Recent Progress in MEMS Technology Development for Military Applications

Paul B. Ruffin and Sherrie J. Burgett
U. S. Army Aviation and Missile Command
ATTN; AMSAM-RD-MG-NC
Redstone Arsenal, Alabama 35898-5254
e-mail: paul.ruffin@rdec.redstone.army.mil
Phone: 256-876-1717

ABSTRACT

The recent progress of ongoing efforts at the Army Aviation and Missile Command (AMCOM) to develop microelectromechanical systems (MEMS) technology for military applications is discussed in this paper. The current maturity level of low cost, low power, micro devices in industry, which range from simple temperature and pressure sensors to accelerometers in airbags, provides a viable foundation for the development of rugged MEMS devices for dual-use applications. Early MEMS technology development efforts at AMCOM emphasized inertial MEMS sensors. An Army Science and Technology Objective (STO) project was initiated to develop low cost inertial components with moderate angular rate sensor resolution for measuring pitch and yaw of missile attitude and rotational roll rate. Leveraging the Defense Advanced Research Projects Agency and other Government agencies has resulted in the development of breadboard inertial MEMS devices with improved robustness. During the past two years, MEMS research at AMCOM has been expanded to include environmental MEMS sensors for missile health monitoring, RF-MEMS, optical MEMS devices for beam steering, and micro-optic 'benches' for opto-electronics miniaturization. Additionally, MEMS packaging and integration issues have come into focus and are being addressed. Selected ongoing research efforts in these areas are presented, and some horizon MEMS sensors requirements for Army and law enforcement are presented for consideration.

Keywords: Inertial MEMS, RF MEMS, Optical MEMS, Environmental MEMS Sensors

1. INTRODUCTION

MicroElectroMechanical Systems (MEMS) are micro sensing systems that combine electrical and mechanical components on the same chip, produced by commercial integrated circuit (IC) manufacturing processes. MEMS sensors can be constructed in tightly integrated environmentally compensated packages. Developments in MEMS technology in recent years have been astounding. The technology is rapidly maturing from infancy to adolescence. MEMS accelerometers have flourished in the automotive industry as sensors for air-bag deployment. The automobile and information technology sectors dominate the market for MEMS devices.[1] Millions of MEMS accelerometers designed for airbags are produced monthly at a cost of less than $10.00 per device. Industry is projecting a cost less than $20.00 for MEMS gyroscopes for use in automobile navigation. A recently patented "smart-tongue" technology is expected to provide the food producers' market with billions of sensors, at a fraction of a penny each.[2] These MEMS devices will be attached to items such as milk and juice on the exterior of the cartoon, and, when scanned, will reveal the viscosity of the contained liquid, and thereby reveal its soundness. MEMS devices are also the basis for "smart wallpaper" that acts as a sound insulator in apartment buildings. MEMS devices are being meshed with biology to form "smart skin", and are being utilized extensively in medical equipment.

MEMS technology provides inherent cost savings and size reduction, and is ideal for application to navigation and control systems for small missiles and munitions.[3] Using MEMS technology, gyroscopes, accelerometers and control electronics can readily be integrated to form a tightly packaged, low-cost, extremely small, high

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performance inertial measurement unit (IMU) suitable for munitions and missile guidance and other applications. MEMS IMUs will significantly reduce the cost of precision-delivered missiles & munitions, as well as expanding precision delivery capability to artillery ammunitions.

The Defense Advanced Research Projects Agency (DARPA) initiated several research projects to develop MEMS-based inertial instruments for acceleration and shock environments. The U. S. Army Aviation and Missile Command (AMCOM) is leveraging the DARPA MEMS technology development projects, via serving as the DARPA agent for research projects initiated to develop inertial MEMS components (accelerometers and gyroscopes), which meet Army missile systems requirements. Available inertial MEMS components from several DARPA MEMS projects and industry are currently being tested at AMCOM under realistic military environments to determine the performance limitations and to identify Army systems for the insertion of the state-of-the-art MEMS technology. The Air Force is serving as the DARPA agent for monitoring several contract efforts, which are developing small, low cost, tactical grade (1 deg/hr) MEMS-based IMUs. These efforts emphasize the high sensitivity aspect of inertial MEMS components.

