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THE POTENTIAL OF MICRO ELECTRO MECHANICAL SYSTEMS AND NANOTECHNOLOGY FOR THE U. S. ARMY

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I. INTRODUCTION

Micro Electro Mechanical Systems (MEMS) and Nanotechnology represent the continuing trend in technology toward smaller characteristic lengths and tolerances. Carpenters work on a scale of .1 to 1 millimeters, machinists work on a scale of 1 to 10 microns while commercial Complimentary Metal Oxide Semiconductor (CMOS) fabrication produces device lengths on the order of 0.1 micron or 100.0 nanometers. Newer fabrication processes coming into use attain smaller lengths.

CMOS fabrication processes, supplemented by micromachining, can also be used to manufacture small machines. Micromachining uses ion beam bombardment, laser irradiation, and epitaxy (gaseous deposition of molecules onto a surface in a vacuum). Multilevel, planarized MEMS are produced by separate fabrication of device layers that are separated by sacrificial layers of polysilicon. Electrical and electronic devices are fabricated on the substrate itself. Sandia labs is a leader in multilevel ratio devices and has announced fabrication of multilevel MEMS with five device levels [1].

The costs of MEMS are similar to current electronic chips; MEMS with large market applications could cost less than a dollar. MEMS can add additional capabilities to strictly electronic devices. MEMS power supplies can use mechanical switching of electrical current to supplement solid state switching. Micro Optical Electro Mechanical Systems (MOEMS) can switch light beams by mechanical movement of mirrors. These can be used for display systems. MOEMS with integral photocells can be used to approximate an all-optical light switch.

Oak Ridge National Laboratories has demonstrated a MOEMS device of this sort. A Light Emmiting Diodide (LED) laser diode shines on a half micron bandgap waveguide, modulating the emission. The laser light, of a different wavelength from the optical signal, physically vibrates the waveguide and stops the light signal. The switching speed is one megahertz and future devices may reach one gigahertz. This MEMS device is the functional equivalent of an optical transistor, which has so far not been realizable within an all-optical framework [2].

Inductors can be built on electronic chips used for Radio Frequency (RF) signal processing. Conventional CMOS fabrication can produce transistors and capacitors but not inductors. Signal processing can now be done with a single discrete unit; separate inductors to supplement RF chips and the interconnections between them can be dispensed with saving weight, cost, and time in the manufacturing process. The first MEMS units built actually were RF units [3].

Due to their size, MEMS are sharply limited in their ability to exert force directly on their surroundings. Piezoelectric units can flex and generate current; alternatively, current can be supplied externally and the piezoelectric unit can flex. In the former case, the piezoelectric unit serves as a sensor; in the latter case, the piezoelectric unit serves as an actuator. Electrostatic motors with power outputs of microwatts and in the size range of 100 microns and below can be fabricated. At these small sizes, electromagnetic motors will not work because the magnetic fields are too small.

The Massachusetts Institute of Technology (MIT) is attempting to build MEMS turbogenerators generating 50 watts within a one cubic centimeter volume. Offering thermal efficiencies of 10 percent or better they could provide greater electrical power for the same weight as an electrical battery [4]. The turbogenerators can be run on butane or other liquid fuel and would be sufficient to power laptops or other similarly sized devices. Logistics for the Army could be simplified with power units permanently built into electronic devices. As the same fuel can be poured into a variety of tanks, logistics can be much simplified compared with the variety of batteries and chargers that the Army is now obliged to maintain. The MEMS turbogenerators operate with frequencies above the range of human hearing; they are apparently silent. No MEMS turbogenerators are in large scale commercial production yet; however, the Army Research Organization is partially underwriting the MIT research [5].

Because of their smaller dimensions, the forces acting on MEMS require a full reanalysis. Volume effects are reduced relative to surface effects. Weight and inertia, which are volume effects, are reduced in magnitude and relative importance. Friction and adhesion, which depend on the area of the component, are simultaneously reduced in absolute magnitude and increased in relative magnitude compared to weight and inertia. Forces depending on a single dimension, such as surface tension and viscosity, have a greater design impact at these size scales. Electromagnetic forces must also be reconsidered as well. Magnetization of the material, dependent on volume, is reduced while electrostatic charge, dependent on area, is also reduced in absolute magnitude and increased in relative magnitude. Less heat is produced in the internal volume of a MEMS component, the area to reject the heat is increased relatively, while the heat has a shorter distance to travel.

MEMS devices currently find their largest application in the areas of control and sensing; where small machines can measure quantities independent of their size.

II. ORDNANCE

MEMS accelerometers, widely used in the commercial world for airbags, now are coming into widespread use in ordnance. They offer reduced volume, cost, power requirements, and increased reliability and resistance to shock and acceleration. Nonspecialized MEMS fabrication facilities could produce fuzes for DOD between larger production runs for civilian products.

Charles Stark Draper Laboratories conducted a program for DARPA measuring the muzzle jump in a cannon. Draper Labs also conducted a program for DARPA to measure the acceleration in a cannon shell from propellant ignition to projectile impact. This necessitated two accelerometers; one to measure the thousands of g's experienced during the acceleration experienced in the cannon tube, and one to measure the fraction of a g experienced during free flight. In both programs data were transmitted in real-time over a RF link. While MEMS can be manufactured to withstand 100,000 g's, no MEMS accelerometer has a dynamic range that matches an artillery shell firing [6].

