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MICRO-ELECTOR-MECHANICAL SYSTEMS: A CATALYST FOR ARMY TRANSFORMATION

BY

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MICRO-ELECTOR-MECHANICAL SYSTEMS: A CATALYST FOR ARMY TRANSFORMATION

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ABSTRACT

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If global force projection through rapid deployability is the Army Transformation vision, then Micro-electro Mechanical Systems (MEMS) are one of the key technological building blocks for the Objective Force. Size and weight are the fundamental characteristics that must be satisfied to create rapidly deploying forces. Versatility, transportability, and small sustainability footprints are the hallmarks of this next generation of platforms. Deployability is the key, deployability of the force, and deployability of its sustainment. MEMS technology will make this possible from two different perspectives. First, it is an enabling technology for the production of miniaturized components. Second, MEMS will be used in the component systems of the Future Combat Systems of the Objective Force. This Strategic Research Project is a survey of the potential applications where MEMS can contribute to size, weight and sustainment reductions, supporting the achievement of the Army Transformation vision.

TABLE OF CONTENTS

ABSTRACT iii
LIST OF ILLUSTRATIONS vii
LIST OF TABLES ix
MICRO-ELECTRO-MECHANICAL SYSTEMS: A CATALYST 1
FOR ARMY TRANSFORMATION 1
ARMY TRANSFORMATION 2
THE FUTURE COMBAT SYSTEM (FCS) 4
THE FUTURE COMBAT SYSTEM (FCS) TIMELINE 6
COMMERCIAL APPLICATIONS OF MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) 7
DEFENSE APPLICATIONS OF MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) 8
DEFINITION OF MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) 9
MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) CONTRIBUTIONS TO FCS 10
MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) AS OFFENSIVE SENSORS 11
MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) AS HUNTERS 12
WEARABLE DISPLAYS 13
NAVIGATIONAL AIDES 14
CONDITION-BASED MAINTENANCE (CBM) 15
POWER ENHANCEMENTS 16
SURVIVABILITY APPLICATIONS 16
LETHALITY - COMPETENT MUNITIONS 17
LETHALITY – UNEXPLODED ORDNANCE (UXO) AND FUZE RELIABILITY 18
CONCLUSION 20
ENDNOTES 23
BIBLIOGRAPHY 25

LIST OF ILLUSTRATIONS

FIGURE 1. ARMY TRANSFORMATION 2
FIGURE 2. FCS MISSION NEEDS STATEMENT 6
FIGURE 3. A THREE PHASE MAGNETIC MOTOR 10
FIGURE 4. A THREE-AXIS ACCELEROMETER 10
FIGURE 5. MICRO-AIR VEHICLE 12
FIGURE 6. FIRE ANT ENGAGING TANK 12
FIGURE 7. FIRE ANT BEFORE AND AFTER 12
FIGURE 8. WEARABLE DISPLAYS 13
FIGURE 9. INERTIAL MEASUREMENT UNITS 14
FIGURE 10. MUNITIONS COMPARISON 17
FIGURE 11. ADXL50 FUZE SAFE-ARM DEVICE 20

LIST OF TABLES

TABLE 1. MEMS MARKET AND INDUSTRY 8
TABLE 2. DOD TECHNICAL ASSEEMENT FOR MEMS APPLICATIONS 9
TABLE 3. MUNITIONS HIT PROBABILITY COMPARISON 18
TABLE 4. UNEXPLODED ORDNANCE OF SUBMUNITIONS 19

MICRO-ELECTRO-MECHANICAL SYSTEMS: A CATALYST FOR ARMY TRANSFORMATION

How long did you avoid using an Automatic Teller Machine (ATM), a Personal Computer (PC), the Internet, email or Instant Messages (IMs)? Most of these items have been available for 30 years or more. In many ways, our reluctance to accept and use new technology is reflected in the way big institutions, like the Army, initiate change. We are slow at first, but once we see the new technology gaining acceptance around us we jump in and give it a chance. The Army is on the brink of taking this same path again.

There are those who say we are trying to do too much, too fast and that we cannot make such a drastic leap forward. Like adventurers before us, starting on a journey across the ocean, some have dropped anchor before leaving the bay never intending to continue on their journey. Yet, there are those who are on board with the sails set and a strong wind behind them. They see before them a clear course, the Army Transformation spearheaded by the Chief of Staff of the Army (CSA), General Eric K. Shinseki. Announced on 12 October 1999, it is a clear, concise transition model for the next 30 years. It incorporates a revolutionary development and fielding schedule for state of the art next generation of platforms. At the same time, it recapitalizes our legacy systems and inserts a medium weight force to bridge the gap between our light and heavy force capabilities.

Global force projection through rapid deployability is the Army Transformation vision. Versatility, transportability, and small sustainability footprints are the hallmarks of this next generation of platforms. Deployability is the key, deployability of the force, and deployability of its sustainment. New technologies and new concepts for employing these new technologies will be the only way to do this. Micro-Electro-Mechanical Systems (MEMS) technology is the catalyst for achieving supportable battlefield deployability in our next generation of platforms.

MEMS operate just like a full-scale piece of equipment. They can be complete systems that are small enough to fit on a postage stamp, sensors capable of detecting temperature changes, or inertial measurement units capable of sustaining up to one hundred thousand gravitational (g) forces. They are reliable, cost effective and rugged. Many such devices are commercially available and the numbers of applications they support are taking off. They are the future and they are available now.

So how do these new technologies fit into Army Transformation? To determine that, we need to understand the vision, the next generation of platforms the Army is developing to support the vision and the catalyst of Micro-Electro-Mechanical Systems (MEMS). The insertion of MEMS into defense systems reduces the size, weight, and sustainment needs of the current generation of platforms resulting in a more deployable force.

ARMY TRANSFORMATION

To explain Army Transformation General Shinseki developed the chart below, which is simple yet flexible and comprehensive. He created a vision that set the course, leaving the details for us to fill in along the way.

