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REVIEW PAPER

Global Environmental Microelectromechanical Systems Sensors: Advanced Weather Observation System

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ABSTRACT

The technological developments in microelectromechanical systems (MEMS) have resulted in conceptualisation of a next generation observation system called global environmental MEMS sensors (GEMS). GEMS consists of a large number of airborne probes that will remain suspended in the atmosphere for long durations and take *in situ* measurements of pressure, temperature, humidity, wind direction and velocity as these are carried by air currents. It is envisaged that GEMS network would provide a systematic understanding of the earth's atmosphere and would improve weather forecast accuracy, well beyond the current capability. In addition to gathering meteorological data, probes could be used for environmental monitoring of particulate emissions, organic and inorganic pollutants, ozone, carbon dioxide, and chemical, biological, or nuclear contaminants. The GEMS concept requires integration of communication engineering and instrumentation with other evolving technologies. This review describes in detail the new observation system designed for environmental monitoring and its potential application in predicting cyclones and monsoon, and measurement of urban air pollution in India. The possible application of the GEMS system during military operations has also been brought out.

Keywords: GEMS, global environmental MEMS sensors, MEMS, microelectromechanical systems, weather forecast, networking, deployment, cyclone, monsoon, military

1. INTRODUCTION

For understanding the earth's atmosphere and weather forecast accuracy, 3-D meteorological and air quality data are valuable. The global environmental microelectromechanical systems (GEMS) will feature a massive, wireless network of *in situ*, micron-scale airborne probes to monitor all regions of the earth with unprecedented spatial and temporal resolutions. The probes are designed to remain suspended in the atmosphere from hours to days and take measurements of meteorological parameters that are commonly used as dependent variables in numerical weather prediction (NWP) models.

The GEMS concept is revolutionary because it foresees the future integration of evolving technologies like MEMS, to realise an environment observation system which will be scalable and applicable over a broad range of weather and climate phenomena that have impact on mankind.

The NASA Institute for Advanced Concepts (NIAC) initiated the Phase I GEMS project in May 2002. The Phase I effort focused on validating the viability of the GEMS concept and defining the major feasibility issues[1]. In the Phase II of the Project, which ended in August 2005, the feasibility issues were studied in detail to examine the potential performance and cost benefits. In January 2006, ENSCO Inc and the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) Weather Office started the GEMSTONE Project to build and field test prototype probes in the natural environment of the earth's atmosphere[2]. It included probe and system engineering as well as laboratory and field tests from September 2006 through May 2007. Though the original idea to pursue miniaturisation of the entire probe towards micron-size was modified based on communication, power, terminal velocity requirement, and available technology, this review paper mainly highlights the original idea behind this revolutionary weather observation system.

2. BACKGROUND

The field of meteorology has undergone many technological breakthroughs during the past two centuries. Increased understanding of the atmospheric processes resulting from these technological breakthroughs has led to vast improvements in the accuracy of weather forecasts. With the advancement in the computer technology, meteorologists have been provided with automated forecast guidance from NWP models which are capable of rapidly solving the equations of atmospheric motion, and integrating these solutions forward in time and thereby providing better and accurate weather forecasts[3].

2.1 Limitations in Present Meteorological Observation

Though significant progress has been made in observing the atmosphere at finer spatial and temporal scales over many areas of the world; yet it can be observed that *in situ* observations are not distributed evenly around the globe, and are sparse especially over oceans, high latitudes, and politically-sensitive regions.

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The following limitations may be found in the current weather observing systems[1]:

(i) Weather balloons lack in both spatial and temporal resolutions

(ii) Space-based observing technology such as low earth orbiting (LEO) satellites currently provide high spatial resolution images, but suffer from inadequate temporal resolution, insufficient vertical resolution, uncertain or unknown calibration, and accuracy errors over years

(iii) The most sophisticated current-generation sensors (e.g., ground or space-based lidar and infrared instruments) do not provide all-weather capability since these cannot penetrate optically through thick clouds

(iv) Satellites, radars, and other remote sensors do not currently provide a complete data set required to initialise NWP models since these measure radiance or reflectivity instead of NWP model-dependent variables such as temperature and moisture.

Without high-resolution observational data to improve the initial conditions, progress toward attaining best predictability with NWP models will likely be hindered.

2.2 Previous Work Done

The design and development of prototype, millimeter-scale probes using MEMS sensors was the focus of the 'Smart Dust' Project at the University of California (UC), Berkeley, since 1998. Kahn[4], *et al*. envisioned numerous applications for smart dust and suggested that air currents could transport the probes to record meteorological observations for as long as they remain suspended in the atmosphere[4].

Researchers at the Centre for Wireless Integrated Microsystems (University of Michigan) have developed an integrated gas chromatography system operating at 1 mW of power in a volume of 1 cm^3, capable of detecting over 40 specific gases[1].

The probe size is important because the devices must be small enough to remain suspended in the atmosphere from hours to days. At the current mm size, a probe deployed at 20 km altitude would reach the ground in < 0.5 h in the absence vertical air motion. Under identical conditions, a probe size of the order of 100 µm would take nearly 70 h to fall from the same altitude[1].

3. CONCEPT DESCRIPTION

The objective of the GEMS project is to design an integrated system of MEMS probes that can provide ultra-high spatial and temporal resolution measurements of atmospheric pressure, temperature, humidity, and wind velocity as these are carried by air currents.