Recently, MEMS Technology Development Programs at AMCOM have expanded to include RF MEMS, Optical MEMS and Environmental Sensing MEMS. Significant progress has been achieved during the past year in launching cooperative developments in these areas. A strong presence has been established among academic, military and industrial research and development experts, instigating a focusing of efforts toward specific needs for Army applications, such as system health monitoring and forward reconnaissance. An update on inertial MEMS efforts is presented in the next section. The status of research and development in the areas of environmental MEMS devices, optical MEMS devices, and RF MEMS devices are presented in sections 3, 4, and 5, respectively. A summary is provided in section 6.

2. INERTIAL MEMS DEVICES

Research scientists at AMCOM, Research Development and Engineering Center (RDEC) are cooperating with scientists at the Department of the Navy, the Department of the Air Force, DARPA, the Department of Energy (DOE), NASA, other Army Agencies, industry, and foreign research organizations to develop militarized MEMS inertial instruments (gyroscopes and accelerometers) and to maximize the leveraging opportunities to meet performance and cost goals. An IMU, which consists of three gyroscopes, three accelerometers and associated electronics, provides three-dimensional changes in angle and velocity and short-term information on the position and attitude of a vehicle. The primary measures of performance for the gyroscope and accelerometer are bias stability or drift rate, scale factor, and dynamic range. The performance requirements for the inertial components differ, depending on the specific application. IMUs can be used in conjunction with Global Positioning System (GPS) as part of an inertial navigation system (INS). The function of an INS, which is comprised of an IMU and signal processor, is to provide long-term position, velocity and attitude information to the missile seeker during flight.

To capitalize on the opportunity for early transition of the advantageous inertial MEMS technology to military systems, scientists and engineers at AMCOM RDEC and the Army Research Laboratory pursued and obtained approval for a joint Science and Technology Objective (STO), which leverages DARPA MEMS Projects in developing MEMS-Based Angular Rate Sensors (ARS) suitable for operating in military environments. The STO is directly addressing military performance and environmental requirements. Affordable militarized angular rate sensors, which can be used in inertial navigation systems in future missiles, micro-unmanned autonomous vehicles, aircraft, and ground vehicles are being developed under the STO project. Reduced cost, size and weight inertial sensors with ultra reliability provide these weapons and platforms with the precision guidance required on the digitized battlefield across the warfare spectrum. These inertial sensors built with MEMS technology will allow favorable tradeoffs in performance requirements.

A distinct class of tactical weapons (hypervelocity missiles, small precision-guided rockets, etc.) imposes additional requirements (must operate through and survive high and wide gravity ranges, high shock and vibration, and high roll and reverse roll environments) on inertial components. AMCOM is serving as the DARPA agent in monitoring several contracts to address the environmental issues associated with military operations. Rugged designs and design approaches are assessed to meet the military requirements. AMCOM is conducting in-house efforts to address the wide rotation range requirement for systems such as the Low Cost Precision Kill system.[4] Fig. 1 shows a schematic of the current developmental roll rate sensor.

Gun-launched systems require inertial components, which must survive large gravity shocks, exceeding 15,000 g. The Army is currently establishing working relations with the other services and DARPA to jointly develop affordable, high-g MEMS inertial navigation systems for precision gun-launched weapons.

3. ENVIRONMENTAL MEMS DEVICES

The Remote Readiness Asset Prognostic/Diagnostic System (RRAPDS) is a program for the development of on-board missile health monitoring sensors and systems.[5] Its purpose is to reduce costs associated with maintenance, supply, transport, and storage of missile systems. A schematic of the technical concept for the system is shown in Fig. 2. The development of such a system requires close coordination of many technologies, with key technological advancements needed in the hardware areas of long-life power supplies; low-power, high bandwidth communications; miniature, low-power sensors; and sensor embedding technologies. The Fiber Optic and Miniature Sensors group within the Navigation and Control Technologies Branch of the Missile Guidance Directorate, a part of the AMCOM RDEC were tasked to determine the state-of-the-art in miniature sensors technology as it applies to the RRAPDS mission; develop concepts for sensors and sensor implementation programs (applying maturing technologies in steps); and investigate the reliability of MEMS for long term storage applications.

The potential applications of health-monitoring, diagnostic, and self-healing technologies are limited only by the imagination. Utilizing budding technologies, one envisions weapon systems that warn the user of exposure to conditions beyond their manufactured specifications; systems that invoke self-healing or corrective actions, such as miniature temperature control agents (mini-fans, micro-air conditioners, or ultra low-power heaters); and systems that answer queries as to their manufacturing identification, location, maintenance schedule, and current health.