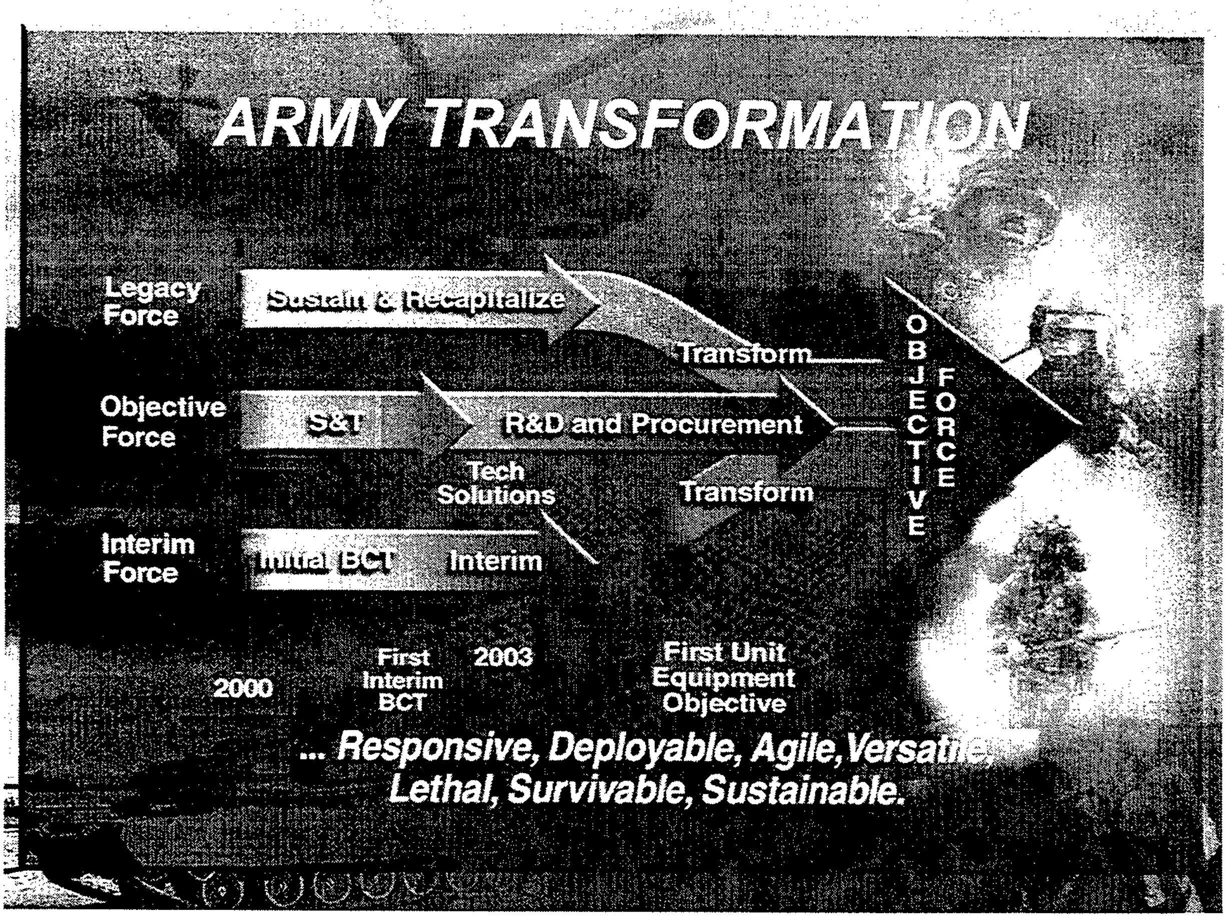

FIGURE 1. ARMY TRANSFORMATION

The first arrow surging forward is the Legacy Force consisting of the combat systems in today's inventory. Legacy force equipment requires Recapitalization to extend its combat effectiveness out to the year 2032, well beyond it programmed life cycle. The bottom arrow represents the Interim Force composed of the Interim Armored Vehicle (IAV). This vehicle has a short duration procurement and production cycle creating a quick turn around vehicle composed of components available today. This is not a high technology platform, but rather a medium force to test concepts for the development of the next generation of platforms. The IAV, scheduled to enter the inventory within the next 2 years has an expected lifecycle through the year 2032. Phased replacement of the IAV by the main thrust of Army Transformation, the Objective Force depicted by the center arrow, begins in 2010. This is the focus of discussion throughout the remainder of this paper. The combat enabler for the Objective Force (OF) is the Future Combat System (FCS), the next generation platform envisioned to replace the majority of the vehicle platforms in the current inventory. One of the details that we will "fill in along the way" is the specific of how many and what types of FCVs are required.

Army Transformation must take on some risks, taking advantage of technological advances to thrust our Army into the future. We may not know what the future holds, but we have enough information to make the first step. As President George W. Bush said in Norfolk, Virginia on 13 February 2001:

> "We do not know the exact shape of our future military, but we know the direction we must begin to travel. On land, our heavy forces will be lighter. Our light forces will be more lethal. All will be easier to deploy and to sustain."[1] Further on in his speech, President Bush said, "We will modernize some existing weapons and equipment," (the legacy force) "a task we have neglected for too long. Our goal is to move beyond marginal improvements to harness new technologies that will support a new strategy"[2] (the objective force).

President Bush's comments complement the CSA's vision for Army Transformation. The parentheses inserted above show the application to the Army Transformation vision. The following excerpts from the Chiefs 12 October 1999 Army Transformation announcement at the Association of the United States Army convention will further illuminate the Army's Transformation vision:

> "100 years ago, another secretary and another chief of the Army stood in the 99th year of their century and tried to divine (D-I-V-I-N-E) and define (D-E-F-I-N-E) what their future might hold and what their Army needed to be ready to do. What did they know? What could they have envisioned? Well, they certainly knew the condition of their Army. It was an Army that had ended a war of near-global proportions just the year before, and it was an Army stretched thin by its post-conflict peacekeeping and peace enforcement responsibilities. ... So what do we know about the world we will face in the next century? Can we be any more clairvoyant about the next 100 years ... ?
>
> Our superb heavy divisions remain unequalled in their ability to gain and hold ground in the most intense, horrifying direct fire battles we could imagine. But these same divisions are challenged to get to other contingencies where we have not laid the deployment groundwork as well. And once deployed, it takes significant effort and cost to sustain them.
>
> Our magnificacent light forces - - the toughest light infantry in the world - - can strike lightening fast but lack the staying power, lethality, and tactical mobility once inserted. In general our logistical footprints for deployed forces are uacceptably large .... .

To adjust the condition of the Army to better meet the requirements of the next century, we articulate this vision: 'Soldiers on point for the Nation transforming this, the most respected Army in the world, into a strategically responsive force that is dominant across the full spectrum of operations.' With that overarching goal to frame us, the Army will undergo a major transformation to accomplish the following:[3]"

General Shinseki goes on to summarize how we will enable our forces to be more Responsive, Deployable, Agile, Versatile, Lethal, Survivable and Sustainable. These are the seven tenants of the Army Transformation vision for the next generation of platforms. The key characteristic to this vision is deployability. If our Army cannot get to the battlefield, it does not matter what it can do. Moreover, if the logistics footprint needed to sustain it is too resource intensive then we have failed again. Today's weapon systems are too heavy to deploy rapidly or too light, lacking the staying power and lethality to be effective and they are both too resource intensive to sustain. As a whole, we are too dependent on petroleum products, ammunition and rations. All of which is heavy and bulky. We need systems that are lighter and easier to support translating into less dependency on a large volume of assets to deploy the force to the theater and then to sustain it.

Deployability hinges on two essential characteristics: weight and cubic volume. Precision guided munitions and a fuel-efficient hybrid engine alone are not enough to make this happen. Neither do they contribute all that is necessary to balance the seven tenants of the Army Transformation vision. Micro-Electro-Mechanical Systems technology, on the other hand, is the catalyst that will get our next generation of platforms to the battlefield with less sustainment needs while also contributing greatly to the seven tenets of the Army Transformation vision.

THE FUTURE COMBAT SYSTEM (FCS)

The objective size for the FCS is less than 20 tons and 300-400 cubic feet internal volume. About 9 tons, less than 45% of its overall weight, will be dedicated to structure and protection. The M1 Abrams Main Battle Tank, weighing approximately 70 tons, has an internal volume of about 650 cubic feet. Its structure and protection weighs 36 tons, which is about 51% of its entire weight. The FCS will be up to 70% lighter and 50% smaller than the current main battle tank.[4]

Therefore, the initial challenge is the reduction in the overall vehicle weight associated with its structure and protection. Since the FCS is a "System of Systems", the second set of targets for weight reduction are the vehicle's interior and externally mounted sub-systems. As with the size and weight changes we expect for the FCS, it is apparent that as an item decreases in size and volume, it proportionately decreases in weight. This is where experts see MEMS playing and integral part. What is incredible about these miniature devices is that they can do so much and use such a small footprint. They require a fraction of the power that a full size item needs. These two primary characteristics will benefit the size and weight reduction requirements of the FCS. If necessary, this benefit may allow a tradeoff to additional weight requirements to insure sufficient armor protection is available.

