# MEMS-Based Sensor Arrays for Military Applications

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## ABSTRACT

Scientists and engineers at the Army Aviation and Missile Command's (AMCOM) Research, Development and Engineering Center (RDEC) are cooperatively working with the Defense Advanced Research Projects Agency (DARPA), other Army agencies, and industry to provide technical solutions for the Army's transformation efforts into the 21st century force. Advanced technologies are being exploited to achieve the performance and cost goals dictated by the emerging missions of the Transformed Army. It is well established that MicroElectroMechanical Systems (MEMS) technology offers the potential solution to cost, size, and weight issues for the soldier, missile, gun, ground vehicles, and aircraft applications. MEMS sensor arrays are currently being investigated to meet system performance requirements and provide more robust mission capability. A Science and Technology Objective, Research and Development Project is underway at AMCOM/RDEC to develop controlled MEMS sensors arrays to provide for full military dynamic performance ranges using miniature sensor systems. MEMS-based angular rate sensors are enhanced with vibration feedback from MEMS accelerometers for output signal stabilization in high-vibration environments. Multi-range MEMS-based accelerometers, cooperatively developed by Government and industry, are being multiplexed to provide dynamic range expansion. An array of integrated accelerometers is expected to increase the dynamic range by an order of magnitude. Future projections suggest that MEMS sensor array technology will be applicable to a broad range of military applications, which include environmental sensor suites for structural health monitoring and forward reconnaissance and surveillance; and optical and radio frequency phased arrays for fast beam steering.

Keywords: MEMS Sensors Arrays, Chemical, RF and Optical MEMS Sensors, MEMS Phased Arrays

## 1. INTRODUCTION

Considerable attention has been focused recently on inertial MicroElectroMechanical Systems (MEMS) sensors development for military applications. The attractive features of MEMS, inherent small size, low power, and low cost, make MEMS devices a viable alternative to optical-based inertial rate sensors for applications requiring >1 deg/hr bias stability. A few years ago the Defense Advanced Research Projects Agency (DARPA) initiated several programs to develop acceleration and shock-resistant inertial MEMS devices for operating in hostile environments.[1] The Army is currently conducting a manufacturing and technology program to develop precision, miniature, low cost, high-g survivable MEMS-based inertial measurement units for a host of weapons.[2] Both these projects employ single MEMS sensor designs.

The thrust of the new Army requires systems that are responsive to current and future warfighter needs and possess wide dynamic operational and storage range capabilities. For these stringent requirements, most single MEMS sensor designs are nearing physics and fabrication limitations. The current approach is to integrate multiple MEMS sensors for performing measurements in high dynamic environments. The Army Aviation and Missile Command (AMCOM), Research, Development and Engineering Center (RDEC) is conducting a research and development program to demonstrate MEMS sensor arrays for improved systems performance. Fig. 1 shows an array of accelerometers that are discussed in this paper.

Although the author serves as contract technical monitor and is aware of unique design approaches for a number of ongoing MEMS efforts in industry, the details of design techniques and processes are not discussed in this paper due to proprietary restrictions. Consequently, most of the material provided here is taken from open literature, but some parts are based on private communications.

An overview of MEMS sensor arrays designed for various applications from the user's perspective is provided in this paper. The paper is structured as follows. Section 2 discusses the Army Transformation. MEMS sensor arrays and the motivation for MEMS arrays are presented in Sections 3 and 4, respectively. Our current MEMS sensor array project is discussed in Section 5. Future projections for MEMS sensor arrays in military systems are discussed in Section 6. A summary is provided in the final section.

## 2. ARMY TRANSFORMATION

The Army has been gradually changing over the past fifty years. The recent Army transformation thrust, which demands a rapidly deployable, flexible, joint force, represents the most ambitious change during this century. It calls for a strategically responsive force to combat current and future conflicts around the world. Since September 11, 2001, the Army has been more visible than ever. Recently, television viewers of the military operations in Afghan received a glimpse of the present status of the combat troops and their gadgets; night vision, light assault guns, communication through GPS, etc. The main point is that future conflict involving the Armed Forces will most likely be small numbers of sophisticated units for unspecified missions.

