Assessment of the Impacts of Packaging, Long-Term Storage, and Transportation on the Military MEMS

J. Zunino III* and D.R. Skelton*
*U.S. Army RDE Command, AMSRD-AAE-MEE-M
Bldg 60 Picatinny Arsenal, NJ, james.zunino@us.army.mil, donald.skelton@us.army.mil

ABSTRACT

The Army is transforming into a more lethal, lighter and agile force. Enabling technologies that support this transition 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 accomplish these objectives. Conditions for utilization of MEMS by the military are unique. Operational and storage environments for the military are significantly different than those found in the commercial sector. Issues unique to the military include: high G-forces during gun launch, extreme temperature and humidity ranges, extended periods of inactivity (20 years plus) and interaction with explosives and propellants. The military operational environments in which MEMS will be stored or required to function are extreme and far surpass any commercial operating conditions. The impact of these environments on the functionality of MEMS has not been assessed. Furthermore, a standardized methodology for conducting these analyses does not exist.

To facilitate the insertion of MEMS technologies in weapon systems, U.S. Army ARDEC is addressing the information gaps delineated above. This will benefit the MEMS user community by providing data on failure modes induced by packaging, transportation and storage for selected devices. These data will then be used to develop a standardized methodology for conducting these assessments. Specific activities of the program include:

- Assessment of the operational environments in which the military MEMS device may be utilized
- Determining & developing methods to preserve MEMS devices during long-term storage before they are designed into products
- Independent assessment of reliability that cannot be obtained from private industry
- Establishment of reliability data that will be fed back into development & design to improve MEMS devices

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 impacts in the early stages of development.

Keywords: MEMS, Reliability, Quality, Failure Modes, Storage

1 INTRODUCTION

Recent conflicts in the Global War on Terror (GWOT) have demonstrated a need for a lighter, more agile and more lethal force. Therefore, the technologies that support these systems must decrease in size while increasing in intelligence. Micro-electromechanical systems (MEMS) are an enabling technology that will allow the Army and Department of Defense (DoD) to meet these objectives.

The conditions military MEMS must operate in are unique. Operational and storage environments for the military are significantly different than those found in the commercial sector. Issues impacting the utilization of MEMS by the DoD include; high G-forces and spin associated with gun launch, extreme temperature and humidity ranges, extended periods of inactivity (20 years plus), interaction with explosives and propellants and stringent requirements for safety and reliability. The military operational environments in which MEMS will be stored or required to function are extreme and in general greatly surpass any commercial operating conditions.

The Army needs to rapidly respond and adapt to varying missions and operational environments. This requires the Army to transform into a lighter yet more lethal "objective force," that must be deployable, 70% lighter and 50% smaller than current systems while maintaining equivalent lethality and survivability[1]. Accordingly, the technologies embedded in military vehicles and weapon systems must be decreased in size and weight while providing improved reliability, capability, and intelligence. To meet these requirements, Army scientists and engineers need to capitalize on new technologies and breakthroughs in emerging technologies such as MEMS.

2 MILITARY UTILIZATION

The transition the Army is facing has led to increased interest the utilization of MEMS. The rapid increase in potential MEMS applications have resulted in a greater need for an accurate assessment of quality, reliability, and survivability. The Army is not alone in facing these challenges. The U.S. DoD (U.S. Army, Navy, Air Force, NSA, OSD, DARPA, ONR, Homeland Defense, etc.), NASA, Homeland Security, Health and Human Services Department, National Sciences Foundation (NSF), and Department of Energy (DoE) are implementing MEMS based technologies. With increased utilization, come increased requirements, qualifications, and safety considerations.

Besides being implemented as an enabling technology for new systems, MEMS technology is also being investigated for replacement of obsolete or unprocurable electronics, switches, sensors, storage devices, mechanical systems, and other components in current weapon systems.

2.1 MEMS for the Department of Defense

MEMS technologies involve complex, systematic fabrication approaches utilizing advantages of wafer-based lithography for the miniaturization of multi-component systems and microelectronics to create these advanced devices. MEMS technology enables the manufacture of small systems with increased functionality that will lead to performance enhancement for both current systems and entirely new systems.