Some reasonably determinable challenges in identifying effectual applications of MEMS devices are: 1) assessing the cost versus benefit for added features; 2) determining the sequencing of implementation (i.e. properly predicting the order and timing of technologies' maturation); and 3) defining system functions that are attractive to multiple users -- in order to boost production numbers and, thereby, lower cost. But, perhaps the more difficult aspect of design faced by the RRAPDS program is, as for many emerging technology implementation programs, determining specific requirements for the proposed sensor system while the mission ambitions remain as obscure as the vastly varying host system possibilities. Many valid questions arise that can be answered definitively only when a specific mission for a specific host system is addressed. Questions such as: Should the missile health monitoring system be designed as a post-production add-on or as an embedded, intricate part of the pre-production missile design? Should it be part of the missile at all? Should the sensors reside in the launch tube, or in a shipping container, or even just 'near' the missile? Is active or passive sensing needed? What needs to be measured? -- To what accuracy? -- Over what range? -- How much data? -- How often? Etc. Nevertheless, there are some commonalties among requirements. Certain sensor issues exist for all host systems -- to some degree. These include power consumption, reliability, maintainability, size, and cost. Therefore, it is essential that these attributes be addressed with predilection. Additionally, certain sensor requirements exist for a majority of systems. These are measurement of extremes in temperature, shock, humidity, and vibration. In order to assure that these commonalties are sufficiently addressed, a baseline system was chosen that exhibits the most technologically challenging requirements in each of these areas. Specifications for the RRAPDS are being developed based upon anticipated requirements and mission for the Future Combat System (FCS).

To date, MEMS sensing devices have been limited primarily by their environments, -- i.e. the very parameters that we wish to measure are those that are least tolerated by the devices. To measure acceleration is not an issue, but to measure it while the temperature is –30 degrees Celsius, or is ramping at 0.5 ° C/sec becomes an issue – and these are not the extremes. Measuring temperature is not a problem, but measuring temperature over the full military range, and beyond, with an accuracy of ± 2 degrees is not easily accomplished. Add to this the possibility of measuring the desired parameter after the sensor has sustained low-g impacts or prolonged vibration or humidity exposure, and the reliability of the measurement is now in question.

In addition to the basic sensor issues, service and storage life requirements present additional dimensions to an already complex problem. In regard to both peek service requirements and storage life requirements, perhaps the greatest technology barrier to be breached is that of miniature, long-life power sources for the health-monitoring sensors. At this point, the power source is the limiting factor for size miniaturization, as well as for service life and, in some cases, for measurement range capability. This is a serious concern, but potential solutions do exist. MEMS energy scavengers and storage devices are in development. With this concept, numerous energy 'cells' can be placed on a single substrate with scavengers (solar, thermal, chemical transducers) and storage devices. In time, these 'mirco-batteries' may provide on-board energy for sensors, leading to autonomous remote sensing devices.

While facing technology challenges on several fronts, the RRAPDS program is making significant progress. A functional prototype has been developed, and great progress has been achieved toward packaging and mounting of MEMS sensors. Additionally, mission scenarios have been much more clearly defined and integration with logistics is going well.

4. OPTICAL MEMS DEVICES AND AGILE LASER BEAM STEERING

As MEMS technology makes progress on all fronts, DOD is constantly monitoring the relevant endeavors for benefit to future Army weapon systems beyond inertial MEMS. A few new items that are of relevant interest, along with a description of the recent activities are provided below.

4.1 Optical MEMS and free space laser communication

Free space laser communication technology has made tremendous progress, which is reflected in the Annual Conference Proceeding published by SPIE. The most recent review articles, Ref. 6, on the subject, provide a general picture. It is reported that WDM configuration at 2.5Gb/sec per channel can transport data, voice and video. Field experiments are conducted through 4.4 km with fixed terminals and 16 channels. The technology is based on present day telecommunication components such as diode laser transmitters, high power amplifiers, operating within 1550 nm optical window, and high sensitive receivers. The transfer of the technologies for a battlefield theater imposes considerable difficulty. The main problem is that the receivers and the transmitters move against one another in unpredicted pace. The need of a quick handshake between the two for communication is the major focus in the near future. The development of an agile beam steering is the thrust of the new DARPA program. In the following paragraphs we describe the critical part of technical background of the agile beam steering, which requires a three-dimensional movable mirror system.