Over time, we have seen this same change occur in many devices we use every day; computers, radios, TVs and on go the examples. Usually, the limiting factors with getting these devices smaller is the ability to insure their reliability, ruggedness and manufacturing costs while also reducing the power source and power requirements for these smaller items. MEMS are contributing greatly in this area as well.

Expected benefits from MEMS with respect to the FCS are high. FCS at this point is a concept using a system of systems network and structure with an open architecture. The FCS will have four major functions: infantry carrier, direct fire, indirect fire and sensor. However, the FCS "will be a multi-functional, multi-mission reconfigurable system of systems to maximize joint inter-operability, strategic transportability and commonality of mission roles including direct and indirect fire, air defense, reconnaissance, troop transport, counter mobility, non-lethal and C2 on the move."[5] This system will strive for information dominance through the next generation of digital systems. It will also integrate a host of sensors to detect threat capabilities with the ability to activate lethal and non-lethal means to neutralize or destroy these targets.[6] An example of these expected achievements will be enhanced fire control systems that will increase the system accuracy by 30% at 3 km under stationary conditions and an overwhelming 500% increase while moving.[7]

In comparison to the Abrams fleet, the FCS equipped force requires 50% less logistical support.[8] The primary reductions occur in fuel and ammunition consumption. Increased weapons accuracy and ammunition lethality reduces the amount of ammunition required to reduce a target. Technologically speaking, the expectation is that while the lethality of ammunition increases, its size and weight will decrease. The same can be postulated for the power generation systems. As the engines that drive these systems and generate power for support equipment become more efficient and capable, their size and weight will diminish along with their fuel consumption. Accomplishing this will greatly contribute to the reductions in volume, weight and sustainability requirements necessary for a truly deployable FCS equipped Objective Force.

In summary, the CSA's vision is for the Objective Force to be more Responsive, Deployable, Agile, Versatile, Lethal, Survivable and Sustainable. FCS units must be a reflection of the seven tenets of this vision articulated in the Mission Needs Statement (MNS) shown in Figure 2.[9] The MNS details the broad characteristic that the material developers must achieve while the Operational Requirements Document (ORD) provides the details of the FCS system requirements.

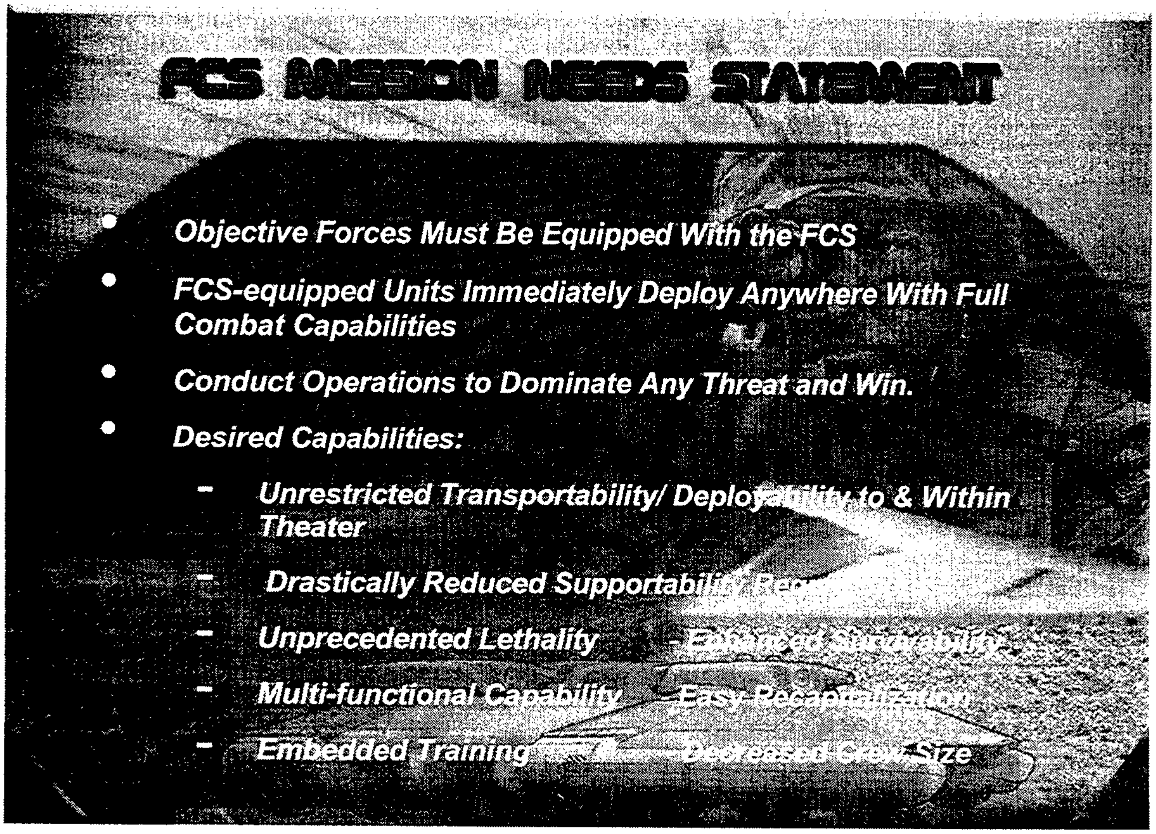

FIGURE 2. FCS MISSION NEEDS STATEMENT

THE FUTURE COMBAT SYSTEM (FCS) TIMELINE

In FY 2010, the Army will field the first fully equipped brigade sized element of the Objective Force. The base vehicle of the Objective Force is the Future Combat System (FCS). The FCS is the next generation platform that will provide four primary functions to the Objective Force. It will have various configurations that will provide indirect fire, direct fire, infantry carrier and sensor capabilities.[10] The specifics about this vehicle are unknown. Many questions are still open, and this system of systems is in the science and technology definition phase, which is designated Concept Exploration. The Army is still formulating what this vehicle will be within the realm of the possible. Even so, the next phase is critical to the success of the follow on phases.

The next phase will start in FY2003 with a decision of what technology and concepts are ready for design and demonstration, this is the Program Definition / Risk Reduction phase. If we do not select the right technologies at the proper level of maturity, then the time it takes to get this vehicle into production will far exceed the goal. This program definition phase will proceed for the next couple of years until FY2006, which will start the Engineering and Manufacturing Development (EMD) phase. At this point, we build an entire vehicle system to further define critical design characteristics and assess production feasibility. This will transition at some point to a Low Rate Initial Production (LRIP) and then lead to full rate production in FY2008 with the first fielding in FY2010.[11]

This background information illustrates the extremely short period in which a phenomenal amount of effort must occur. Therefore, the technologies needed must be mature enough to go into production with a level of confidence that will insure success. MEMS are at that point. Kurt Peterson, an IBM researcher, wrote a seminal paper giving MEMS their start in 1980.[12] Others before him devoted research to these tiny machines. Since then, a significant investment of research in this technology is leading industry to the point of commercial production in mass quantities. This is especially true in the wireless communications and computer networking arenas.

COMMERCIAL APPLICATIONS OF MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS)

The current investment that industry is making in MEMS will benefit many defense programs with a relatively low cost basis for our limited production needs. Table 1 illustrates where the MEMS market is and how industry is moving to get their share of these areas.[13] It displays the general technical area for these devices and the expected area of application. The far right columns display information on current market and an estimate of future market sales. The center column displays the contractors and any current or previous contracting efforts with the U.S. Government.