Since technology is advancing at such a fast pace, the future scenario cannot be defined in present terms. However, a partial list of sensors and devices proposed for the near future is provided: thermal sensors, chemical sensors, communication devices, and robotic sensing devices. Many small units will function independently and cohesively interact with other units under the new weapon system implementation.

The phrase " transformed army" is perceived as not to define the future Army operation but the entire weapon systems to go with it. Obviously the following items characterize the new weapon systems.

1. The US must be ready for a conflict at any time and place. Therefore, the ever-evolving technology can never settle on a given system to suffice for many years. A large number of weapons must be produced at low cost.
2. Lightweight and small volume packs to fit and be carried by a small number of people are needed.
3. Automatic sensing devices and deployment of remote robotic sensing are required to eliminate casualties.
4. Effective interfacial communication gadgets for individual identification are needed.

Doctrine and requirements dictate technological trends. The envisioned doctrine, which is evolving to make use of new sensor technologies, focuses on precision engagement, dominant maneuver, and information operations.[3,4] Advanced technology development is required to sense the enemy at operational and strategic depths and select attacks on prioritized targets. Attention is rapidly moving toward military operation in urban terrain, especially in the case of low technology adversaries. Next generation sensors must be capable of operating in urban settings where thermal and dynamic environments are evident. A proper mix of sensors for urban and rural environments is needed. Multiple integrated sensors are proposed for information awareness, target detection, location and identification. The distinct types of MEMS sensors arrays are discussed in the next section.

## 3. MEMS SENSOR ARRAYS

The challenges to meeting the stringent requirements of the transformed Army are insurmountable using single MEMS sensor designs. MEMS sensor arrays are being investigated to enhance system performance and provide for robustness required for military systems.

Table 1 (Ref. 5), which outlines the general characteristics of microsensor array devices, shows three different generalized categories (identical, different, and similar) of sensor arrays. The obvious theoretical advantage of arrays of identical sensors is the enhancement of the signals by a factor N, where N is the number of the identical sensors, while the random noise of a combination of N sensors should increase proportional to the square root of N. In practice, the manifold of sensor arrays is much more involved. Fig. 2 (Ref. 5) shows the integration of N sensors and their associated components. The most rudimentary sensor arrays should have an array processor, which can hardly achieve the major expected function of sensor arrays without integration of both sensing and preprocessing. The ideal sensor arrays (smart microsensor array devices [SMAD]) can perform far beyond many single sensors, as shown in the self-explanatory Fig. 2.

A good example in the identical sensors category is the radiation sensors arrays to increase sensitivity. Sometimes a two dimensional array is essential for a thermal map of a radiated signal in the spatial arena. Since the technology is relatively mature, we will not dwell on the subject. Similarly, the development of optical SMAD has been both technically and commercially successful.

One example of different sensors is the pressure sensor with temperature compensation in the same module. Similarly, the electronic nose developed recently requires far more capability than that of an individual sensor. First ambient conditions such as temperature and humidity can affect the sensitivity, and the selectivity for a group of similar chemicals can further complicate the efficacy of the system as demonstrated in odor sensing. Integrated signal processing plays a major role. We will come back to this point later.

An array of multi-ranged accelerometers is an example of similar sensors. Each accelerometer is designed with a certain dynamic range. How to incorporate these similar accelerometers for a combined larger dynamic range will be discussed in Section 5.

The integration of microsensors for multifunctions can be challenging. The theoretical and physical limitations on single MEMS sensor designs are addressed in the next section.

## 4. MOTIVATION FOR MEMS ARRAYS

The direction of current microsensors research is stimulated by the need for telecommunication and biomedical and health products. As MEMS technology advances to more mature levels, the next challenging issue that must be addressed is how to push MEMS devices from the micro-scale to sub-micron levels. High frequency resonators and associated arrayed filters push for smaller dimension, and ensuing technical issues need increased attention. Since they are the building block of other MEMS applications, force-sensing MEMS devices are selected here to address the concerns associated with the ultimate limit and constraint imposed on the design. Ref. (6) provides a good example. A typical accelerometer, which has a proof mass of $10^{-9}$ kg and minimum detectable acceleration of 0.5 milli-g, corresponds to a force of 0.5 pico-N with a displacement of 0.5 p-m. This force approaches the thermodynamic limit, as illustrated here. The minimum force that can be measured by a vibration system, limited by the Brownian motion, is[6]