The U. S. Navy's Enhanced Range Guided Munition is an artillery shell using MEMS accelerometers, GPS guidance, an airframe with an improved lift to drag ratio, solid rockets for post-firing acceleration, and guidance fins to attain ranges of 100 kilometers with a circular error probable of 20 meters [7].

The U. S. Navy Indian Head ordnance lab has a program for a MEMS projectile fuze. The safing and arming apparatus can be complete in one MEMS device. The MEMS electronic control unit, when given the appropriate signal, will command an actuator to remove a barrier to the movement of the firing pin. The firing pin can itself be fired by a small charge when the charge is detonated by a signal from a MEMS accelerometer. This will be used on a Navy torpedo Advanced Concept Technology Demonstration (ACTD) with test firings scheduled for FY 2003 [8].

The U. S. Air Force Armament Directorate Fuzes Branch at Eglin Air Force Base is developing MEMS fuzes for bombs and air-to-air missiles for the Air Force and DOD. Their Electronic Safe and Arm Device Program (ESAD) has the goal of producing fuzes that are simultaneously smaller, more reliable, and cheaper. The Hard Target Smart Fuze program has conducted tests of earth and reinforced concrete penetrators with real-time measurement of shock and deceleration using MEMS [9]. The data are being used to improve the shape of earth penetrating ordnance and to compare aircraft trajectories prior to release of the weapon. In the future, instead of simple delayed action fuzes, new smart fuzes can measure the deceleration encountered during the penetration of the earth and concrete and determine when the bunker has been penetrated and reliably detonate while the projectile is passing through the interior of the bunker [10].

The Sandia Intelligent Micromachine Initiative has produced a unique MEMS combination lock. An arm, which is MEMS actuated, projects downward through a groove cut completely through a disk. When a number for the combination lock is input, the arm is at a T intersection. At the T intersection, the arm can move in or out from the center. If the correct number is input, the MEMS electronics directs the arm to move to a groove leading to the next intersection or to the end and the disk rotates. If the wrong number is input, the MEMS electronics directs the arm to move into a groove with a dead end. The lock cannot fully unlock unless the disk rotates through the full arc [11]. Mechanical locks are preferred for some applications as electronic locks can be reset if power is interrupted, permitting retries after wrong numbers are input. Computer controlled locks can be reprogrammed by an intruder. With the Sandia MEMS lock one wrong number and the unlocking sequence is halted. To allow one failure and one retry, two disk locks can be provided.Uses include locks for nuclear weapons such as the Permissive Action Link (PAL) and other high security systems [12].

III. RECONNAISSANCE AND SURVEILLANCE

MEMS allow Army commanders to conduct reconnaissance and surveillance through a greater volume for longer periods without risking soldiers. In some applications, wireless communication without RF links can be accomplished.

The Micro Unmanned Air Vehicle (micro UAV) concept is being developed by both government contracts and independently. Micro UAVs measure less than 6 inches in any dimension and have a payload less than 100 grams. Their Reynolds numbers (the ratio between dynamic and viscous forces) would be on the order of magnitude of a bird or insect's (less than 10,000). Manned aircraft have Reynolds numbers measuring in the tens of millions. Aerodynamic properties do not scale with constant shape across orders of magnitudes in size and loads. In particular, wings have less than 1/3 the lift-to-drag ratio while propellers are 50 percent less efficient. This translates to a loss of specific impulse for fuels. Micro UAVs may require new concepts of propulsion such as pulsed detonation jet engines [13].

Micro UAVs can carry a variety of sensors such as chemical, radiation, Infrared (IR), and visual. In a test carried out by the U. S. Marine Corp's Warfighting Lab, UAVs were used to successfully photograph a simulated enemy's vehicles, troops, and positions in real-time while executing a preprogrammed flight pattern. The camera was a Charge Coupled Device camera with a fixed focal length; the photographs were processed with software stored on a laptop to enhance detail and correct for focal length aberrations. Micro UAVs are envisioned as company and platoon assets. The aircraft would be programmed for a flight path and would carry out a mission lasting up to an hour. This permits "over the next hill" knowledge for the infantry commander [13]. Micro UAVs can utilize GPS navigation (the antennae can be in the wings).

Another envisioned application is for a micro UAV to be released when a pilot ejects from an aircraft. Circling overhead, the UAV can act as locator beacon for rescue aircraft [13].

MEMS weather stations, smaller than a pack of cigarettes, could be emplaced by infantry patrols or dropped by parachute from an aircraft. MEMS weather stations can carry temperature, precipitation, humidity, and atmospheric pressure sensors. Locating themselves by GPS receivers, they would update meteorological information in real-time for commanders and their staffs throughout the area of operations and beyond the front lines [14].

MEMS weather sensors could be worn on the wrists of soldiers or carried on their equipment. This could be important for artillery and air forward observers. Atmospheric pressure, humidity, and temperature affect the accuracy of trajectories for artillery and bombs [14].