4.2 Optical MEMS in three dimensions

Movable structures, or micro-optical elements can be manufactured monolithically on the same substrate, using batch-processing technologies. Some notable optical devices for telecommunication including optical switches, optical cross-connects are discussed elsewhere, Ref. 7. Here we emphasize the integration of an entire free-space optical system in a single chip. The system consists of optical elements, refractive and diffractive lenses, etc. well established in the optical MEMS. The three dimensional opto-mechanical supports, and adjustable structures like micro-positioners are the focal point of present interests as demonstrated here.

The basic structure has five polisilicon sections, as shown in Fig. 3, which are joined by polarity hinges, which are surface machined. These hinges, the major contributions of the UCLA group under leadership of Prof. Wu, can rotate relative to each other with accurate control of position to 2μm for both vertical and lateral directions. The most important point is that the whole system is self-assembled, with the flexibility, in addition to the three dimensional movement, that it has a traveling distance of 100 μm with fine resolution of 27 nm. The precision controls along with applications are demonstrated. Fig. 3b shows a setup for testing how a micro-ball, one hundred times heavier than the supporting plate, is raised by 100 μm above substrate. It shows the versatility of what can be added to the original setup. Fig. 3c shows the integration of vertical cavity surface-emitting lasers (VCSEL). Fig. 4 shows a scanning micro-lens flipped over a VCSEL whose light beams focused or collimated by the micro-lens. A two-dimensional scanning with a range of 8 degrees has been demonstrated. The extension to optical interconnect in free space would not be a problem in principle.

The drawbacks of the present RF communications are: it needs a tower site, it can be easily jammed, intercepted and targetable, and it has relatively limited bandwidth. The advantage of laser communication is the enormous bandwidth, which permits voices and images to be transmitted. Also narrow beam width helps covert operations, as laser propagates in an extremely narrow direction. The comparison above made laser communication very attractive, but there are several issues to be resolved before a system becomes useful: eye safety, which has drawn a great deal of attention in recent years. Secondly, because the scattering cross of light is proportional to $(1/\lambda)^4$, the shorter wavelength (λ) of the laser light makes it very difficult to propagate through rain or fog. This intrinsic problem limits the application to shorter path length, which is indeed the case for the Army. Another issue is the narrow beam direction of the laser that requires an instrument for steered agile beams that is the subject of discussion here. Fig. 5 shows the evolution of communications in the Army.

The general purposes of the DARPA program are reduction of the size of gimbals steering system by a factor 30, and weight by a factor 60.[8] Roughly speaking, the weight is about 100 lbs for a mounted vehicle and 10 lbs for dismounted (backpack) ones. It is to be man-portable, and electronically steered lasers. Fig. 6 summarizes the new system. The system comprises three essential parts as depicted in the figure. Transmitters use VCESEL arrays in the wavelength around 1310 – 1550 nm. The major component is beam forming for two functions: deflection and steering of the beam with rapid steering speed. Micro-optical diffraction grating and the liquid crystal films, as discussed in the literature, can address both issues. However, the optical MEMS undertaken at Berkeley by K.Y. LAU (one of the principal investigators of the DARPA project) has the attractive feature of the fast scanners using electrostatic comb-drive actuated micro-mirrors. The scanner has a response time less than 16 ms with beam width of 30 mrad. The micro-mirrors used here are similar to those discussed in the previous section.

5. RF MEMS DEVICES: RF–MILLIMETER WAVE SENSORS IN MISSILE SYSTEMS

In Ref. 9, Prof. Brown gives an overall review of RF-MEMS, for general purposes and present technology available. Our colleagues in Ref. 10, in particular review specific potential application for missile system and RF-radar. For those not familiar with the subject Ref. 11 provides the background material.

MEMS techniques cannot come at a more opportune time from the military standpoint. As the world politics changes, so is the emphasis of the weapon system, as we all can understand. As a result, the current research in RF-radar aims at replacing a large, powerful and centralized system for long range to a distributed system for shorter range. The general ideas behind the military applications in addition to many other commercial interests fit the capability of MEMS so well.

RF-MEMS has two main advantages. First is the fact that MEMS operate for the actuation or adjustment of a separate RF device or component. A variable capacitor or filter is one example. Low power consumption is another obvious advantage. These special features of RF-MEMS, low insertion loss, high isolation, and minimal power consumption are well recognized, but we have to point out some critical issues: the material compatibility of silicon-based MEMS with existing RF components, has to be addressed. In addition, the mechanical control by MEMS is intrinsically much slower than the electronic control. The realization leading to an integrated RF-RADAR has a long way to go. In the following paragraphs, we review briefly the essential part of RF-Radar system for those in MEMS community.