$$(F_{min})_{noise} = [4kK_BTB/Q\omega]^{1/2} \quad (1)$$

where k, $K_BT$, B, $\omega$ and Q are the structure stiffness, temperature in energy unit, bandwidth, resonance frequency, and the quality factor, respectively. When expressed in terms of the geometric factors of a cantilever beam, $(F_{min})_{noise}$ is proportional to

$$[2tW/LQ*K_BTB]^{1/2} \quad (2)$$

where L, W, and t are the length, width, and thickness, respectively. It is clear that the thickness t and width-length W/L ratio can help a great deal with producing a Q value as high as possible for reduced $F_{min}$. This very much-idealized example can be used to discuss several issues of interests. It is clear that the high aspect ratio L/W is desirable as undertaken by professors at Michigan Ref. (7). Another effort is to reduce the thickness, which most MEMS-based fabrication techniques in silicon-based wafers cannot be reduced much more. Processes that start with silicon-on-insulator (SOI) wafers or molecular beam epitaxy (MBE)-grown GaAs/AlGaAs hetero-structures are promising. SiC gains more importance and owns its recognition for high stability, which is essential for resonators in communication.

High quality (Q) value is always critical for performance. However, there are many contributing factors to reduce Q value. Gas damping is always a dominant degradation factor, and can be addressed by better vacuum condition at much higher cost. Other dissipation mechanisms are not qualitatively characterized, except the surface interaction, which can be a significant factor. Surface interaction is reportedly improved with annealing process.[6] In summary, the Q factor is in general decreased with device size, and this fact needs constant attention.

In conjunction with the force, we consider the displacement transducer to detect the deflection. We mention here a few general pickoff methods: optical, piezoresistive, tunneling and capacitive. All have been used successfully with associated intrinsic problems as discussed here. The optical method requires a reflecting target larger than the operational wavelength, which puts a constraint on the size of miniaturized cantilevers for better sensing. Piezoresistive cantilever is essential for some applications such as pressure gauges, but is characterized by the temperature sensitivity leading to larger (1/f) noise. Overall both the piezoresistive and capacitive will face severe intrinsic problems when the size is pushed below 1 micron or pN/Hz. The tunneling method is the most impressive method to detect deflections on the order of pico-m, at the expense of higher cost.

## 5. AMCOM'S MEMS SENSOR ARRAYS PROJECT

AMCOM's approach is to combine MEMS sensors into arrays to improve performance. Several Government programs have been initiated to develop MEMS devices for use in military applications requiring systems and sub-systems that have wide operational and storage range capability. AMCOM/RDEC is currently conducting a Science and Technology Objective (STO) project to develop integrated MEMS sensor arrays to solve the dynamic range problem associated with hypervelocity missiles and missile health monitoring systems. This project is discussed in more detail below.

### 5.1 Inertial MEMS Sensor Arrays

Fig. 3 (Ref. 8) shows a MEMS-based angular rate sensor output signal, plotted as a function of time. As shown, the output signal can be corrupted or become very noisy in high-vibration environments. The AMCOM research and development project is developing schemes to enhance MEMS angular rate sensors by using vibration feedback for signal stabilization in high-vibration environments. Fig. 4 shows the output signal, plotted as a function of time, after processing of acceleration measurement using a separate accelerometer. This output signal is in a form that the angular rate sensor can easily distinguish and measure.

Multi-range MEMS accelerometers are being developed at AMCOM, as well as under DARPA/industry, and other Government agencies programs. MEMS accelerometers are designed to operate in a specific acceleration range. Three of these MEMS sensors are multiplexed to provide acceleration range expansion over an increased operational range. An array of integrated accelerometers is expected to increase the dynamic range by an order of magnitude.[9] An array of MEMS accelerometers has been presented in Fig. 1.