The DoD has identified several key benefits of MEMS utilization [2]. 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
- Advanced Capabilities

The DoD is focusing on four primary areas of interest for MEMS utilization: 1) Inertial Measurement, 2) Distributed Sensing, 3) Power Systems, and 4) Information Technology [3]. While the majority of the DoD's MEMS efforts are focused on these areas, although there are ongoing efforts in other areas such as Safety & Arming, Fuzing technologies, and Energetics. Some examples of advanced MEMS technology applications in DoD Systems include [2]:

- Acoustic Microsensors
- Velocimeters
- Magnetometers
- Micromechanical-Based Spectrometers
- Low Power Wireless Integrated Microsensors
- Surveillance Systems
- Multifunctional Electro-optical Sensors
- MEMS Infrared Remote Micro Sensors
- Magnetic Resonance Imaging Systems (MRI)
- MEMS Un-cooled Infrared (IR) Imaging Arrays
- Gyroscopes
- Embedded Sensor Systems
- Remote Weapon Systems
- Unmanned Vehicles (Land, Air, Space, Sea, etc.)
- Battle Space Awareness
- S&A Devices
- BITs (Built In Test)

The four primary areas are facilitated through cooperation with commercial industries, while the emergence of the secondary area is rapidly increasing. Unfortunately, commercial expertise to assist in MEMS fuzing and energetics is very limited.

2.2 Storage, Transportation, & Operational Environments

There are vast differences between military and commercial operating and storage environments. Commercial MEMS devices are usually designed, fabricated, shipped, and used within a relatively short period of time. Conversely, the DoD expects MEMS systems to function and survive through extended periods of inactivity, which may be greater than 20 years, and potentially extreme transportation profiles. Corrosion, materiel migration, device anomalies, and other potential failure mechanisms, may directly result from the conditions military devices are exposed to. Operational environments for military MEMS are far more severe than those encountered in the commercial sector. Mission profiles for Army weapon systems often include operation in harsh environments. These operating profiles may 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

Another issue related to the extreme environments is that Military Standards currently used 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 [5]. Unfortunately the conditions in the Middle East are often out of this range. The operational, transportation, and storage environments to which military MEMS may be exposed play a critical role in determining reliability of those devices. An assessment of the environment in Iraq [6] recorded temperatures as high as 115F^o–125F^o with 1.0 kW/m^2 of insolation. Average daytime temperatures ranged from 95F^o–105F^o. Large diurnal cycles occur in the summer because of the inability of the dry air to retain heat. Besides the temperature variations, missions in the Middle East have brought another environment condition to the forefront: sand. Sand exposure and intrusion is a significant issue with all military equipment that is deployed in current operations.

As previously stated, long-term storage is expected to be a major factor affecting the reliability of MEMS devices. Long-term storage assessments must include material compatibility. This assessment should include the materials within and adjacent to the device, hermeticity of packaging, creep of materials, and stresses on interfaces caused by temperature, shock, vibration, and other variables.

Material compatibility may be the most critical issue with regard to long-term storage. The MEMS industry is employing numerous new material combinations in emerging devices, with minimal data on their compatibility. Materials such as metallics, polymers, composites, ceramics, and numerous fluidics are all being incorporated into MEMS devices. With reliability directly affected by material compatibility, understanding all the potential interactions and problems is critical. Material interfaces and their affects are currently under investigation.

Because of the vastly different types of devices, DARPA & Sandia National Labs divide MEMS into four classes based on functionality. ARDEC has added a fifth class which is unique to the military in that the device contains energetic materials. Descriptions of each are detailed below [7]:

Class I - These devices posses no moving parts. Some common examples include RFID, flexible electronics, pressure sensors, thermal indicators, etc.

Class II - Devices have moving parts or components, but no contact surfaces: Gyros, accelerometers, resonators, etc.

Class III - Devices with moving parts that possess impacting or contact surfaces and often include relays, valves, pumps, and fluidics.

