lighter and more lethal force to combat such issues. This transition by the Army necessitates secure, accurate, and timely transmission of information while being 70% lighter and 50% smaller than current systems [1]. Therefore, current and future technologies utilized in military systems must decrease in size and weight, while providing improved reliability, capability, and intelligence. In order to meet these requirements, scientists and engineers must capitalize on advanced technologies and novel materials including, Micro-electromechanical systems (MEMS). MEMS is an enabling technology that the Department of Defense (DOD) and the Army will rely on to meet these emerging requirements.

The U.S. Army Corrosion Office (ACO) defines MEMS as Micro-electromechanical systems that employ an ever-expanding set of micro-fabrication methods to create and integrate micro-machined sensors, actuators, mechanical elements, and microelectronics on a single substrate. The ability to manufacture small systems with increased functionality will lead to performance enhancement for both current systems and entirely new systems.

The DOD is investigating numerous applications for MEMS devices for both current and future military systems. Military systems that may utilize MEMS include: safety & arming devices, fuzing, guidance systems, sensors/detectors, reduced power consumption/micro power systems, inertial measurement units, tracking devices, radio frequency identification tags (RFIDs) and network systems, global positioning systems (GPSs), radar systems, mobile base systems, information technologies, satellites, and missiles [2,3]. By incorporating MEMS into weapon systems, new levels of speed, awareness, lethality, and information dissemination are possible. The system capabilities enhanced by MEMS will translate directly into tactical and strategic military advantages.

Although MEMS will be required to survive and function in harsh environments, the impacts of storage, transportation, and operating environments upon the long-term performance of MEMS are not well understood. Performance of tests in accordance with standardized test methods is essential to demonstrate the desired reliability of MEMS that are, or will be, used in critical military applications. These devices must often serve a number of functions within a particular system, and the functions can be degraded by continuous operation and storage in aggressive environments as well as extended periods of dormancy.

2 DISCUSSIONS

2.1 Background

All departments of the DOD to include U.S. Army, Navy, Air Force, NSA, OSD, DARPA, ONR, Homeland Security, NASA, Health and Human Services Department, National Sciences Foundation (NSF), and Department of Energy (DOE) are investigating the utilization of MEMS devices.

The DOD has identified several key benefits of MEMS utilization [4]. These include: cost savings, life savings, weight reduction, space reduction, miniaturization, reduce integration risk, combination/integration of components, increase Plug-and-Play capabilities, potential reduction of system risk, power reduction, and advanced capabilities

DOD is focusing on four primary areas: 1) Inertial Measurement, 2) Distributed Sensing, 3) Power Systems, and 4) Information Technology [4]. Although the majority of the DOD's MEMS efforts are focused on these areas, there are ongoing efforts in other areas such as Safety & Arming, Fuzing technologies, and Energetics.

These areas are facilitated through cooperation with commercial industries, while the emergence of secondary areas is rapidly increasing; there are little or no commercial expertise and/or partners to assist in this domain. With the Army's transformation the need for robust, safe and reliable MEMS devices is essential. Figures 1& 2 illustrate some key benefit to military MEMS implementation.

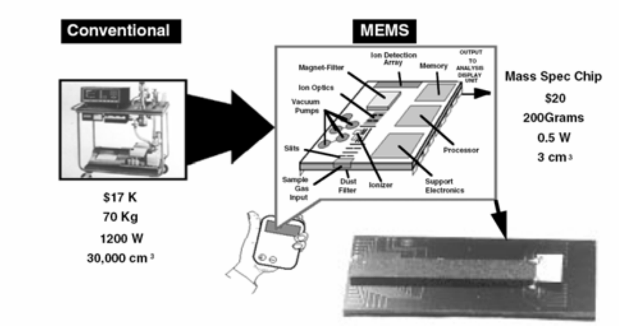

Figure 1. Mass Spec Analysis [5]

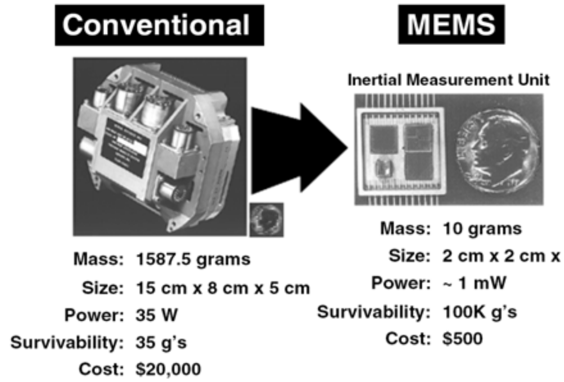

Figure 2. IMU [5]