### 5.2 Environmental MEMS Sensor Arrays

Environmental sensors designed for missile health monitoring applications must be capable of measuring at least 10% beyond military specifications for tactical missile systems. Currently, there is no known temperature sensor that operates at low or ultra-low power (3.3V or 1.5V) that will meet the specifications for the Remote Readiness Assets Prognostics and Diagnostics System (RRAPDS) at the low power requirement. The AMCOM project is integrating two MEMS-based temperature sensors to form a multiplexed temperature sensor array for operation over military specifications plus 10%.

### 5.3 Combined MEMS Sensor Arrays

Fig. 5 is an illustration of a multi-chip/die module containing MEMS-based inertial sensor arrays. The three MEMS sensor arrays discussed in this section are combined to form a multi-dimensional integrated array of temperature-compensated MEMS accelerometers and angular rate sensors with averaging and bracketed, multi-level feedback control. An illustration of the integrated system is shown in Fig. 6.

## 6. FUTURE PROJECTIONS

### 6.1 Chemical MEMS Sensors

From a military perspective, a chemical sensor is intrinsically a composite device consisting of several other sensors (optical, acoustics, ultraviolet, or infrared). Generally speaking, it is a device for sensing some specific toxic gas from a remote site. To develop chemical sensors for a specific element/species one can use the spectroscopic method, which is not well established in optical MEMS. How to analyze and to ascertain the chemical is another issue. Some available methods use ultraviolet light to detect the changed absorption of the florescence or use infrared light which changes the wavelength; both methods depend on a coating material or an agent interacting effectively with the targeted chemical. There are many examples on this topic as quoted in Refs. (10,11).

AMCOM is developing a hybrid fiber optic data link for robotic operations and remote chemical sensing capability. It is only at the beginning stage. Future progress on this project will be reported at a later date.

### 6.2 RF MEMS Sensors

Radio Frequency (RF) MEMS techniques, which appear in a variety of forms, have gained enormous momentum in research and development. MEMS array devices applied to UHF (300 MHz – 3 GHz) systems are emphasized here. The advent of MEMS technology in recent years comes along at the right time for new weapon systems in a changed global political world as discussed by Brown Ref. (12). In RF radar systems one wants to replace a large powerful and centralized system for long-range operations within a distributed system for short distance operations. The manufacturability of Silicon VLSI leads to "RF system-on-a-chip". The family of integrated circuits available for global positioning systems (GPS) receivers is an example. The next phase of development is the design and fabrication of MEMS for RF -circuits that enable the integration of VLSI readout circuits or processors with miniaturized sensors and transducers. Specifically, from the perspective of military applications, there are many issues associated with the RF radar for advanced systems as pointed out by Yao.[13] Several issues include: many transmitters and receivers on the same platform demand high dynamic range, consideration for electromagnetic compatibility in general requires narrow-band filtering for both receivers and transmitters, and the all-important anti-jam in military applications necessitates high degree of frequency agility. It seems all these issues can be addressed within the framework of MEMS with a great deal of effort, because of the overwhelming advantages: isolation of the components reduces insertion loss and power consumption. The potential reduction of cost is another factor. The challenges for the future are plentiful. Mechanical actuation is much slower than the electronic switches. The "stiction" that can bond parts of devices are well known, and the problem can be exacerbated in the arrayed sensors. Finally, we mention the concern for material compatibility of the silicon-based devices and other materials such as gallium arsenide (GaAs).

Brown in (Ref. 12) elucidates how MEMS actuation is related to RF circuits by listing three categories: RF extrinsic, RF intrinsic, and RF reactive. Tunable micromachined transmission lines, switches, and capacitatively coupled micromechanical resonators are, respectively, examples in each category. The latter two are more rewarding to work with at present, as presented in current literature. The building blocks of RF circuits including switches, tunable capacitors, high-Q inductors, filters and high Q-mechanical resonators are meticulously reviewed by Yao in Ref. (13), who also includes the present achievements in each category at various laboratories. There are so many parameters involved to fulfill different requirements. A fair comparison of available MEMS switches is not possible. However, it seems MEMS relative to solid-state switches are better in high power handling at high frequencies.