Class IV- Devices have moving and rubbing surfaces. Common Class devices types include switches, scanners, and discriminators.

Class V - Unique to the military. Devices contain or are packaged with energetic materials. Some examples are IMUs, Safe and Arming (S&As) devices, fuzing, etc.

In all, the environments that MEMS will be exposed to during deployment play a critical role in determining reliability of these devices.

2.3 Barriers to Implementation

Besides the physical demands, there are other barriers to implementation military MEMS must overcome. Another barrier impeding both military and commercial adoption of MEMS is the lack of documented reliability data for MEMS. This lack of data has adversely affected the "trust" in MEMS as an enabling technology. Furthermore, recent MEMS research has primarily focused on development of new devices, but little consideration is paid to reliability, interfaces or packaging. Vast array of devices types have been developed with little knowledge or consideration of the failure mechanisms, quality, reliability, or safety of these devices. Of the limited data that does exist from the commercial sector, it is nearly impossible to track, or is not readily accessible due to its propriety nature [8]. Also most MEMS manufacturers will not allow unpacked devices "out" until they are packaged, limiting the ability to collect valuable reliability data on fabrication and assembly process employed. As a result, failure mechanisms and failure rates for many devices are not well characterized.

The lack of trust in MEMS as an enabling technology has left many end users reticent to adopt this technology. System developers and program managers are unwilling to utilize MEMS since they are unwilling to assume the potential risks of an "unknown technology". 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. The unknown responses of MEMS to their storage, transportation, and operational environments must be determined if MEMS are to be widely implemented into DoD systems.

2.4 MEMS Reliability Assessment Program

These barriers must be addressed for successful integration of MEMS into weapon systems. In response to this need, researchers at ARDEC's Materials, Manufacturing, and Prototyping Technology Division have a comprehensive program to reduce and eliminate these barriers.

As part of the team's efforts, Dr. Ivars Gutmanis, of Hobe Corporation, has written a report entitled, "*MEMS*

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Standards, Tests, and Applications in U.S. Department of Defense Activities," which provided a snapshot of the current state of MEMS.

Several members preformed a Lean Six Sigma Project, "*MEMS and NEMS Assessment Using Six Sigma,*" to develop risk mitigation tools to facilitate the transition to and implementation of MEMS for the U.S. Army. Some results included [9]:

- MEMS materials of construction selection hierarchy
- Assessment of the impact of corrosion/material degradation on failure mechanisms
- Physics of failure for MEMS devices
- Environmental Stress Screening (ESS) for ARDEC devices
- Test Guidelines
- Barrier to Implementation Matrix
- Cause and Effect
- Assessment and Summary of Current MEMS practices
- Preliminary identification of DoD MEMS utilization
- Benefits of MEMS Utilization

To address the lack of standards and common test methods, test guidelines have been developed with the intent that they become standards for the DoD, and potentially 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.

Along with the guidelines, more specific Joint Test Protocols (JTPs) are under development. The intent is to develop JTPs based on MEMS device classes as described previously. Work to date indicates that failure modes are common among device class. Once approved, these documents will form the basis of assessing reliability of potential MEMS for the DoD.

3 CONCLUSIONS

Due to the benefits associated with miniaturization, MEMS, is an enabling technology the DoD plans to utilize to meet their current and future objectives. The DoD continues investigating MEMS and related technologies to react to emerging threats, enhance weapon systems performance, reduce life cycles costs, and improve system reliability. Before the military begins to employ MEMS into weapon systems, MEMS must be highly reliable in extreme environments, and furthermore the reliability must be demonstrated. To be integrated into weapon systems, reliability of MEMS devices must be demonstrated. The current relative inexperience using the emerging MEMS technologies in military applications is a barrier to its implementation. Members of ARDEC and their partners are providing tools to assess and improve the reliability of military MEMS. Through the MEMS Reliability Assessment Program and other programs the US Army is being proactive in meeting these objectives. As detailed above, ARDEC 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 identification or 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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