MEMS Market and Industry

Technology Area	Typical Devices/ Applications	Companies	Market Baseline ($Millions)	Market 2003 (Est.) ($Millions)
Inertial Measurement	Accelerometers, Rate Sensors, Vibration Sensors	TI, Sarcos, Boeing, ADI, EG&G IC Sensors, AMMI, Motorola, Delco, Breed, Systron Donner, Honeywell, Allied Signals	$350-$540	$700-$1400
Microfluidics and Chemical Testing/ Processing	Gene Chip, Lab on Chip, Chemical Sensors, Flow Controllers, Micronozzles, Microvalves	Battelle, Sarnoff, Microcosm, ISSYS, Berkeley MicroInstruments, Redwood, TiNi Alloy, Affymetrix, EG&G IC Sensors, Motorola, Hewlett Packard, TI, Xerox, Canon, Epson	$400-$550	$3000-$4450
Optical MEMS (MOEMS)	Displays, Optical Switches, Adaptive Optics	Tanner, SDL, GE, Sarnoff, Northrop-Grumman, Westinghouse, Interscience, SRI, CoreTek, Lucent, Iridigm, Silicon Light Machines, TI, MEMS Optical, Honeywell	$25-$40	$450-$950
Pressure Measurement	Pressure Sensors for Automotive, Medical, and Industrial Applications	Goodyear, Delco, Motorola, Ford, EG&G IC Sensors, Lucas NovaSensor, Siemens, TI	$390-$760	$1100-$2150
RF Technology	RF switches, Filters, Capacitors, Inductors, Antennas, Phase Shifters, Scanned Apertures	Rockwell, Hughes, ADI, Raytheon, TI, Aether	(Essentially $0 as of 1998)	$40-$120
Other	Actuators, Microrelays, Humidity Sensors, Data Storage, Strain Sensors, Microsatellite Components	Boeing, Exponent, HP, Sarcos, Xerox, Aerospace, SRI, Hughes, AMMI, Lucas Novasensor, Sarnoff, ADI, EG&G IC Sensors, CP Clare, Siemens, ISSYS, Honeywell, Northrop Grumman, IBM, Kionix, TRW	$510-$1050	$1230-$2470

■ Companies currently under contract. ■ Companies with past contracts.

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TABLE 1. MEMS MARKET AND INDUSTRY

DEFENSE APPLICATIONS OF MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS)

Table 2 "summarizes the present level of MEMS funding, insertion activities and technology maturity of the twelve major, identified MEMS defense applications."[14] There are three categories of MEMS Applications. Between table 1 (above) and table 2 (below) developed by the DOD, there exists an intersection of these technology categories and application areas. This confirms the connection between the commercial and defense related research in these areas. This will benefit the FCS through the maturity of technology and its availability for mass production.

	MEMS Application	Current DoD Technology Funding	Current DoD Insertion Activities	Technical Maturity
Inertial Measurement Applications	Weapon Safing, Arming & Fuzing	◒	◒	◒
	Competent Munitions	◒	○	●
	Platform Stabilization	○	○	◒
	Personal/Vehicle Navigation	○	○	○
Distributed Sensing and Control Applications	Condition-Based Maintenance	○	○	●
	Situational Awareness	◒	○	◒
	Miniature Analytical Instruments	○	○	○
	Identify-Friend-or-Foe	—	—	○
	Biomedical Devices	◒	◒	◒
	Active Structures	○	—	○
Information Technology Applications	Mass Data Storage	○	—	○
	Displays	●	◒	◒

Key

- ● strong
- ◒ modest
- ○ weak
- — none

MEMS technical funding and insertion status summary chart. DoD applications are broadly categorized in the areas of inertial measurement, distributed sensing and control, and information technology.

TABLE 2. DOD TECHNICAL ASSEEMENT FOR MEMS APPLICATIONS

Examining the far right column of table 2 indicates that seven of the twelve major categories of application have a strong or modest level of technical maturity. These areas may be ready for immediate or near term insertion into the FCS and its components. Later in this paper, some examples of current applications in these areas are presented.

DEFINITION OF MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS)

Until recently, familiarity with MEMS was less than notable. Recent breakthroughs in the wireless communications and computer networking industry are revealing the power of these tiny devices. However, earlier, less complex applications of MEMS started showing up in "impact sensors that trigger airbags in cars and devices that direct ink onto paper in ink-jet printers."[15] In their basic form, MEMS are "silicon structures that act as sensors to detect heat, cold, speed, etc."[16] Others describe MEMS as "the realization of complete systems-on-a-chip.

This system would include: sensors, microprocessor, data acquisition, radio transceiver and batteries all on one component about the size of a postage stamp."[17]

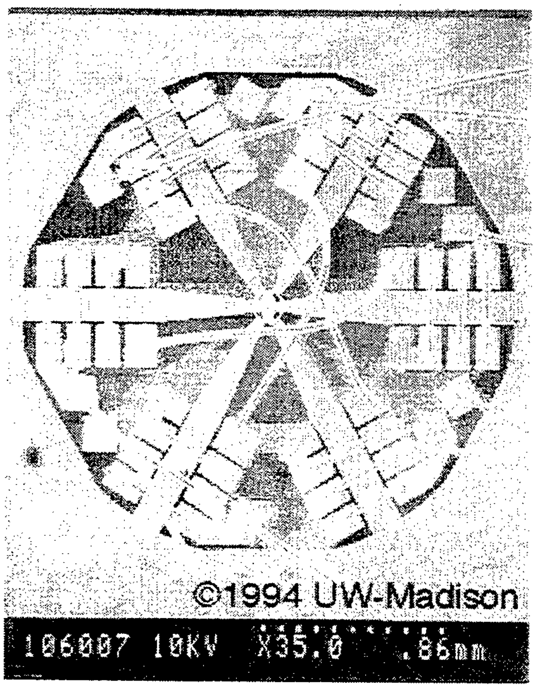


FIGURE 3. A THREE PHASE MAGNETIC MOTOR

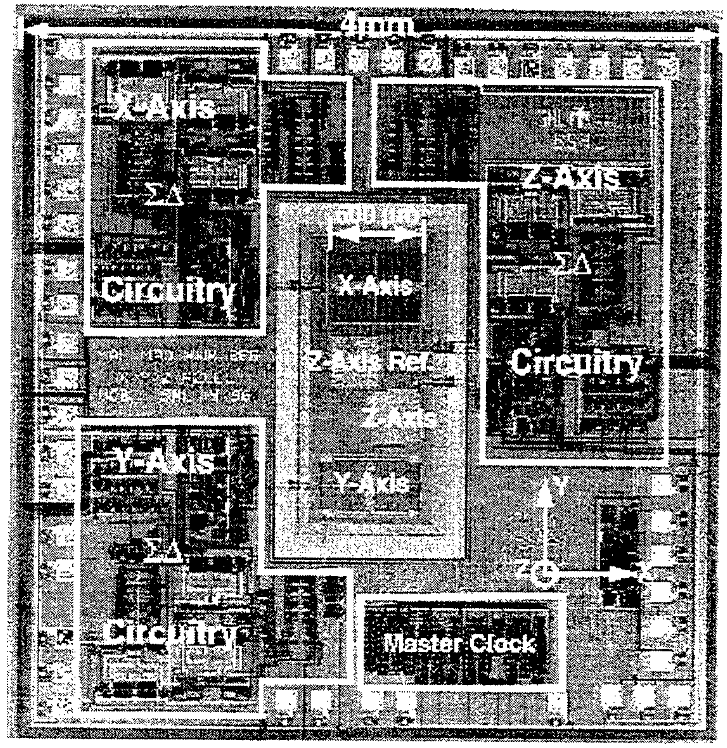


FIGURE 4. A THREE-AXIS ACCELEROMETER

Figures 3 and 4 are examples of what MEMS looks like. Figure 3, is a three phase magnetic motor constructed from Permalloy. The rotational machine shown illustrates a fully integrated micro motor.[18] It is only .86 millimeters (mm) wide, which is about the size of 4 periods, like the one at the end of this sentence, stacked in a square.