Dr. Kris Pister of the Berkeley Sensor and Actuator Laboratory is developing Smart Dust on behalf of DARPA. Vibration, chemical, meteorological, and other sensors could be packaged in units one cubic millimeter. Dr. Pister expects to reach the one cubic millimeter size in 2001. They could be dropped throughout a large area and function full time for two weeks or on a 1 percent duty cycle for two years. After being dropped by troops, aircraft, or rockets, the units would assemble themselves into networks. They would communicate by laser diodes and photocells. The dust would incorporate steerable mirrors covering 40 percent of the visible hemisphere. In a test in 1999, a laser pointer was used in a pulse mode and transmitted 21 kilometers between Coit Tower and Twin Peaks in the San Francisco bay area. Signal processing software was able to pick the signal out against the haze, glare, and smog of the bay area. Smart Dust could be used to map terrain, monitor weather, and act as a navigation grid [15]. Vehicles or enemy troops could be detected by ground vibrations. Chemical sensors could be used to give warning of poison gas attack. Radiation sensors could give warning of nuclear attack or monitor radiation from fallout and nuclear bomb craters. Radio units or real-time display terminals could be connected to the Smart Dust network by lightwave communications. Artillery fire could be called down on the appropriate areas. The enemy's movement could be channeled by his desire to avoid detection. Thus, Smart Dust could augment or replace land mine fields and human sentries. Smart Dust would not need expensive and hazardous demining operations, as it would pose no threat to operations by friendly personnel. Containing no explosives, it could be abandoned in place [16].

Dr. Pister is also conducting a project to build artificial insects called "Smart Dust on Legs". After deploying from an airdropped or ground carrier, the artificial insects could walk through a preassigned area making observations similar to Smart Dust and return to the carrier. The carrier could communicate the artificial insect's findings by radio [17].

IV. MACHINE INTERFACES

Dr. Pister is applying Smart Dust to use in Smart Gloves for communicating for machines. Smart dust equipped with accelerometers on the fingertips could report to a central unit by laser diodes and the movements of the fingertips could be interpreted as typing on a virtual keyboard. Previous Smart Glove concepts used optical fibers running to fingertips to measure finger movement. Smart Dust gloves would offer improvements in cost, weight, and power [18].

MOEMS can offer improved visual displays. Micromirrors tilting under computer control can reflect light from laser diodes onto a flat screen to create pictures. Combining light from laser diodes radiating the primary colors can produce colors. This does not require high voltages or weight.

Banks of eyesafe laser diodes mounted on eyeglass frames can be used to create “3-D TV glasses”. By using micromirrors that scan left to right, the light can be rastered onto the lenses. Television or alphanumeric data can be superimposed on the normal Field-Of-View (FOV) or the glasses can be opaque. They can be used for television or computer displays.

DARPA has a program called Warfighter Visualization that will embed MEMS into machine interfaces for the military. The Honeywell, Inc. See Through Turret Visualization System (STTV) mounts MEMS accelerometers and angular rate sensors onto a tank crewman’s helmet to determine his Line-Of-Sight (LOS) within the vehicle compartment. The corresponding video feed from cameras mounted on the exterior of the vehicle can be displayed on the crewman’s goggles by MOEMS. In effect, the crewman could “see through the armor”. The goggles would display a 10 X 7 degree FOV segment of a full 360-degree panorama. The video can include IR vision. This ameliorates the situational awareness problems of tank crewmen; to get an unimpeded view they currently have to stick their heads out of their vehicles, forgoing protection of the armor. With the hatches shut, tank crewmen can only get a small FOV with their vision blocks [19].

Raytheon Systems Company is integrating the DARPA Geospatial Registration of Information for Dismounted Soldiers (GRIDS) program. Data from several navigational systems, including GPS, are synthesized and displayed onto goggles on a soldier’s helmet. A helmet-mounted tracker unit would determine the soldier’s LOS. Geographic data would be matched to the LOS and displayed on the soldier’s FOV. Landmarks could have names, bearings, and distances superimposed along with the soldier’s location and a compass display. Celestial navigation and GPS would be used to update inertial navigation data. The entire unit must account not only for a small fraction of the soldier’s load, but must employ passive sensors [20].

As part of the Warfighter Visualization, MIT and Carnegie Mellon University are developing MEMS based tactile displays. This project includes characterization of the sensitivity of human skin. Touch arrays can silently provide data to the soldier in the dark without a light. Vibrations and raised patterns on surfaces convey information to the soldier. MEMS tactile arrays may be mounted upon forehead and gloves; rifle magazines may be equipped to indicate the number of rounds [21].

Vibration and noise are major human factors problems for aircrew and armored vehicle crewmen, reducing alertness and increasing fatigue. By embedding MEMS vibration sensors and actuators within the vehicle, the vibrations can be actively damped.

V. INERTIAL NAVIGATION

MEMS angular rate sensors and accelerometers are fabricated as a single unit and offer the advantages of low-cost, lightweight, small volumes, low power requirements, and large production runs. MEMS angular rate sensors can be fabricated with proof masses that oscillate in one dimension. Interdigitated capacitor surfaces extending from the proof mass and the main body are the active elements in the sensor. The sensor utilizes the Coriolis force; the axis along which rotation is sensed is normal to the plane of the capacitor surfaces [22].

Another type of angular rate sensor is the "tuning fork". The sensing element is a microminiature double headed tuning fork fabricated from quartz as a single unit (similar to that in quartz watches). The axis of measured rotation runs through the center axis of both pairs of tines. An electronic circuit in the MEMS sends regular electrical signals to one head of the tuning fork (the driving fork), to drive it at its resonant frequency. Piezoelectricity flexes the tines of the fork. The tines move alternately closer and further away from one another. The other fork (the pickoff fork) is unpowered. When rotated about the sensed axis, the tines of the pickoff fork make out-of-plane movements due to Coriolis force. The out-of-plane movements generate piezoelectric signals. The electronics in the MEMS device derive angular rates from the signals [23].