There are three classes of the MEMS actuation that are related to RF components: 1) turnable micromachined transmission, wave-guides and resonators are located outside of RF-circuit line, 2) the shunt electrostatic microswitches, tunable capacitors and inductors are inside the RF-circuit with decoupled role of actuation of RF circuit, and 3) the third class has the capacitively coupled resonator as an example, which has both RF function and is coupled to the actuation. At present, the second class is the most rewarding area by taking advantage of the MEMS devices capable of operating on a few to 100 GHz frequency.

The primary device for present attention in RF-MEMS is the switch, which function in many different places: RF circuit, mechanical structure, or contacting device. The common types are now discussed. The cantilever consists of a metal strip and dielectric that is fixed in one end and suspended over free space. A bias voltage can force the top contact in free space in the "off" position to the bottom in the "on" position. The bridge-type also has a metal and dielectric fixed at both ends and suspended over free space with operation similar to the cantilever.

Now let us focus on a radar system. Various actuation techniques involved are investigated in different directions, electrostatic, magnetic piezoelectric, shape memory alloys and thermal-electric mechanical. Among these efforts, the electrostatic method is the most advanced. However, the slow switching speed at millisecond range requires a high voltage and this limitation urges other alternatives. A block diagram of RF radar is shown in Fig. 7, where the potential devices of RF MEMS components to replace the existing system are indicated.

Switches, which control variable phase delay and attenuation among the antenna and transmission lines via the use of ferrites or p-i-n junctions, deserve the attention of MEMS. In addition, there are many RF-components that should be of interest to MEMS: couplers and hydrides for divisions and combinations of the signal, various filters for detection and mixing, and channel switching for time multiplexing and pulse modulation. Each subsystem in the front end has loosely similar components, and we name a few here and leave the actual work for the experts in the field. As pointed out in Ref. 9, these RF components are the most rewarding area at present. How to extend the effort to achieve a low power radar system is a challenge for the future.

6. SUMMARY

It is obvious from the literature that progress in MEMS is made in incremental steps on an annual basis with the exception of some dramatic achievements, which are being made in the material and/or electronic aspects of the manufacturing process. Traditionally the military tends to be very conservative, which makes the transition to advance technology a lengthy process. Military acquisition strategy and component qualification play a major role in the lengthy process for acceptance of new technology for system applications. AMCOM is playing a key role in evaluating and qualifying inertial MEMS components for transitioning the new technology into current and future tactical missile systems. Testing over military environment is the first step in integrating the new technology into weapon systems. AMCOM, which has first class inertial testing facilities, would like to test your inertial MEMS components. As MEMS technology and new applications evolve, manufacturing processes and testing techniques must be devoted to meeting new requirements and military budget constraints. For example, it is already envisioned that MEMS devices for high-g launch environments for use in both missiles and projectiles must be addressed in the near future. MEMS is a rapidly evolving transitioning technology and many opportunities cross the boundaries of both commercial and military applications. Progress is dynamic and MEMS-based devices will help shape the future fighting materiel.

Inertial sensors and environmental sensors represent near-term applications for the more mature MEMS devices. It is becoming more evident that MEMS technology can inherently enhance Army mission capabilities. The proper selections of MEMS technology to accommodate the Army's emerging missions can directly improve performance, reduce the cost of integration, and enhance reliability. The AMCOM RDEC is working diligently with DARPA and other Government agencies, academia, and industry to ensure the qualification of MEMS instruments for Army applications.

It was found that commercial-off-the-shelf (COTS) sensors meeting the full requirements of the RRAPDS program do not exist. Developing sensor technologies, however, show promise of providing many of the sensor needs. Four sensing parameters were selected for the baseline system. Sensors with limited performance do currently exist for measurement of these parameters. Prototype MEMS sensor suites developed by the University of Michigan and Berkeley University address the sensing parameters of primary interest and represent the state-of-the-art in miniature sensor suite development. However, these sensor suites still fall short of the ultimate RRAPDS goal, and remain only in the prototype stages of development at this time. Manufacturablity and packaging also remain issues for this program. These are obstacles that RRAPDS faces in implementing a suite of miniature, low-cost, low-power sensors for missile health monitoring applications. It is absolutely essential that the purpose of the RRAPDS not be thwarted by itself becoming a maintainability or reliability issue. In summary, much work is needed to push the envelope for environmental sensor technology in order to address the needs of the RRAPDS program.