The applications, operation, transportation, and storage conditions are vastly different between commercial and military MEMS. Most commercial devices are designed, fabricated, shipped, and used within a relatively short period of time, while MEMS functionality and performance in military systems often experience extended periods of inactivity and extreme transportation profiles. MEMS in military systems will be expected to endure extend storage, which may be greater than 20 years, in extreme environments. This poses a tremendous challenge with respect to corrosion, materiel migration, and device anomalies. Even the types of environments that military MEMS devices are expected to operate in are far more severe than commercial applications. Harsh environment aspects of a typical Army weapon system's mission profile could include any or all of the following [4]:

- Continuous operations in high humidity & moisture
- Continuous operations in areas of high wind
- Significant off-road driving
- Continuous operations in areas of high heat
- Continuous operations in sub-zero temperatures
- Extreme high & low pressured environments
- Continuous operations in sandy regions, where sand ingestion, infiltration, & contamination are commonplace
- Large variations and rapid changes in temperature due to diurnal cycles and deployment from aircraft
- Extreme G-forces due to airdrop delivery & gun launch

Transportation and shipping induces considerable shock and vibration to exposed devices. 70% of military vehicle mission profiles involve off-road conditions [6]. The environments that MEMS are and will be exposed to during deployment play a critical role in determining their reliability.

2.2 Department of Defense MEMS Utilization

There are several barriers slowing the implementation of MEMS into both military and commercial applications. Besides the physical demand on the devices themselves, there are other barriers to implementation. There is a lack of documented reliability data for MEMS and their related devices. This lack of knowledge can greatly affect the ability to "trust" MEMS as an enabling technology. While many companies and organizations are attempting to develop new devices, few are giving consideration to reliability or packaging. Furthermore, data on MEMS reliability from the commercial sector is nearly impossible to track, or is not readily accessible due to its propriety nature [2].

The lack of trust in MEMS as an enabling technology has left many end users reluctant to commitment to this technology. Most end users fear the limited history of reliability. The majority of manufacturers will not allow unpacked devices "out" until they are packaged, limiting the ability to collect valuable reliability data on fabrication and assembly. This has retarded the collection of failure mechanisms and failure rates for many devices as failure modes and effects can often be difficult or impossible to detect once packaged.

Many military users are unwilling to transition to MEMS because they are unsure about how MEMS technologies will respond to storage, transportation, and operational environments. Successful utilization of MEMS in military systems will be largely dependent upon their long-term performance within these systems. There are many aspects of MEMS performance in military applications that have yet to be explored.

Thus, for MEMS to be integrated into weapon systems by the DOD these barriers need to be addressed. The ACO is currently identifying devices for DOD applications, development of test protocols and testing capabilities, assessment of modeling packages and guidance for design, manufacture and packaging.

Military standards for assessing the functionality and survivability of systems and ammunition in potential operating and storage environments were developed to cover 99% of global operational environments [7]. Unfortunately, current operations are often performed in conditions out of this range. Military Test Standards do not exist for MEMS devices and most of the Mil Specs used currently were developed for ICs and micro-electronics. The fact that MEMS may contain moving parts and work in additional domains, (e.g. electrical, mechanical, chemical, fluidic and optical), may make these standards incomplete or inapplicable for testing of MEMS. In all, the environments that MEMS are and will be exposed to during deployment play a critical role in determining reliability of these devices. Long-term storage assessments should include compatibility of materials within and adjacent to the device, hermeticity of packaging, creep of materials, and stresses on interfaces caused by temperature, shock, or vibration.

Material compatibility may be the most critical issue regarding long-term storage. The MEMS industry is employing numerous new material combinations in emerging devices, with minimal data on their compatibility. The compatibility of materials directly impacts reliability.

Due to the vast differences in MEMS device types, DARPA and Sandia National Labs divide MEMS into four classes based on functionality. The ACO has added a fifth class which is unique to the military in that the device contains energetic materials.

- Class I, devices posses no moving parts. Common examples include RFID, flexible electronics, pressure sensors, thermal indicators, etc.
- Class II, devices have moving parts or components, but no contact surfaces. Common examples include gyros, accelerometers, resonators, etc.
- Class III, devices posses moving parts that may impact or contact surfaces. Common examples include relays, valves, pumps, and fluidics.
- Class IV, devices have moving and rubbing surfaces. Common devices include switches, scanners, and discriminators.
- Class V, unique to the military, includes devices that contain or are packaged with energetic materials. Common examples are IMUs, Safe and Arming (S&As) devices, and fuzing systems.