Currently, commercial devices have bias error of about 30 degrees per hour. For example, the BEI Gyrochip Model QRS11 from Systron Donner Inertial Division has a startup time of less than 1 second, a Mean Time Between Failure (MTBF) of 100,000 hours and an operating voltage of 5 volts. Operating temperatures range from -40 to +80 °C; storage temperatures range from –55 to +100 °C. Its mass is 60 grams and its operating life is 10 years.

Short-term bias stability (100 seconds at constant temperature) is less than or equal to 7.2 degree per hour; long term bias stability (1 year) is less than or equal to 720 degrees per hour [24].

MEMS accelerometers work by measuring capacitance changes. One plate of the capacitor is suspended above the other on a cantilever or by twin bars, one on each side. The force of the acceleration deforms the supports of the suspended plate and reduces the gap, increasing the capacitance. Electronics in the MEMS chip process the signal and convert it to a measurement of acceleration [25].

Analog Devices ADXL150 is a typical single axis accelerometer with a self-test function and a dynamic range of +-50 g with 10mg resolution. It has an industrial operating range of –40 to +85 °C, with a dynamic dynamic range of 80dB [26].

MEMS accelerometers give good results for shock and vibration. With smaller military budgets and forces, survivability for individual pieces of equipment is more important than ever. MEMS accelerometers are increasingly used in shock tube testing of weapons and vehicles. Because of their small size and cost, more components in the tested system can be monitored [27].

An upper limit for high frequency accelerometer response is the upper frequency to which it can be calibrated. The current figure is about 20,000 hertz for devices fabricated by the National Institute of Science and Technology (NIST). Above this level the MEMS devices' mechanical impedance tends to modify the response of the structure to which they are attached [27].

Pyroshock, a short duration, high amplitude, high frequency, transient structural response is a feature in many aerospace vehicles, as in staging of rocket boosters. Pyroshock will often excite the resonant frequency for conventional accelerometers, distorting the results. MEMS accelerometers are quite adequate to measure pyroshock while current non-MEMS commercial devices are limited to about 4,000 hertz [27].

Structural modal analysis testing may require sensors that can measure frequencies below 1.0 hertz. For example, the first vibratory mode for the Boeing 737 or the McDonnell-Douglas DC-9 occurs below 1.0 hertz, the "butterfly" mode. The space station will require sensing modes lower still. MEMS can sense modes as low as 0.1 hertz [27].

MEMS accelerometers today have the largest markets of any MEMS devices in airbag deployment. While many companies are developing products, as yet there is no operational navigation system that is MEMS based. Packaging costs for MEMS are similar to other solid state devices. Their power requirements are usually less than 5 volts dc with milliamp currents.

VI. ENVIRONMENTAL SENSING

MEMS are being developed for environmental and medical sensing. Sensors are fabricated on the chip, which are sites reactive to chemicals of interest. The sites react to the target chemicals and the electrical resistance changes. The electronics on the chip detect the change, analyze and interpret the sensor data, and send an appropriate output. This approach can be used for airborne and blood or water carried chemicals. The analysis samples are nanoliter or millionths of cubic centimeter volumes for each site. The fluid mechanics at these small volumes and velocities require a full analysis. Adequate flow of samples to all sites must be assured.

At CalTech, Dr. Nate Lewis, Dr. William A. Goddard III, Dr. James Bower, and others are developing a vapor sensor to detect buried nonmetallic land mines. The project is entitled "The Artificial Nose" and is inspired by mammalian olfaction. Some mammals have 10,000 or more detector organs, 2,500 or less respond to any chemical. Neural nets identify the smells in the brain [28].

Each MEMS detector site consists of a polymer composite and carbon black combination. Carbon black serves as a conductor as most polymers are insulators. When a vapor sample is passed across the sensor array some polymer sites expand, changing their conductance characteristics. An electronic neural net receives the signals and determines the composition of the sample [29].

An especially interesting aspect of their research is that polymer sites can be designed on a workstation using a Quantitative Structure Activity Relationship (QSAR) model. The QSAR model calculates the proper composition of the polymer-carbon black matrix. Automated workstations can produce sensor array for specific chemicals within a few hours [30].

Each soldier could carry a small device to warn him of nearby land mines or booby traps. With appropriate polymer sites it could also be an individual nerve gas detector. Additional applications include environmental health monitoring and air quality monitors in DOD vehicles. Patient's exhalations have distinctive trace gasses in many diseases and medical health monitoring can be augmented with appropriately equipped devices.

DARPA has a program called the Dog's Nose Program. The program's aim is to develop a land mine detector that does not require detection of metal, as many land mines are now completely nonferrous. Explosives outgas signature compounds that can now be detected in the femtogram (10E-15) per milliliter quantities. A number of contractors demonstrated their products at Fort Leonard Wood, MO with actual buried land mines. To establish a baseline, dogs went through the minefield first and found 79 of 79 mines. Several systems were equal to the dogs at mine detection. False alarms could be eliminated through multiple passes of the sensor. Supporting research included characterization of the chemicals emitted by land mines, the aerodynamics of the chemical plume, and the aerodynamics of the dog's nose [31].