We have emphasized the need for a rapid and covert communication system for mobile forces of future Army. The present technology advancement in free space laser communication can be introduced for military applications. We explained in this paper the advantage of laser communications over the present system and the difficult and challenging issues involved. We also introduced the new DARPA program initiated to solve the major problem of providing a system for continuous and agile laser beam steering. The critical components, as we discuss here, are a direct product of optical MEMS – the self-assembled micro-mirror system that can be subject to rapid precision control of both translational and rotational motion.

RF-MEMS techniques have enormous potential for military RADAR systems, but current MEMS developments in this area make progress only in the component level. How to reach the system level remains a challenge for the future. Although we cannot predict the pace of progress for RF-radar, it is clear that a joint military-industry development path is required. The military market volume for RF radar is limited, whereas the commercial wireless market is enormous. The technical similarity of the two makes it imperative for the military to leverage Industry's commercial development to achieve affordability.

In addition to the inherent cost savings provided by MEMS technology, MEMS devices will provide major cost savings to the military via expanded production through utilization of cross-system commonality, as well as industrial-base production. While there is currently little commercial support for military applications, military programs for MEMS sensors development would make it economically feasible for commercial plants to commit to producing the militarized MEMS sensors.

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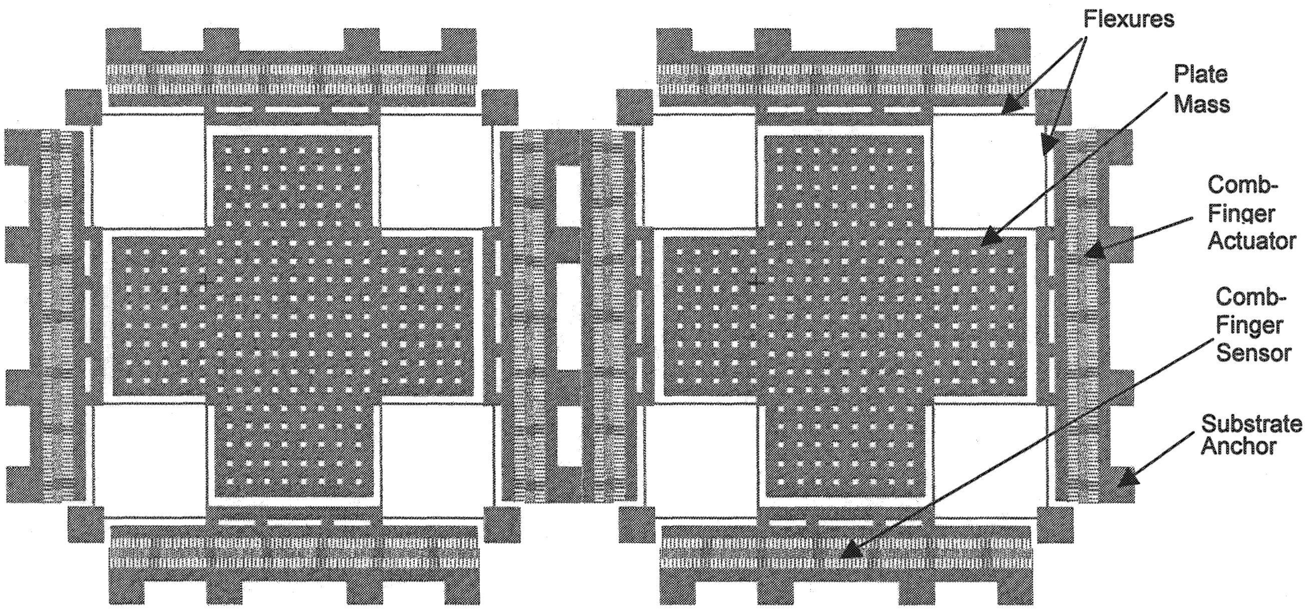