Increasing the operating frequency to the UHF range on a chip would be an extremely attractive goal, which is undertaken by Ayazi at Georgia Tech.[7] One can achieve UHF by either reducing the mass or increasing the stiffness of the resonator. The required small mass (0.1 pico-gram) of the beam calls for nano-lithography, whereas very large stiffness can be obtained through high order degenerate vibration modes of a silicon disk. Manufacturing techniques are available with HARPSS (high aspect-ratio combined poly- and single-crystal silicon) MEMS technology, which is still an all-silicon process capable of producing arrays of silicon resonators of size around a few microns with lateral gap spacing of 10 nm between isolated silicon structures. Consequently, resonant element of the resonators, electrode and substrate are all silicon clamped free beams. Large forces are needed to drive the stiff resonator, resulting in large electric fields that can only be generated with extremely small air-gap capacitors on the order of 10 – 50 nm. Needless to say, such a small capacitance (3-4 femto-farad) is susceptible to parasitic capacitance, which must be integrated with the resonators. Another issue is the high vacuum required to achieve a large quality factor. It is reported that a Q value of 85,000 can be reached at 1 milli-Torr.

As we discussed earlier, cascading identical resonators can enhance the signal-to-noise ratio or quality factor. This effort naturally leads to narrow bandwidth filtering at UHF frequencies or improved selectivity. How to make the device CMOS compatible and to connect resonators through nano-scale wires for the final product are challenges for the future.

Finally, we mention MEMS-switched reconfigurable multi-band antennas, which is supposedly capable of serving different frequency bands from L (1-2 GHz) to X (8-12.5 GHz) with reconfiguration time on the order of a few milliseconds. It was reported that a patch module consisting of 3 by 3 arrays of patches can be connected together via MEMS switches. Needless to say, this part of work is in the preliminary stage.[14]

Whereas, MEMS holds much potential for RF radar, unfortunately, with technical issues to be resolved in the coming years, optical MEMS and laser radar find instantaneous matches. Progress of both areas, RF and optical, because of the low power and small sizes, conceivably, could be integrated together in one system in the near future. In view of the great prospect and optical MEMS as an intrinsically array sensors, we discuss in details in the next section.

### 6.3 Optical MEMS Sensors

The National Science Foundation is supporting the development of high-performance chip-scale beam steering micro-mirror arrays that can be heterogeneously integrated into infrared countermeasure modules.[15]

#### 6.3.1 Laser Radar and Optical Phased Array Technology

Laser radar can be considered as a large optical system. The performance is limited by cost associated with mechanical control and stabilization. The intrinsic difficulty in sub-micro-radian steering precision (optical wavelength), coupled with mechanical beam directing system, is almost insurmountable. Phased array technology using liquid crystals as the actuators has great potential for operating on low power even for large apertures and being inherent random-access devices. The device, which is independent of acceleration, is another good feature for missile interceptors.

A few words are in order on phased array techniques.[16] The same principle is used in microwave radar, where horn antennas are replaced by MEMS phased arrays. The fact that optical arrays are monolithically fabricated without discrete elements for phase shifters in contrast to transmitters/receivers modules in RF radar, the basic concept involved is similar with different implementations due to the enormous wavelength difference. RF radar beams usually are formed and steered into a two-dimensional array of elements, i. e. each transmitter forms its own beam with specific phase shifter, whereas optical laser phase arrays consist of phase shifters (passive) only with the beam space-fed. One-dimensional arrays are easily cascaded into two dimensions, however the implementation of many interconnects would be demanding future work.

The first step of beam steering is to introduce a linear gradient of optical path delay across the wave front, and this relative phase shift in the wave front will tilt the direction or steer the beam. Liquid crystals, which change the orientation of the molecules as well as the index of refraction under a static field, can serve this purpose. As the wave front experiences different values of index of refraction, the liquid crystal operation serves as a prism.

In order to gain a reasonable tilting, the thickness of the liquid crystal should be of the order of (wavelength/birefringence), which is about 5 microns at a 1-micron wavelength for a typical liquid crystal. Another good example is the use of cascaded micro-lens arrays. An effective device requires the agile motion of one micro-lens array with respect to another. The mechanical motion involved is very small, but must be precise, and can be achieved with piezoelectric transducers. Another possibility is to combine micro-lens arrays with liquid crystal-based optical arrays. This approach maybe preferable over piezo-electrically driven motion at the expense of speed.