Oak Ridge National Laboratories has also developed a nose-on-a-chip that can measure as many as 400 airborne chemical species in the part per billion range and report. (DARPA's mine detector has accuracy in the part-per-trillion range but is specialized for the chemicals emitted by explosives). It has microcantilever sensing devices. Chemicals on the microcantilevers react to the appropriate chemicals in the air and bend them. The resulting change in resistance is sensed and electronic logic determines the atmospheric chemical and reports. The U. S. Navy installed a network of sensors that reported on shipboard environmental conditions aboard the U. S. Navy destroyer USS The Sullivans and successfully reported the data while conforming to the Electromagnetic Interference (EMI) requirements [31]. Microcantilever thermal and humidity sensors have also been developed [32].

The Instrumentation and Controls Division at Oak Ridge National Laboratory has developed a wireless sensor system architecture. This is a niche in the market that has not received much attention. In some environmental applications MEMS sensors can measure humidity, temperature, vibration, chemicals in the air, etc. at many points, but must report the data to a separate location. Many of the benefits of the economy, small size, and low weight of MEMS devices will be lost if there is not an economical, small size, and low weight network to report the data. Wiring adds weight, cost, and complicates manufacturing. Older networks suffer from lack of spare parts and increasing inspection and maintenance costs. For example, the Federal Aviation Administration (FAA) announced in the wake of the TWA Flight 800 disaster that aircraft wiring would no longer be considered a lifetime, fault-free technology [32].

The first wireless interconnects had to send data across standard narrow band FM channels. This greatly limited the available bandwidth in closed areas [32].

Oak Ridge is developing a series of standard wireless interfaces for sensors and central units that can accept a wide variety of sensors and conform to Bluetooth; a networking protocol that is becoming the de facto industry standard. The Bluetooth consortium includes Nokia, Toshiba, IBM, Intel, and 1,100 others. Wireless spread spectrum technology allows greater bandwidth and lower power transmissions. Pseudo random spacing of transmissions complicates unauthorized listeners’ tasks, as they don’t know which frequency is next. Transmissions use 64-bit words. Spread spectrum technology reduces multipath interference.

Possible uses include installing and upgrading sensor systems on pressure vessels in electrical power plants. This is especially important as nuclear power plants are beginning to reach their designed lifetimes and must be fully inspected to determine whether they can operate past their design lifetimes [33].

VII. INTRODUCTION TO NANOTECHNOLOGY

Nanotechnology extends the control of matter from less than one micron down to the size of molecules. While the tolerances are small, nanotechnology products can be of any size. The relevance of nanotechnology to Army missile systems is that it will increase structural strength, fuel efficiency, and allow much greater capabilities to be built into computers.

In 1959, Richard Feynman gave a dinner talk at the American Physical Society's Annual Meeting entitled, "There's Plenty of Room At The Bottom". Some attendees saw the title and thought it was about the physics job market, i.e. "There's Plenty of Crummy Jobs in Physics". But no, he wanted to discuss building objects with features on the scale of molecules. He discussed storing information by means of differing metal atoms in a space 5x5x5 atoms in volume. He foreshadowed epitaxy by a scheme for metal deposition and vaporization. He discussed getting down to nanometer scales by building machines to make smaller machines and using them to make smaller machines in an extended sequence. He discussed friction and suggested lubricating machines built on this scale would lead to greater problems as oil molecules would be discrete objects jamming the machinery. He suggested letting the machines run without lubrication as heat transfer characteristics would be changed at this scale [33].

Feynman, who would later receive the Nobel Prize in Physics in 1965 for his contributions to Quantum Electrodynamics, discussed extensively the changing physical characteristics of matter at the molecular scale. In this regime, quantum properties of matter must be taken into account; the Heisenberg Uncertainty Principle and Brownian motion become of interest. Yet, he stated:

"The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big" [34].

In later years, he did little or nothing with the idea; leaving it to be explored by others.

Until fairly recently, research on the atomic and molecular level had been a backwater of physics. Interest centered on particle physics and theories of space and time on the large scale.

Four Nobel prizes, beginning in 1986, have been awarded in the last 15 years for research at the atomic scale. In 1986, Gerd Binnig and Heinreich Rohrer shared the Nobel Prize for Physics for their invention of the Atomic Force Microscope (AFM); a device that can measure features on surfaces angstroms in height. A small probe is dragged across a surface and piezoelectric devices measure the height. The probe can also be used to drag or "herd" atoms across a surface.

In 1989, Dehmelt and Paul received a Nobel Prize for their development of and research with atomic traps. In 1994, Schull and Brockhouse received a Nobel Prize for their development of neutron diffraction techniques for structure determination. In 1997, Chu, Cohen-Tannoudji, and Phillips shared a Nobel Prize for their development of methods to cool and trap atoms with laser light.

In 1990, Dr. Don Eigler and a team at the IBM Almaden research center used an AFM to move 35 argon atoms across a silicon surface in a vacuum chamber. The group produced the "IBM" logo. Other researchers followed suit producing maps of the Earth and pictures of Einstein or their university's logo, etc. Molecules have been disassembled and reassembled by AFMs.

The quantum uncertainty principle states that the product of the uncertainty of measurement of a particle's energy and its frequency or the particle's momentum and position is a constant at least equal to half Planck's constant, 5.275 X 10E-35 joule-seconds. Brownian motion occurs because of the thermal agitation of all objects above absolute zero. The atoms in an individual molecule constantly move relative to each other [35, 36].