Figure 1: AMCOM Developmental Roll Rate Sensor

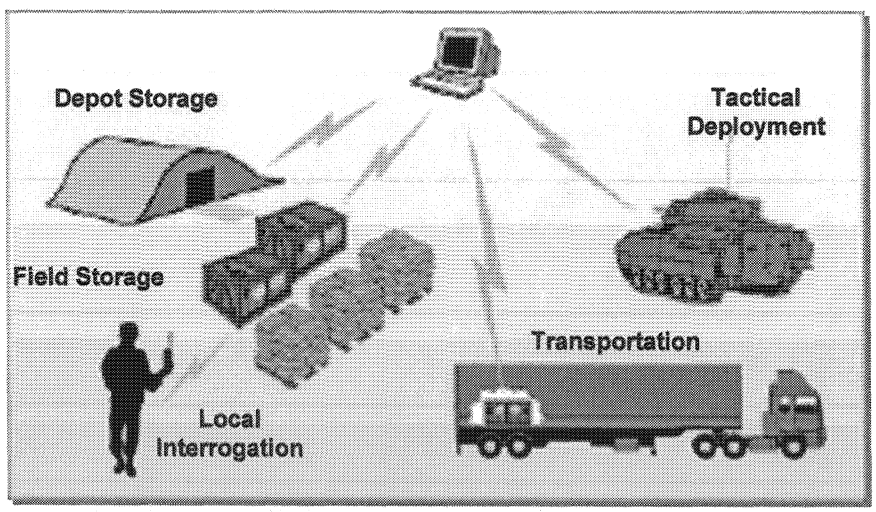

Figure 2: RRAPDS Technical Concept

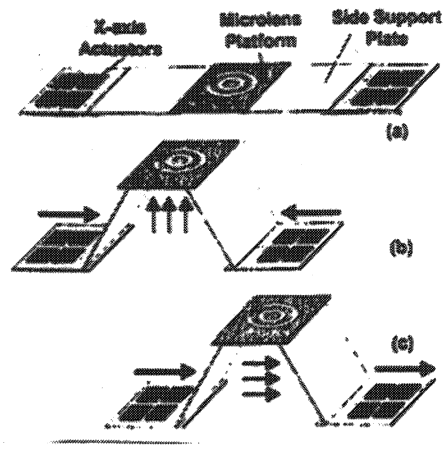

Figure 3: Micro Positioner Basic Structure

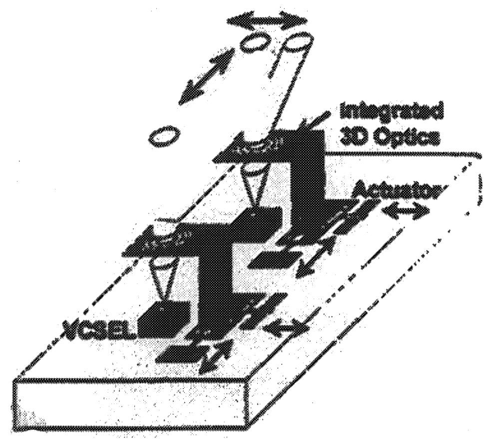