Figure 4, is a three-axis accelerometer, sometimes referred to as a system-on-a-chip. "This system-on-a-chip is a realization of a full three-axis inertial measurement unit that does not require manual assembly and alignment of sense axes."[19] This device is approximately 4 mm square, which is about half the diameter of a number 2 pencil eraser. To put these sizes in perspective, it is helpful to know that one inch is 25.4 mm in length.

MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) CONTRIBUTIONS TO FCS

Micro-Electro-Mechanical Systems technology is the catalyst that will get FCS to the battlefield and contribute greatly to the seven tenets of the Army Transformation vision. MEMS will be the key enabler that makes the FCS deployable while insuring it is survivable, lethal and sustainable. The FCS mission needs statement makes a good backdrop to examine how MEMS will contributions to the success of the FCS. The first of these capabilities is unrestricted transportability / deployability to and within theater. The smaller footprint for size and internal volume discussed earlier in the paper accomplishes this.

Because of the size and weight reduction associated with MEMS, this will be an immediate gain. MEMS will reduce the size and weight of the vehicular equipment. In the communications area, an example is the SINGARS radio. It currently weighs 15.4 pounds, not including the radio mount and wiring harness, which is estimated to be another 15 pounds. It takes up 363.8 cubic inches of space for the radio alone. Estimates project that MEMS enabled radios weighing less than a pound and approximately 32 cubic inches in size could replace SINGARS radios.

The MEMS enabled radio system will also reduce vehicle weight because the FCS is a system of systems. With lighter, smaller communications equipment, more systems can be equipped with communications links. This will provide the ability to distribute capabilities among platforms of various sizes to maintain the aggregate requirements of the force. This ability to distribute capabilities also increases survivability of the force. If a system is knocked out, then only a portion of the system is degraded until it can be replaced by establishing a link with another system possessing the lost capability.

MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) AS OFFENSIVE SENSORS

Small, unmanned ground and air vehicles will allow the distribution of sensors. These sensors may be visual, acoustic or magnetic. Miniature radios provide the ability to network communications between sensors and the FCS. Distribution of the sensors is done either within the FCS force unit vehicles or on a designated FCS sensor carrier. By distributing these sensors, we distribute the associated weight. Using the same logic, we can distribute weapon systems, like unmanned shooters, in the same way as unmanned sensors. An employment option that contributes to the lethality and survivability of the FCS is to create unmanned hunter-killer teams and deploy them in front of the FCS unit.

When it comes to unmanned vehicles in support of the FCS, they operate in two mediums; air and ground based systems. These devices are relatively small and break the paradigm of what we expect to encounter on the battlefield. In the air, Micro Air Vehicles (MAV) are small, low cost vehicles with limited use. Currently, they have a short loiter time, but can fly virtually undetected over the enemy. At six inches in length or less, at an altitude of 300 meters they are transparent to the world below. Figure 5 is an example of the MAV, unmanned sensor.

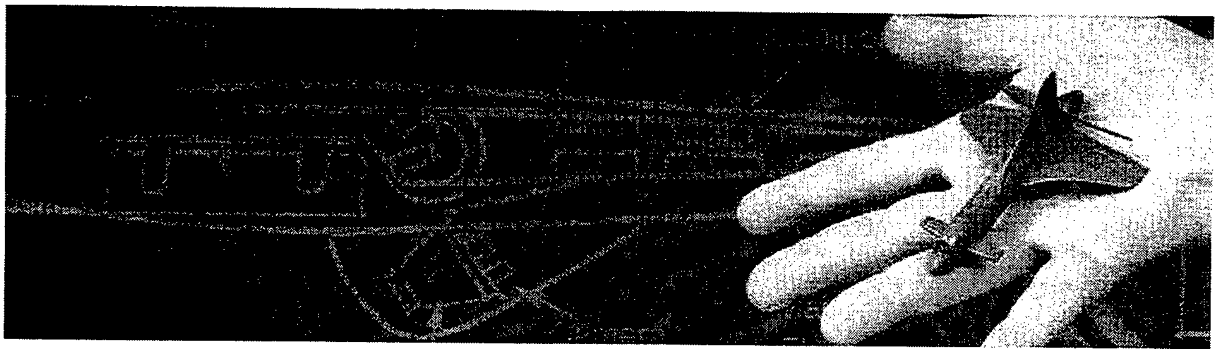


FIGURE 5. MICRO-AIR VEHICLE[20]

MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS) AS HUNTERS

The unmanned ground vehicles are much larger, but vary greatly in their size and designed use. Figure 6, is an example of an unmanned ground vehicle designed to kill tanks. The Fire Ant is a teleoperated vehicle that has video tracking software. This software package detects moving vehicles and engages the target with an Explosively Formed Projectile (EFP). Because the Fire Ant was designed as a single use weapon, it is destroyed when the EFP is fired, figure 7. The Fire Ant is a less sophisticated unmanned vehicle, however it illustrates some capabilities in the hunter-killer direction of the future.[21]

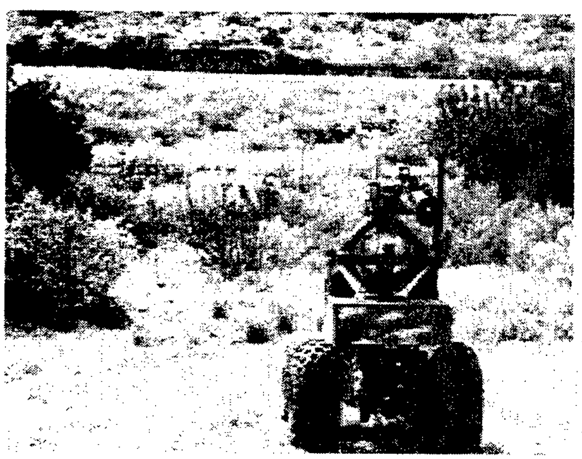


FIGURE 6. FIRE ANT ENGAGING TANK

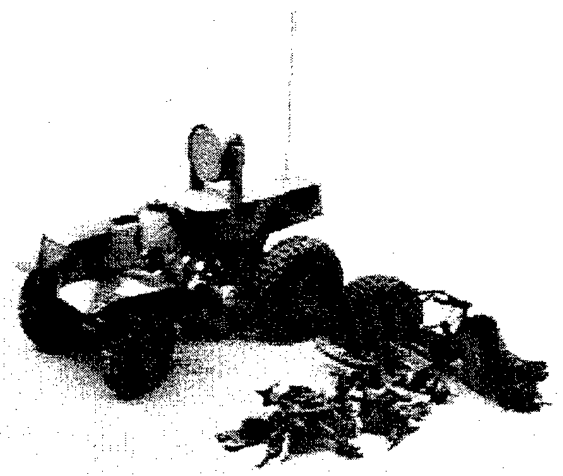


FIGURE 7. FIRE ANT BEFORE AND AFTER FIRING EXPLOSIVE FORMED PROJECTILE (EFP)

Realizing the potential of unmanned ground and air vehicles is important to the FCS concept and its sustainability. These sensors can replace humans on the battlefield and they are expendable. Several sensors can be carried for the same weight and cubic displacement of one soldier. Granted, one soldier has more intelligence and combat capability, but several sensors can cover and detect more area than a single soldier in rugged or dense terrain. If our sensors can be deployed in front of the force, we can engage the enemy further out in front of the force exposing the force to less hostile activity.