### 6.3.2 Steered Agile Beams for Laser Communication

The drawbacks of RF communication include: the need for a tower site and easily jammed or intercepted, relatively limited bandwidth, and easily targetable. Advantages of laser communication include: an enormous bandwidth (1.2 Gb/s), which allows voices and images to be transmitted. Also narrow beam-width helps covert operations, as laser propagates in an extremely narrow direction. This comparison shows that laser communication is very attractive. However, there are several issues to be addressed: eye safety, which may be a solvable problem, as it draws a great deal of attention. Secondly, because the scattering cross-section of light is proportional to $(1/\lambda)^4$, the shorter wavelength of the laser light makes it very difficult to propagate through rain or fog. This intrinsic problem cannot be easily solved, unless the path-length is rather short. Another issue is the narrow beam direction of the laser that requires an instrument for steered agile beams, which is the subject of the discussion here.

DARPA is conducting a program to develop micro mirrors and lenses for optical beam steering. The general purposes of the DARPA program are reduction of the size of gimbals steering system by a factor of 30 and weight by a factor of 60. Roughly speaking, the weight is about 100 lbs for vehicle mounted and 10 lbs for dismounted (backpack). It is to be man-portable and electrically steered lasers.

In summary the system comprises three essential parts: the receiver and transmitters using vertical cavity surface emitting lasers (VCSEL) arrays in the 1310-1550 nm wavelength range. The major component is beam forming for two functions: deflection of the beam and steering of the beam with rapid steering speed using micro-optical diffraction grating and the liquid crystal films, as discussed earlier. This method has advantages and disadvantages over optical MEMS undertaken in Berkeley by K. Y. Lau. The major attractive feature in the new project is the response time of the fast scanning beam using electrostatic comb-drive actuated micro-mirrors. The scanner has response time less than 16 ms with beam width of 30 mrad.

## 7. SUMMARY

Several approaches for integrating MEMS-based sensors to increase system performance have been presented. AMCOM/RDEC's technical involvement in inertial MEMS development and most recent efforts to team with other innovators in the emerging field of radio frequency (RF) and optical MEMS for developing phased arrays for missile seekers illustrate AMCOM's commitment to advancing MEMS technology for use in military applications. AMCOM/RDEC is conducting several Science and Technology Objective (STO) projects to address the wide rotation rate and operational acceleration ranges of current and future weapons. Single MEMS sensors designs are nearing physics and fabrication limitations. MEMS sensors arrays are proposed to enhance overall system performance and substantially reduce cost via multiplexing low cost commercial-off-the-shelf (COTS) devices. An array of low cost accelerometers is expected to permit acceleration measurement from 1 milli-g to 1 kilo-g.

## ACKNOWLEDGEMENTS

The author wishes to thank C. C. Sung for fruitful discussions and technical input. The author also wishes to thank Sherrie Burgett, Guilford Hutcheson, Ralph Halladay, Sonya Read, Joseph Grobmyer, and Randal Cannon for useful contributions from their technical area.

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**Table 1: General characteristics of microsensor array devices**

| Sensors | Processor | Special function(s) | Example |
|---|---|---|---|
| **Identical** | **Adder** | **Signal amplification, Noise reduction** | **Thermopile** |
| | **Or logic** | **Parallel redundancy, Enhanced reliability** | **Process plant** |
| | **Voting logic** | **Fault-tolerance** | **Safety-critical systems** |
| **Different** | **Multiplexer** | **Concurent monitoring of many variables** | **Multisensing** |
| | **Microprocessor** | **Automated compensation of dependent variable** | **Pressure sensor with temperature compensation** |
| **Similar** | **Microprocessor** | **Extraction of features from multivariate data** | **Electronic Nose, intelligent cameras** |