Figure 4: Scanning Micro-optics for VCSEL

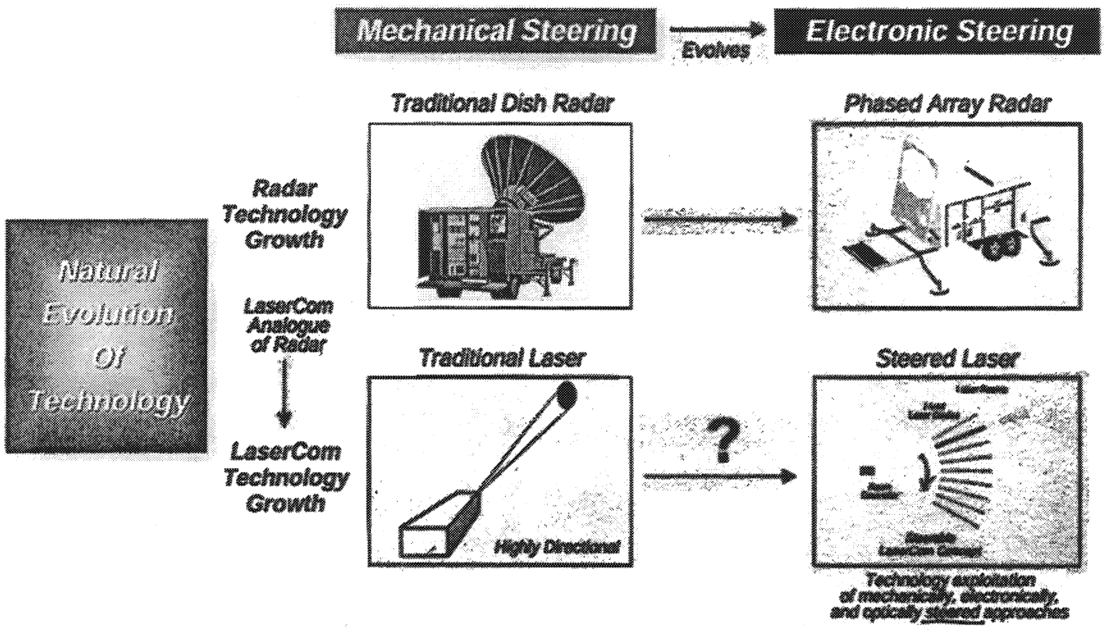

Figure 5: Evolution of Communications in the Army

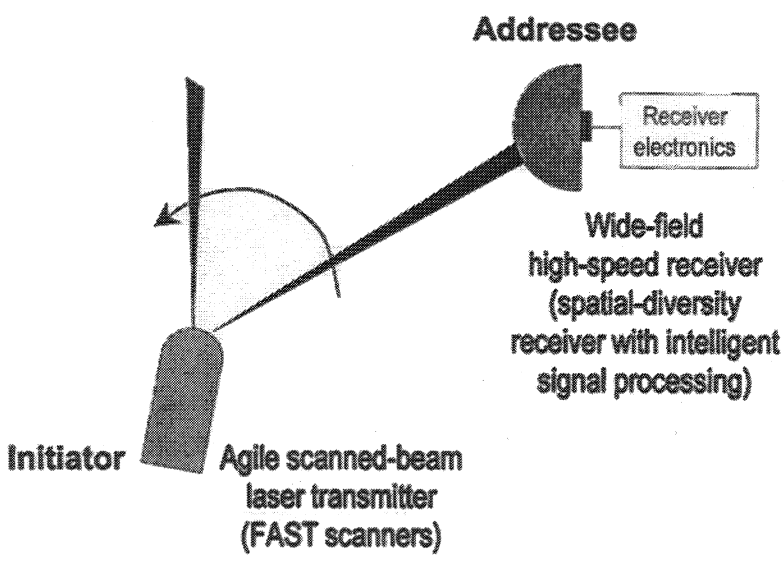

Figure 6: Steered Agile Beams (STAB)

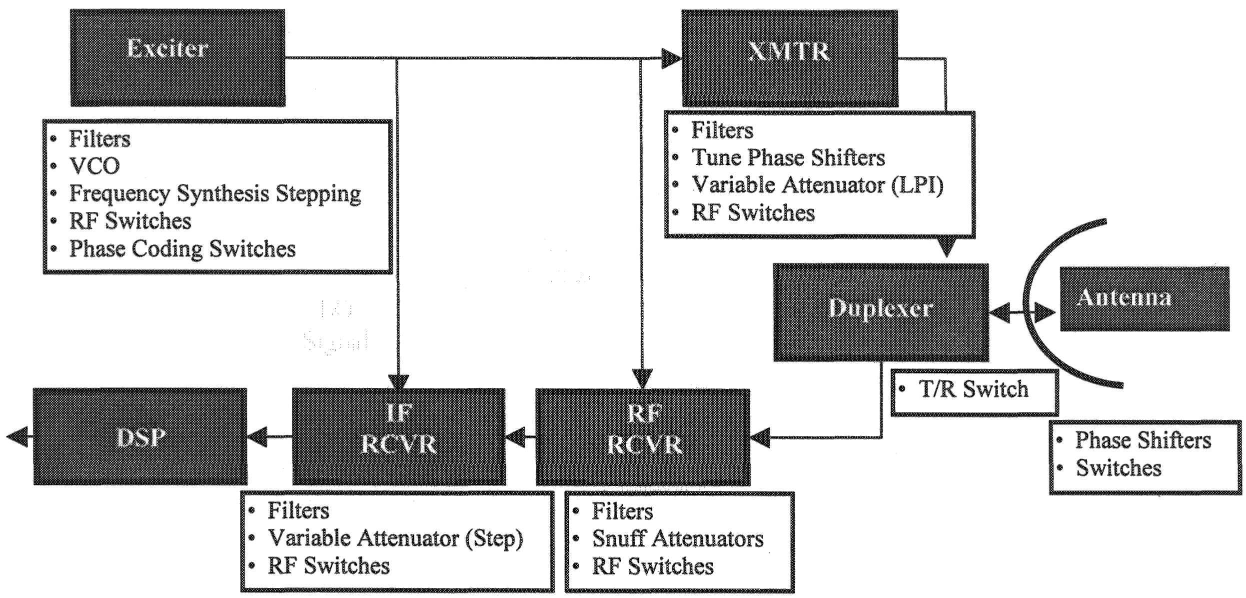

Figure 7: RF Radar Block Diagram