One manned vehicle may be able to control several unmanned vehicles employed as hunters or killers. This stand off capability provides enormous survivability gains to the force. These unmanned vehicles range anywhere in size from under a hundred pounds to three tons, having varying capabilities, sensor suites and attack capabilities. At the high end of weight for unmanned systems, one manned FCS at 20 tons could be replaced by six unmanned vehicles and numerous aerial vehicles. The unmanned vehicles may only need to be resupplied with fuel. However, if they contain MEMS generators augmented by solar power, they will consume a greatly reduced amount of fuel. In making these manned to unmanned vehicle tradeoffs, we avoid the need for rations, water and vast amounts of fuel.

WEARABLE DISPLAYS

MEMS make it possible to eliminate the need for difficult to produce, military unique video display terminals. Each operator has a set of glasses that provides a heads up display of all needed information. The computer industry is working on these wearable displays now for wearable computers. If there is a commercial application for this type of technology, then there will be an option to incorporate this technology advancement into a military application with a lowered initial and overall investment. Figure 8 is a set of eyeglasses with a head mounted display developed by the MicroOptical Corporation under contract to DARPA.

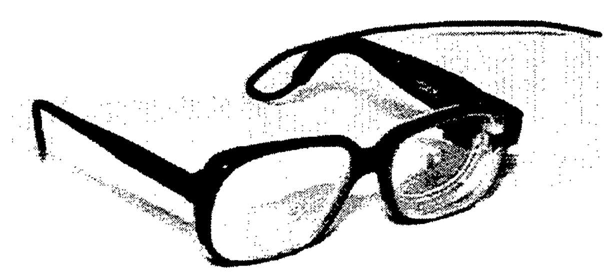


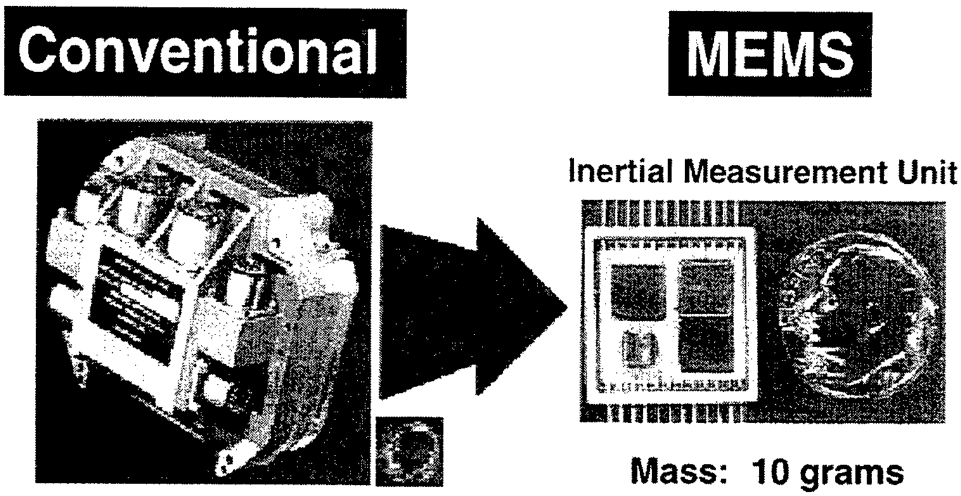
FIGURE 8. WEARABLE DISPLAYS

Wearable Displays may not add greatly to the weight and volume savings, but it is another example of the shrinking footprint that our systems will achieve. The current flat panel displays are approximately 320 cubic inches in volume and weigh approximately 15 pounds.

The wearable displays are insignificant in cubic volume and weight. The benefit is that every soldier in the vehicle can wear a set and have the same view as the vehicle commander.

NAVIGATIONAL AIDES

Another contributing factor to weight control is in the area of accelerometers and gyroscopes. MEMS can do the same thing at a major reduction in weight, power consumption and cost.[22] Notice the comparisons in Figure 9, especially for the size in relationship to a dime. On the conventional side, the dime is under the large black arrow.



Conventional

Mass: 1587.5 grams
Size: 15 cm x 8 cm x 5 cm
Power: 35 W
Survivability: 35 g's
Cost: $20,000

MEMS

Mass: 10 grams
Size: 2 cm x 2 cm x 0.5 cm
Power: ~ 1 mW
Survivability: 100K g's
Cost: $500

FIGURE 9. INERTIAL MEASUREMENT UNITS

A MEMS device can replace almost any item in the inventory with an accelerometer or gyro. This includes, but isn't restricted to "aircraft, missiles, tanks, and ships. MEMS gyros could be implemented in avionics, autopilots, gun mounts and stabilizers (tank turret), shipboard and radial tracking antennas, and ejection seat stabilization. For example, each UH-60 Black Hawk helicopter contains 13 gyroscopes. All are potential MEMS insertions."[23]

Pairing these gyros and accelerometers or inertial measurement units (IMU) with Global Positioning Devices will provide a smaller, lighter GPS than currently available. This connection of GPS with a MEMS IMU would lighten the individual soldier load and allow for operations free of jamming or disruptions caused by urban obstacles. Once the GPS position is established, the IMU will continue to update the soldier's position location until the next GPS update occurs.[24]

The potential for weight savings is excellent and because of this, these IMUs will be available on more items. They can contribute to greater accuracy of weapons effects, target location and soldier orientation. As seen in the figure 9, above, there is a approximately a 99 percent savings in weight and size and more than a 97% savings in cost and power consumption and it is substantially more durable.

CONDITION-BASED MAINTENANCE (CBM)

MEMS sensors on the FCS will take on many other roles. The first example will be on the equipment itself. MEMS sensors will provide advanced warning of failures and replacement needs and other information about the mechanical readiness of various pieces of equipment on the vehicle. This is termed Condition-Based Maintenance (CBM).[25] MEMS devices inside of the equipment will monitor critical performance characteristics such as "temperatures, pressures, flow rates, vibrations, surface wear rates, fluid contaminants and accelerations."[26]

The CBM method of maintenance has the potential to save time, money and reduce sustainment weight and needs on the battlefield. The saving of time and money comes from not replacing parts solely on a timed maintenance schedule based on miles and hours. By detecting a failure earlier than anticipated by a scheduled maintenance system, it has the effect of an early warning system. Catching the repair on inexpensive items first, may reduce the need to repair parts that are more expensive later. By basing our sustainment package on actual usage data, rather than scheduled replacement data, we may need to carry fewer repair parts into the battlefield. There even exists the possibility that no parts may need to be carried, because the advanced warning of the failure allows sufficient time to request the part from higher echelons outside the area of operations.

The following is an example of the benefits of a condition based maintenance program from a study on the H-46 helicopter.

> "A focused study was performed to determine the benefit of using CBM on the maintenance-intensive H-46 helicopter used by the Navy and the Marine Corps. The study considered a number of factors such as the number of aircraft (328), annual flying hours (300 each), maintenance costs ($2400 per flight hour), and major accident rates.

The study determined that the annual H-46 cost for maintenance, aircraft losses, and fatalities was $276 million. The study concluded that if an aggressive CBM program were used on this helicopter, the result would be a 50% reduction in downtime, providing improved operational availability. The H-46 would also realize $60 million savings in maintenance costs, and a 30% reduction in accidents resulting in fatalities."[27]

POWER ENHANCEMENTS

An Army Research Lab estimate of the usefulness of MEMS sensors reported their ability to withstand high temperature and measure air and fuel flows in combustion engines will provide a two fold benefit. The first is in the power generation unit for the vehicle, MEMS sensors will improve fuel efficiency by insuring precise fuel air mixtures during operations. The second is by recording the results of how current engines operate; engines that are more efficient engines can be developed for use in the future.[28]

The use of separate MEMS power generation units will provide power to auxiliary equipment. It is estimated that MEMS micro turbine generators could provide extremely high power to weight ratios in the order of 100 watts per gram.[29] These units provide a significant reduction in fuel consumption powering mission related equipment without producing a noise signature. Since these devices are so small, they will generate a relatively insignificant heat / infrared signature as well.