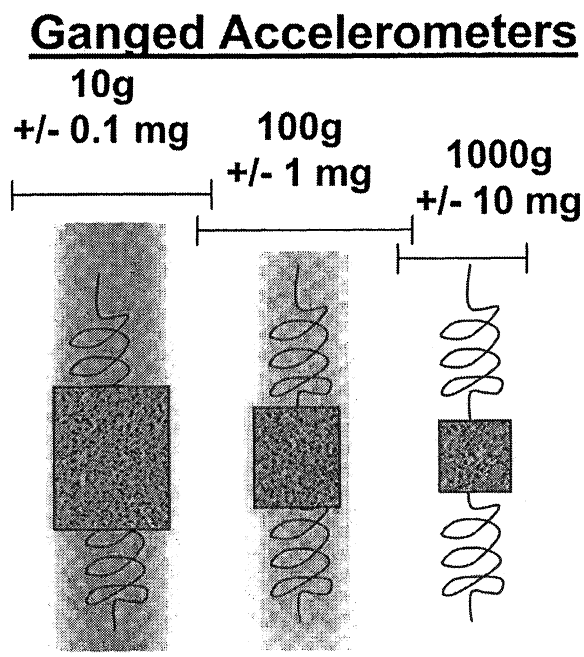


Fig. 1. Sensor Array for Accelerometer

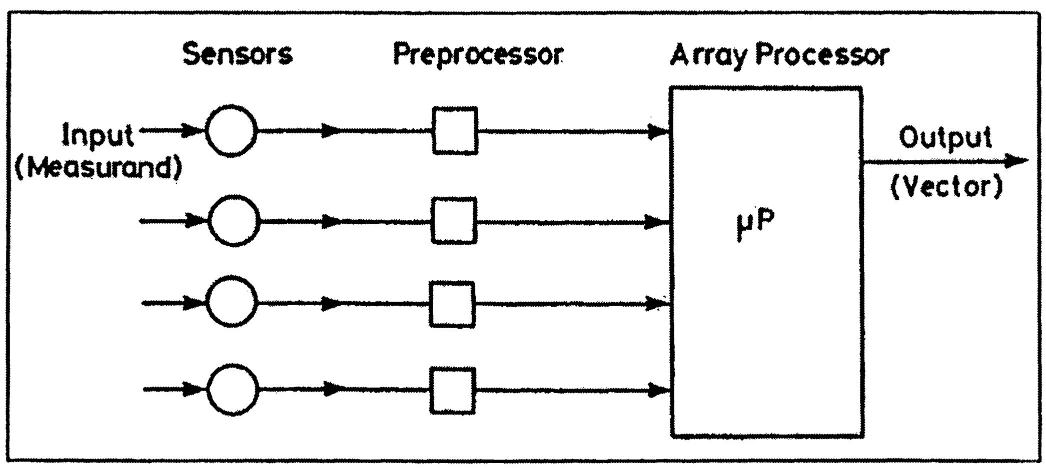


Fig. 2. Ideal Array Sensors: Smart Microsensor Array Devices

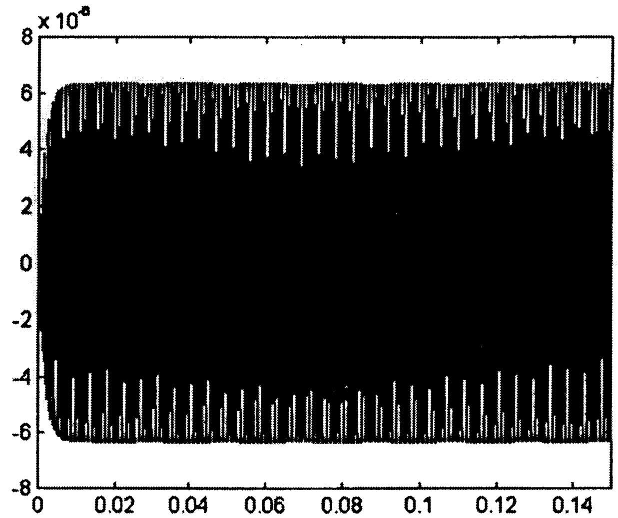


**Fig. 3. Output Signal of a MEMS-Based Angular Rate Sensor Undergoing Large Vibrations**

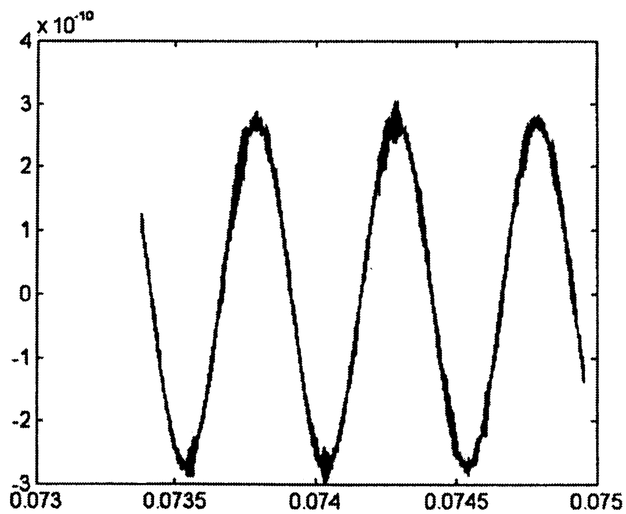