Yet molecules hold together and can store information reliably; DNA is an example. Brownian motion need not rend molecules at room temperatures. The Heisenberg Uncertainty Principle affects electrons far more than atoms, an electron is 1836 times less massive than a proton. Dr. William Goddard III at CalTech has simulated molecular scale machinery with commercial chemistry software incorporating quantum mechanical force fields, ab initio calculations, and picosecond (10E-12 second) intervals. Some designs have survived [37].

One detailed analysis shows that above the nanometer scale the classical thermal effects dominate the quantum effects [37]. Approximations by classical statistical mechanics can be used to save on computer time and expense. It would be impractical to design devices and materials by simulating quantum molecular interactions for all possible cases to determine failure rates. Statistical mechanics can be used to calculate quantities such as pressure, entropy, free energy, and average temperature. Statistical mechanics is well suited to provide estimates of failure rates by analyzing the frequency with which extreme conditions occur [38].

Structures incorporating stiff materials are easiest to analyze and have the best chance of survival. Silicon has a stiffness to density ratio three times as great as steel. Diamond has a stiffness to density ratio over 11.6 times as great as steel. MEMS diamond structures can be produced industrially today with vapor epitaxy [39].

Dr. Don Noid and Dr. Bobby Sumpter, physical chemists of the Chemical and Analytical Sciences Division at Oak Ridge, are heavily involved with computational nanotechnology. Their work incorporates quantum mechanics and statistical mechanics in simulating molecular dynamics. They have devised algorithms reducing the required complexity in molecular modeling from many equations per atom to a few lines of code. This approach is amenable to parallel processing. Nevertheless, their programs require large amounts of computer time; many simulations have run for a week at a time. The time simulated amounts to several nanoseconds, a substantial length of time on the molecular scale. Video dramatizing the results of the simulations can be produced. Their software incorporates the conservation of energy for better accuracy; commercially available packages have systematic errors that make energy monotonically increase with time [40, 41].

They have investigated flow of helium and argon atoms through a carbon nanotube. Their model simulates atomistic behavior of the stream and structural effects on the nanotube. Among their findings are that *He* flows faster than *Ar*, rate of flow depends on fluid density and tube diameter, fluid flow suppresses low frequency modes in tubes, stiffer tubes leak more, and effective viscosity must include wall interactions. They have simulated dynamics of a molecular bearing, nanometer scale laser driven motors and He-C60 flow in a carbon nanotube [42].

Drs. Sumpter and Noid have demonstrated that molecular dynamics could give reasonable answers in electron transport in nanowires by comparing the results of molecular dynamics and quantum mechanics over a length of several hundred microns. Nanowires may have diameters as small as 10 nanometers. Ab-initio quantum mechanical calculations are prohibitively expensive in computer time for substantial nanowire lengths [43].

In conjunction with James von Ehr of Zyvex, Dr. Noid and Dr. Sumpter have simulated movement of molecules across a surface by laser and by STM [44]. Along with a team of other Oak Ridge scientists they have modeled spherical polymer nanoparticles, electronic switching devices that are called quantum drops. They have controllable radius, composition, chemical reactivity, and magnetic properties [45, 46].

Drs. Sumpter and Noid have also investigated the limits of classical molecular dynamics modeling in shock and pressure wave propagation in fluidic systems at the nanometer size [47]. Tuan Vo-Dinh, in conjunction with Drs. Sumpter and Noid, has developed nanoprobes that are waveguides with dimensions less than or equal to ultraviolet wavelengths. This unique MEMS-nanotechnological system incorporates near-field laser probes, photocells, and electronics to study the interiors of living cells. Cells could be moved in 3-D while 50 nanometer probes, in some cases tipped with biologically active chemicals, could manipulate organelles within the cell. The waveguides illuminate the process with ultraviolet. The investigator watches the cell through a microscope with an ultraviolet sensitive screen [48].

NASA formed an integrated product team at its Ames Research Center in the fall of 1996, to investigate nanotechnology. This group has grown to 40 scientists. They have conducted research on nanotube formation with two chemical vapor deposition reactors. Seeking better methods to control carbon nanotube diameter and chirality (twist) is a research focus. Experimental determination of mechanical and electrical properties of nanotubes is another focus. Among the applications for nanotubes are as tips for AFMs. Storage of hydrogen in nanotubes for use in fuel cells is also a potential application. So far, the lack of absorption of hydrogen in nanotubes has been an obstacle [49].

Ames is attempting to build optical information storage devices which utilize photochrome bacteriorhodopsin, a retinal protein found in the organism halobacterium salinarium. The envisioned performance of a mature system is 10 E+11 bits/cubic centimeter or 100 to 500 gigabytes on a CD sized unit [50].

Dr. Toshihige Yamada of Ames is investigating the electrical characteristics of long chain molecules on a substrate using a scanning tunneling microscope. The appropriate chemical composition can determine the electrical characteristics of the molecules, i.e. a silicon chain is metallic while a magnesium chain is semiconducting. Group I atoms are electron donors and Group VII atoms are electron acceptors. Interactions with the substrate are also being investigated [51].

VIII. MOLECULAR ELECTRONICS

Moore's Law, stating that every two years the density of circuitry elements doubles (now every 18 months), predicts molecular size devices by 2020. Unfortunately, the cost of the fabrication facility using conventional fabrication techniques is subject to exponential growth as well. It would be desirable to chemically synthesize molecules and assemble them on a substrate. In July 1999, Hewlett Packard and UCLA jointly announced that researchers had built an electronic switch by synthesizing rotaxane molecules and placing them on a substrate. By connecting them, the researchers built a switch. Unfortunately, the molecules could only switch once [52].