Compare the MEMS power generator to a traditional 5 KW generator that weighs over fifty pounds. At estimates of 100 watts per gram, an equivalent MEMS power generator would only weigh 50 grams. Although this technology is not proven capable to that magnitude, it illustrates the significant difference in weight savings that is possible. Also reflected in this is a drastic reduction in fuel consumption and cost.

SURVIVABILITY APPLICATIONS

MEMS will also be an important piece of the vehicle survivability package. These MEMS act as vehicle attack detection sensors. They can detect engagement by enemy laser rangefinders and other targeting devices. There will be another set of sensors that can detect incoming munitions and activate countermeasures to neutralize or defeat them. Another set of sensors will detect and analyze biological and chemical hazards. The possibilities for these types of applications are enormous.

LETHALITY - COMPETENT MUNITIONS

Lethality has two dimensions with respect to munitions. The first is munitions accuracy and the second is unexploded ordnance. Inserting inertial measurement devices to reduce the dispersion pattern of the projectiles when attacking point targets can increase munitions effectiveness for dumb munitions, like artillery projectiles. Artillery is an area fire weapons as opposed to a point fire weapon. It achieves this area coverage through the natural dispersion of the rounds due to circular error probable. However, with the simple addition of MEMS, these area fire weapons can become more accurate when engaging point targets. Nevertheless, they will not be precise enough to be considered a point fire weapon or precision guided munitions.

Range 30km, Target Size 20m x 30m

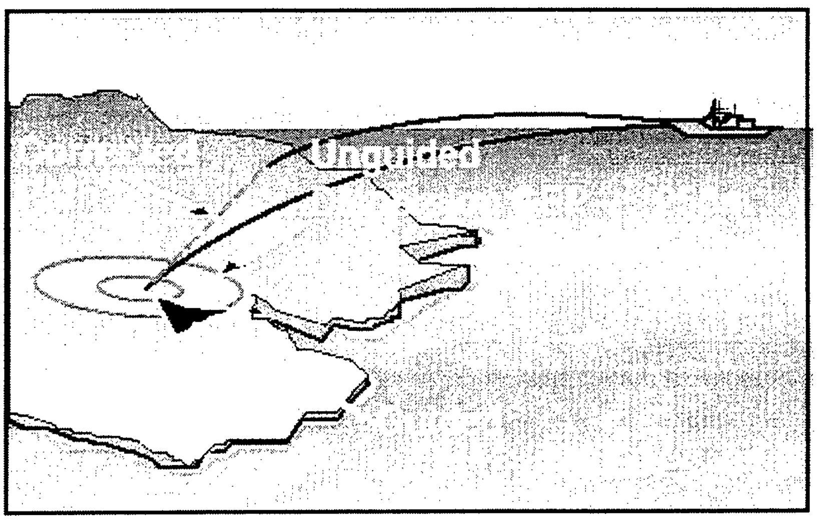


FIGURE 10. MUNITIONS COMPARISON

Figure 10 illustrates the potential increase in precision by adding MEMS guidance to unguided projectiles. The unguided munition has a Circular Error Probable (CEP) of 250 meters. When a guidance system is added, the CEP improves to 64 meters.[30] Further analysis indicates that 110 rounds must be fired in order for the unguided projectile to achieve a 50% hit probability. To increase the probability of hit with fewer rounds, add a guidance package, which decreases the CEP, and then only nine rounds need to be fired to achieve a 50% hit probability. If the required probability of hit increases to 90%, then for the unguided projectile, the required number of rounds moves to 364 and the guided requirement reduces to 30 rounds.[31]

Number of rounds after spotting correction

Munition Type	Hit Probability	
	50%	90%
Unguided Rounds	110	364
Inertially Guided Rounds	9	30

10X REDUCTION IN REQUIRED ORDNANCE

TABLE 3. MUNITIONS HIT PROBABILITY COMPARISON

Table 3 reflects the "high dynamic range accelerometer MEMS technology insertion. Inertially guided round improves accuracy and is estimated to reduce required ordnance by a factor of 10."[32] Such improvements, if achieved, provide not only a significant improvement to weapon system lethality, but also a tremendous reduction for ammunition resupply needs. Enhanced precision and lethality contributes to the "drastically reduced supportability requirements" of the MNS.

The measurable reduction of ammunition required for attacking targets can significantly reduce the replenishment requirements of the FCS force. Artillery projectiles range in weight from 33 pounds for 105 millimeter to almost 100 pounds for 155 millimeter systems. In the example above, the weight savings for the projectiles (not counting powder) for a 155 weapon system is over 5 tons for a 50% probability of hit requirement and over 16 tons for a 90% probability of hit requirement. Multiply these factors by the number of tubes firing and the potential impact to the logistics tail is measurably impressive.

LETHALITY – UNEXPLODED ORDNANCE (UXO) AND FUZE RELIABILITY

The second dimension to munitions effectiveness is the reduction or elimination of unexploded ordnance. According to recent information developed from Operation Desert Storm and Bosnia, unexploded ordnance continues to be a problem. On this matter, two factors appear. The first is that unexploded or dud ammunition has little effect on the target. The second factor is the adverse affect on future military operations or civilian populations in the area. Unexploded ordnance is a hazard to both groups.[33]

Air-Delivered Submunitions

	Total Expended Munitions	Calculated Number of Duds (Based on a 5% Dud Rate)
Subtotal	16,976,215	848,810
Artillery-Delivered Submunitions		
	Total Expended Munitions	**Calculated Number of Duds (Based on a 5% Dud Rate)**
Subtotal	13,773,328	688,666
GRAND TOTAL	30,749,543	1,537,476

TABLE 4. UNEXPLODED ORDNANCE OF SUBMUNITIONS

Unexploded Ordnance (UXO) requires reattack of the target and the expenditure of more ammunition. The information in Table 4, from the Office of Munitions, Secretary of Defense, is an estimate of the unexploded submunitions based on the types and numbers of rounds expended during Desert Storm. These numbers come from the maximum allowable dud rate acceptance per lot of 5%.[34] It is estimated that MEMS fuze safe-arm mechanisms are on a magnitude of five to ten times more reliable, perform better and have a greater service life than current technology.[35] At an estimated 10% replacement rate per year, DoD safing, arming and fuzing requirements would represent a 3 million unit/year MEMS safing, arming and fuzing market."[36]

Fuze reliability is a key factor affecting submunition dud rates. Figure 11 is an example of the more reliable MEMS fuze safe-arm device. The noticeable increase in dependability of this device will have three benefits. First, a better fuze will reduce the dud rate decreasing the number of rounds fired to defeat targets. Second, a reduced dud rate decreases UXO, which in turn reduces the hazards associated with UXO to civilians and follow-on forces operating in the area. Finally, firing fewer rounds reduces the logistical tail.

Looking at the potential impact of a better fuze on the logistics tail reveals additional volume and weight savings. Carrying forward the 5 percent factor for dud rates yields a five round savings per one hundred rounds fired. By inserting MEMS enabled fuzes, you should obtain almost a 100 percent yield. For a 155-millimeter weapon system, that is a potential savings of 500 pounds for every 100 rounds fired.