2.3 Current Efforts

The ACO and its team members have performed extensive literature searches, interviews, and data mining in an attempt to collect information about devices, reliability data, and test methods. These studies have lead to determining that most reliability data and tests methods currently being used are based on Micro-Electronics (MEs) and Integrated Circuits (ICs) tests and standards; whereas MEMS being utilized by the DOD and government agencies are far more complex than typical MEs & ICs. MEMS devices have unique properties, materials, applications, etc. They also work in domains beyond electrical, to include mechanical, optical and fluidics. Because of these facts, current IC and silicon chip standards and tests are often not applicable.

To address the lack of standards and common test methods, the ACO is developing test guidelines with the intent that they may become standards for the DOD and potentially for the MEMS industry. The first set of test guidance documents developed were Environmental Stress Screening (ESS) test plans for several Army MEMS devices including the ARDEC S&A and the Common Guidance IMU. Testing of the S&A was completed in accordance with these test plans.

Along with the guidelines, more specific Joint Test Protocols (JTPs) are under development. The ACO intends to develop these JTPs based on classes of MEMS devices as described above. Work to date indicates that failure modes are common among device class. The first, entitled "Reliability Testing Guidelines for Unpackaged Class V Microelectromechanical Systems." This JTP predominantly focuses on the corrosion of MEMS. Once approved, these documents will form the basis of assessing corrosion potential of MEMS for the DOD.

A MEMS Test Hierarchy was developed by the Army Corrosion Office to define potential issues that may occur during the life-cycle of MEMS from "cradle to grave." Several major issues were identified and this lead to the

NSTI-Nanotech 2007, www.nsti.org, ISBN 1420061844 Vol. 3, 2007

creation of a generic cause and effect diagram. There are six major areas were potential failures can occur, during the design phase, materials selections, assembly of components, packaging of the device, the environmental impacts, and system integration failures. The ability to identity and control these failures is a critical barrier that must be overcome for successful MEMS implementation.

In conjunction with the identification and development of test methods for the assessment of reliability, the ACO is developing the capability for conducting these tests and the subsequent failure analysis. To date, several DOD and non-DOD facilities have been identified as potential test facilities. The ACO is also developing and expanding in-house test capabilities for MEMS with the hopes that agreed upon tests and standards can be utilized and officially approved.

An assessment of reliability modeling and simulation software is underway. Several reliability software packages, including PRISM, CALCE and Coventor software, are being evaluated under the program. Since the PRISM software models system reliability from a component level, it will still be necessary to obtain parts lists for the MEMS devices of interest in order to model them using this software.

As more information is obtained, further reports and papers will be published to disseminate information that will help further the design, development, and testing of MEMS devices.

Several testing initiatives are ongoing. The ACO directed NASA/JPL to assess the effects on extreme temperatures and temperature cycling on MEMS sensors encapsulated on Kapton E. The sensors were individual inspected and optical photographed. The sensors were thermally cycled from -55^{0}C to 100^{0}C at 10^{0}C/minute temperature ramp. Relative humidity was recorded and ranged from 5% at 100^{0}C to 45% at -55^{0}C. The sensors are currently under going pressure/strain testing to determine if the thermal cycling affected the flexure and functionality of the devices. Other on going testing includes ESS testing of the ARDEC S&A device, as well an IMU for the Common Guidance Program. By running ESS tests to induce and detect failures, failure analysis can be performed and the information can be fed back for future test plan development, assessment of applicability, and design and packaging criteria recommendations.

The ACO has tasked Sandia National labs to conduct baseline characterization, focused on material properties, tribological characteristics, and fatigue lifetime assessment, leading to a Long Term Storage/Accelerated Aging study on Silicon on Insulator (SOI) diagnostic structures. Worcester Polytechnic Institute is currently testing/modeling the impacts of packaging on reliability and the impacts of long-term storage.

3 CONCLUSIONS

The DOD is currently investigating enabling technologies, to meet emerging threats, enhance weapon systems performance, reduce life cycles costs and improve system reliability. Because of the benefits associated with miniaturization, MEMS, is one such technology the DOD may rely on to meet their current and future objectives. Before the military begins employing MEMS into weapon systems, MEMS must be highly reliable in extreme environments, and furthermore the reliability must be demonstrable. The ACO at Picatinny Arsenal has initiated the MEMS Reliability Assessment Program to be proactive in meeting these objectives. As detailed above, the ACO is continuing to identify the devices, operational conditions, and applications of MEMS in military systems. The development of test protocols and testing of representative devices continues. Work towards the adoption of standards has begun. The information gained from these activities, and the data gained from failure analyses will aid in the transition of MEMS technologies from the labs to the field where it is needed.

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