Dr. James Tour and Dr. Mark Reed added chemical moieties to oligocenes that could hold electrons when subjected to a specified voltage. The result could act as a switch. The device actually consisted of a layer of perhaps 1000 benzenethiol molecules between two metal contacts. By changing moieties, the device could be modified to hold electrons for long term storage; acting as a memory [52]. Synthesizing the large molecules is done by self-assembly. The molecular components assemble by reactions starting with oligocenes; the useful fragments, the thiol, assemble onto a gold particle. Further work can be done by an AFM [52]. Drs. Tour and Reed have formed Molecular Electronics Corporation to develop their research into marketable products.

In 1997, Dr. Robert Metzger's group at the University of Alabama synthesized a molecule that could act as a diode [53]. Molecular electronic devices are sometimes called "single electron devices" as a single electron can be used to carry a signal. So far, no one has announced a molecular transistor that could be used to amplify signals. The power requirements of molecular electronics are not clear; as theoretically the devices could operate with power requirements below kT if the devices were built employing reversible logic. The physics of information processing devices has, as a lower power limit, the erasure of bits; this is equivalent to an increase in entropy. Theoretically, devices could be made with the number of inputs equal to the number of outputs, obviating the erasure of input information [54].

Drs. Doug Lowndes, Gyula Eres, Vladimir Merkulov, and Yayi Wei of Oak Ridge are using chemical vapor deposition sometimes enhanced with plasma heated to make arrays of carbon nanotubes for use as field emitters in an Oak Ridge developed electron lithography process [55].

Dr. Simpson (no first name mentioned in the report) is developing nanotube field emitters to function as information interfaces for future supercomputers on a chip. With the functionality that molecular electronics permits, the small number of pins on regular size chip would present a bottleneck in the input-output process. Arrays of carbon nanotube field emitters on the chip and off would communicate with one another [55].

C. E. Thomas and a team at Oak Ridge's Department of Instrumentation and Control are developing an electron lithography process using nanotube field emitters that they expect can write features on a chip in the 10 to 100 nanometer range by 2004 [55].

Drs. Wei and Eres are investigating the behavior of carbon nanotube circuit elements. Electron beam lithography is used to pattern electrode sets with catalysts for nanotube growth. Following vapor deposition, the nanotubes' electron beam transport characteristics are investigated. Current-voltage relationships are linear at room temperature, while the circuit elements are being cooled to 2K the I-V relationship becomes nonlinear, evidence of semiconducting behavior [55].

Dr. P. G. Datskos, A. S. Rajic and others at Oak Ridge are developing Nano-Electro Mechanical Systems (NEMS). Novel uncooled photon detection devices are fabricated on chips. Micromechanical devices can constrict the sensors and affect their electron bandgaps, allowing photon wavelength tunability [56].

Dr. Eli Greenbaum, Dr. James Lee, and Dr. Ida Lee are studying photosynthesis of spinach. A 10 nanometer long spinach protein called Photosystem I absorbs photons and emits electrons on picosecond timescales; more than 100 times quicker than conventional silicon photocells. Also, it does this in one direction only. This suggests that this phenomenon could serve as a basis for a new photodiode, a device that passes electrons only one way when illuminated and blocks it altogether when dark [56].

At Mitre Corporation, Dr. James Ellenbogen and J. Christopher Love have written a series of analyses for molecular electronic computers under the title of "Architectures for Molecular Electronic Computers". Their first publication is "Logic Structures and an Adder Built from Molecular Electronic Diodes," in which they sketch a logic architecture for AND, OR, and XOR gates that are built from molecular wires and diodes. They conclude that diodes are not sufficient for complex circuitry, that a switch that amplifies the signal (a molecular transistor) is required. In future papers they will analyze logical architectures built with molecular transistors and memory cells built with molecular electronic devices [57].

IX. NANOSTRUCTURED MATERIALS

Structural materials could be made with carbon fibers precise on the atomic scale. In 1985, Smalley, Curl, and Kroto discovered a third allotrope of carbon called Buckminsterfullerene. The molecule, C60, resembles a soccer ball or one of Buckminster Fuller's geodesic domes. The molecule was produced by vaporizing graphite with a laser. The researchers realized that by cutting the molecule at the equator and adding more carbon atoms, a long fiber could be produced. Actually, graphite is vaporized by an electric arc in an inert atmosphere and assembles on a metal catalyst. The electrical and structural properties of nanotubes are a function of the presence of metal atoms in the interior nanotube volume and the nanotube's chirality. Nanotubes can conduct electricity 50 or more times better than copper if properly doped. Theoretically, single walled nanotubes could have a Young's modulus of over a terapascal (10E+12 newtons/meter squared) and tensile strength of over 10E+11 pascal. Nanotubes can be stretched over 10 percent of their lengths or bent beyond a right angle and return to their unstretched size, no worse for the wear. Nanotubes are the strongest materials theoretically possible [58].

Nanotubes can be made with double walls. Dr Robert Ruoff and his group at the Center for the Study of Novel Carbon Materials pulled the inner tube out from the outer tube of their double walled test fibers and measured a tensile strength of 63 gigapascal [59]. Currently, nanotubes can be bought for $500/gram. Many companies are researching new methods of manufacture [60]. The impact of nanotube production in bulk would be immense. Aircraft and missile structural weights would decrease along with engine and fuel requirements.