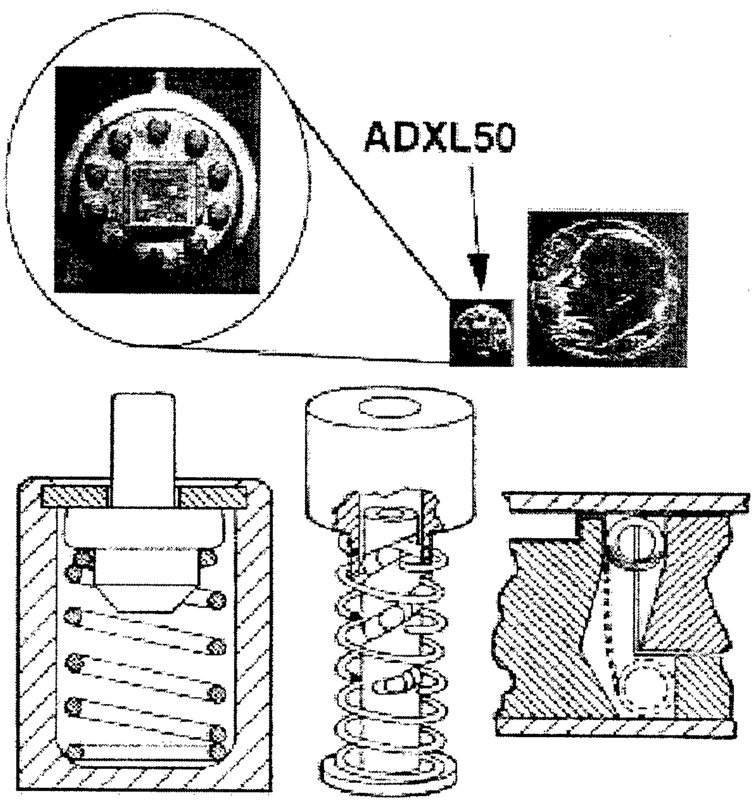


FIGURE 11. ADXL50 FUZE SAFE-ARM DEVICE

CONCLUSION

Many advocates consider MEMS as the technology of the future. A true "disruptive," "change-the-world[37] type of technology that may result in "a wholesale overhaul" of how we view the relationship between size and capability.[38] The possibilities that MEMS represent to the future of our defense forces are sizable. The application of technology on the battlefield is one of the strengths of the US Armed Forces. To continue this trend and our ability to meet and defeat any adversary, we must persist by infusing promising technology into our combat systems. MEMS have enormous potential benefit to many applications that support the deployability, survivability, lethality and sustainability of the Army's next generation platform - the Future Combat System.

Taking into account the overall impact of MEMS on the Future Combat System and its sustainment profile, the Army expects reductions in cost, weight and cubic volume. Examples of these savings include the next generation of radio systems, graphic visual displays, navigation aides, power generation units and sensors. Other savings will occur through Condition-Based Maintenance systems by implementing MEMS for early warning of component failure or replacement. Unmanned Aerial and Ground Vehicles will provide early detection and engagement of the enemy. This translates into less human battle casualties and equipment losses. Enhancing the accuracy and reducing the dud rate of our munitions will reduce the overall ammunition consumption requirements for indirect fire systems. These last two areas will significantly reduce the logistics tail for the Objective Force. The prospective benefits for reducing not only the size and weight of the FCS, but the overall support requirements of the Objective Force are vast.

If we are to achieve the Army Transformation vision by 2010, then we must continue to invest in MEMS. Industry is already heading in that direction. They are taking advantage of these miniature machines to reap the benefits that they provide while attempting to gain an edge in their highly competitive markets. In the same way, we must apply this burgeoning technology to insure we maintain the lead over our competitors around the world. These devices will be one of the key enablers to our future force.

If we expect the Army to be a strategic instrument of our national power, then we must create a force that is lighter, more lethal, more deployable and less dependent on its logistics tail. Therefore, the first characteristic we need to exploit in the Army Transformation vision is deployability. A smaller, lighter force is much easier and faster to move than what we have today. MEMS are the catalyst that will make this all possible.

WORD COUNT = 6,165

ENDNOTES

[1] David E. Sanger, "Bush Details Plan To Focus Military On New Weaponry," New York Times, 14 February 2001, p.1.

[2] Ibid.

[3] General Eric K. Shinseki, "Address to the Eisenhower Luncheon at the 45th Annual Meeting of the Association of the United States Army (As prepared for presentation)," 12 October 1999; available from <webpage/docs/csa vision statement.html>; Internet; accessed 21 February 2001.

[4] LTG Paul Kern, "Objective Force Science and Technology," 10 October 2000; available from <http://www.sarda.army.mil/docucenter.cfm>; Internet; accessed 14 December 2000.

[5] John Pike, "Future Combat System," 17 May 2000; available from < http://www.fas.org/man/dod-101/sys/land/fcs.htm>; Internat; accessed 17 November 2000.

[6] Ibid.

[7] Ibid.

[8] Ibid.

[9] LTG Paul Kern, "Future Combat System," 2 September 2000; available from <http://www.sarda.army.mil/docucenter.cfm>; Internet; accessed 14 December 2000.

[10] Dennis Steele, "The Army Magazine Hooah Guide to Army Transformation," ARMY, February 2001, 38.

[11] Ibid, 40.

[12] Ivan Amato, "May the Micro Force Be With You," Technology Review, 102 (September/ October 1999): 77.

[13] Dr. William C. Tang, "MEMS Programs at DARPA," 6 September 2000; available from <http://www.darpa.mil/mto/mems/presentations.html>; Internet; accessed 14 December 2000.

[14] "Microelectromechanical Systems Opportunities: A Department of Defense Dual-Use Technology Industrial Assessment," available from <http://www.dtic.mil/dtic/dtic-e/mems.pdf>; Internet; accessed 17 November 2000.

[15] Kelly Barrett, "MEMS packaging: Is it Ready for Prime Time?," Electronic News, 46 (27 November 2000): 51.

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[17] "MEMS," available from <http://www.lerc.nasa.gov/WWW/MED/skills/mems/>; Internet; accessed 13 December 2000.

[18] H. Guckel, "Micromechanisms," available from <http://mems.engr.wisc.edu/ publications/ROYAL.html>; Internet; accessed 15 December 2000.

[19] Sandia National Laboratories, "MEMS Overview, Sandia National Laboratories Intelligent Micromachines Initiative," available from http://www.mdl.sandia.gov/micromachine/ overview.html>; Internet; accessed 17 November 2000.

[20] David Pescovitz, "Tiny Spies in the Sky," available from <http://www.discovery.com/ stories/technology/microplanes/weblinks.html>; Internet; accessed 11 December 2000.

[21] Sandia National Labs, "Fire Ant," available from http://www.sandia.gov/isrc/ Capabilities/Integration_Technologies/Fire_Ant/fire_ant.html>; Internet; accessed 11 December 2000.

[22] Microelectromechanical Systems Opportunities, 10.

[23] Ibid, 9.

[24] Ibid, 11.

[25] Ibid, 13.

[26] Ibid, 13.

[27] Ibid, 14.

[28] Army Research Lab, "Modeling of Flows in Microelectromechanical System Devices," The 1999 Annual Review of the Army Research Lab, 24.

[29] Office of the Secretary of Defense, Director of Defense Research and Engineering, Basic Research Plan, (May 1996), 3-7.

[30] Microelectromechanical Systems Opportunities, 8.

[31] Ibid.

[32] Ibid.

[33] Ibid, 5.

[34] Ibid, 6.

[35] Ibid.

[36] Ibid.

[37] Andrew Leonard, "As the MEMS Revolution Takes Off, Small is Getting Bigger Every Day," Wired, available from <http://www.wired.com/wired/archive/8.01/mems.html>; Internet; accessed 17 November 2000.

[38] Ibid.

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