**Fig. 4. Output Signal After Processing of Acceleration Measurement Using a Separate Accelerometer**

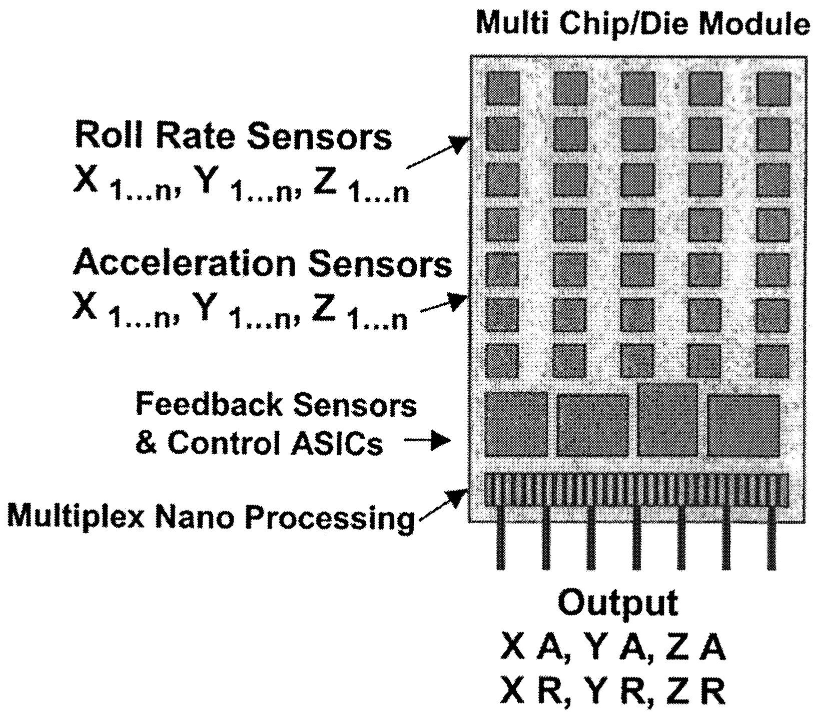


**Fig. 5. Multi-Chip/Die Module Showing MEMS-Based Inertial Sensors Arrays**

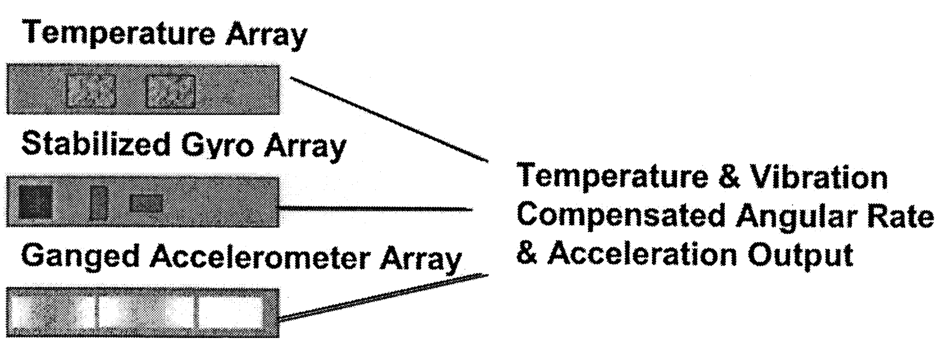


**Fig. 6. Integrated Sensor Array**