Nanopropulsion, a limited liability corporation based in California, is developing solid fuel technology based on nanotechnology. Currently, solid rocket fuel is produced in grains around 230 microns in diameter. Nanopropulsion's approach is to reduce the size of the aluminum flake diameter by a factor of a thousand or more. The ratio of surface area to volume increases correspondingly and the fuel burn time is decreased. By controlling fuel grain size, the fuel burn time can be tailored. Specific impulse can be increased, in part because combustion is more complete [61].

Nanopropulsion's data show an increase of linear burn rate by a factor of 100 or more. The Aerospace Corporation has verified this in independent experiments with fuel Nanopropulsion furnished [61].

Currently, solid rocket engines are built with an empty central volume to increase fuel burn rates. With Nanopropulsion's technology, a solid rocket need not have an empty central volume. Combustion could simply propagate from the rear of the fuel to the front. This would eliminate the time and expense of machining the fuel. The engine cases would be shorter for the same weight of fuel eliminating the weight and expense of longer sections of casing. Missiles could have higher initial accelerations and tailored acceleration patterns [61].

The same technology could be applied to gunpowder making a lighter, cleaner propellant with reduced flash capable of tailored acceleration within the gun barrel [61].

Applied to explosives, the Nanopropulsion technology would make explosives that produce higher intensity overpressures and heat pulses with more abrupt and shorter pulses [61].

Nano-Tex, a Limited Liability Company started in 1998, is applying nanotechnology concepts to textile applications. By reducing the diameter of cotton fibers and adding additional molecular chains to the fibers, superior fabrics can be developed. They are stronger while being more water and stain resistant. Color patterns last longer as well. Test garments have been demonstrated that wearers report are as comfortable and breathe as well as conventional garments. Developers say that their process is compatible to conventional weaving machinery. Galey & Lord and Burlington Fibers have licensed the technology. A possible application is longer lasting, more rugged camouflage uniforms [62, 63, 64].

X. CONCLUSION

Initially, the impact of MEMS and Nanotechnology on the Army’s systems and operations will be incremental. However, in the long term, MEMS and Nanotechnology will substantially transform the Army’s equipment and operations.

Discrete MEMS devices such as inertial sensors and safing & arming devices will be produced first and may be introduced into product upgrades. They will have little or no impact in handling, operation, or outward appearance. Discrete MEMS devices will find application where they are smaller, lighter, more reliable, or cheaper than currently fielded technology. The Army will be able to leverage development from the larger civilian market with its wide variety of markets and large production runs. Meeting Army requirements for ruggedness and assuring a continued supply of components may be problems as the Army will be a comparatively small market.

In the longer term, unexploded ordnance, medical, and environmental sensors built around MEMS will be acquired and will make their presence felt as soldiers operate them. MEMS unexploded ordnance and poison gas detectors will be more common in the future Army and will provide more reliable data. MEMS turbogenerators will replace a wide variety of batteries and chargers and simplify logistics.

Systems impossible to build without MEMS will have the greatest impact in the long run. Smart Dust and Micro UAVs will provide future Army commanders greater real-time information about the weather, the battlefield, and the enemy. MEMS machine interfaces will provide data to the soldier and enable more effective operations. In particular, the GRID system for infantry and the Honeywell STTV system for armor will offer improved land navigation and situational awareness. Human factors research must determine the priority and quantity of data provided to the soldier.

Nanotechnology will first find its application in nanoelectronics. It will continue the trend toward greater computation and memory within a fixed volume. Army missiles and aircraft will have at least a thousandfold increase in onboard computer capability within 20 years. Sensors will be more able to distinguish targets from decoys and background. Identification Friend or Foe (IFF) will become more certain. Machine vision could become a reality in missiles. Internal sensing of missile and aircraft system status will be more thorough and accurate. Bandwidth will be a concern, both internal and external. Aircraft system architectures may become more distributed with rerouting of links and reconfiguration of systems to compensate for battle damage. Greater intercommunication of data within a force will be tempting but electronic signals discipline must be maintained.

The first use of nanostructured materials may be as solid fuel and explosives. The time scale for this is uncertain as Nanopropulsion, LLC is pursuing development without disclosure of results in the open media.

Carbon nanotubes for structural applications are an application under wide development. With a current price of $500/gram they are too expensive for airframes. Yet much research and development is going on in nanotube production. It was only in 1991, that carbon nanotubes were detected and the time scale for industrial production is unclear.

Nanotube structural materials and nanoelectronics will transform the design of aircraft and missiles. Airframes and avionics will weigh only a small percentage of what they do presently. The fuel supply and engines will be smaller as well. Improved accuracy due to improved avionics may lead to smaller warheads. The expectation then will be for smaller, more lethal aircraft and missiles.

The Future Combat System will be a light armored vehicle capable of deploying in a C-130. The vehicle weight must be less than 20 tons. A 10-ton weight would be desirable, as 2 vehicles could be carried in a C-130 and 1 in a CH-47. Carbon nanotubes can greatly increase the armored protection within these weight limits.

The insertion of MEMS into operational systems may not be obvious at first, but increasingly, Army operations will be defined by the operation of MEMS sensors. The individual soldier’s situational awareness and safety will depend on MEMS sensors and displays. His commanders will use MEMS sensor data to comprehend the battlefield.

Nanotechnology will make possible improvements in degree so great that they may be regarded as improvements in kind, such as improving computing a thousandfold. In addition, nanotechnology applications will emerge that cannot now be foreseen.

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