The major considerations for the development of the GEMS weather observation system are that the probes be[5]:

(i) Mass produced at very low unit cost

(ii) Disposable, meaning that these are biologically inert and biodegradable

(iii) Able to remain suspended in the atmosphere for longer periods of time

(iv) Carried by wind currents

(v) MEMS and/or nanotechnology-based sensors

(vi) Self-contained with power source for sensing, geo-location, communication and limited computation

(vii) Able to form mobile, 3-D wireless network with communication among other probes, intermediate nodes, data collectors and remote receiving platforms.

A brief summary of the key issues and enabling technologies[6] identified in Phase I is given in Table 1.

Table 1. Major feasibility issues and enabling technologies affecting GEMS design and development

Major feasibility issues	Primary enabling technologies
Probe design	Material science, nanotechnology, biomimetics.
Power	Batteries, micro fuel cells, solar energy.
Communication	MEMS-based radio frequency and/or free-space optical systems.
Navigation	Global positioning systems, MEMS-based accelerometers/gyroscopes.
Measurement	MEMS-based pressure, temperature, humidity sensors.
Deployment/Dispersion / Scavenging	NWP models.
Data Impact	Observing system simulation experiments.
Networking data collection/ management	Artificial intelligence, data mining.
Cost	MEMS mass production, deployment strategies, networking and data collection infrastructure.
Environmental	Biodegradable and/or bioinert materials.

4. OVERALL DESIGN

To substantiate the GEMS concept, it is necessary to define the major feasibility issues for miniaturising the volume of prototypes and provide baseline parameters and realistic projections for some of the characteristics mentioned:

4.1 Probe

Buoyancy control and aerodynamic design will probably be the most effective way to reduce the terminal velocity of probes and keep these suspended for much longer periods of time. There are many examples of such designs in nature including dandelion seeds, threads of balloon spiders, and auto-rotating maple seeds[6].

In the GEMSTONE Project, tests were carried out with GEMS probe featuring a helium-filled super pressure balloon designed to maintain a constant volume when inflated to maximum capacity at sea level pressure. The sensor board and the electronics were attached to the bottom of the balloon using a piece of shell material with adhesive after inflation. The shell was constructed from 48-gauge (12 µm) thick MylarTM. When inflated, the balloon was pumpkin-shaped measuring ~ 1.2 m in width by ~ 0.6m in height. The antenna boards were positioned at the edges of the material and secured from slipping below the electronics package which otherwise would have obstructed these from transmitting and receiving signals during flight[2].

With rapid developments in technology and biomimetics, it is expected that a better design will evolve in the near future.

4.2 Power

Power for the probes will come from a combination of batteries, fuel cells, and solar power. Battery series resistance could be a problem at the very cold temperatures of the upper atmosphere. It will be important to identify power requirements of each GEMS probe. To regulate consumption, active power management may be necessary using adaptive measurement strategies whereby the temporal and spatial frequency of sensing and communicating are linked to vertical and horizontal changes in atmospheric parameters[5].

4.2.1 Batteries

In the GEMSTONE Project, the GEMS power board was designed to house primary and secondary power systems. The primary power source was either a standard 9 V battery or a 9 V thin film solar panel. The decision to use solar cells or batteries depends on requirements for flight duration and time of day, as well as frequency of data acquisition, primarily related to satellite communications. The secondary power system consisted of two rechargeable lithium coin cells. The batteries were connected in series to supply 7.2 V of backup power during night time and cloudy conditions. Two 3.6 V 120 mAh batteries connected in series would provide the necessary 5 V required for the satellite communication transmitter[2] (SATCOM).

As compared to alkaline batteries with an energy density of ~120 Wh kg^{-1}, lithium-FeS_2 batteries provide 200 Wh kg^{-1} at 1.3 V with a temperature range of 20 °C to 60 °C. The best off-the-shelf lithium batteries available today are lithium-thionyl-chloride that provide[1] 740 Wh kg^{-1} at a nominal 3.6 V.

4.2.2 Fuel Cells

Fuel cells provide promising long-term solution for autonomous system power generation. The energy densities of fuel cells are higher than these of batteries, because the oxygen needed to release the energy is not counted in the mass balance of the system. The two basic classes of fuel cells, that appear to be potentially useful for GEMS, are hydrocarbon-based (energy from oxidation of hydrocarbon) and metal-based (energy from the oxidation of either zinc or aluminum). However, problems with fuel cells, which include storage and plumbing of the fuel, fouling of the chemistry, and elevated temperature requirement for operation, must be addressed before usage[1].

4.2.3 Directed Radio Frequency Power

RF power can be beamed to autonomous probes and rectified, as in many commercially available RF-ID systems. This approach is quite effective at short ranges (few meters), but is more difficult at ranges above one kilometer. To be useful for GEMS, harvestable power levels on the order of at least a microwatt would need to be available[1].

4.2.4 Thin-film Solar Cells

Thin-film solar cells are commercially available and are made from amorphous silicon. Efficiencies of the thin-film solar cells are around ~10 per cent but expect ~ 30 per cent in the next decade and can be used for GEMS application[5].

4.2.5 Super/Ultra Capacitors

These are also commercially available and are thin-film-based devices. These capacitors efficiently store electrical charge for extended periods of time and can be charged/ discharged many times with no adverse effects[5].

4.3 Communication

Two types of communications can be considered for the GEMS network, viz., RF communication and the optical communication.

4.3.1 RF Communication

The development in CMOS technology has made it possible to make very low power single-chip radios with reasonable efficiency in the low GHz frequency range. With technological advancements, RF-ID tags, originally nearly passive devices with almost no onboard energy storage, have now emerged with onboard power. These new tags have the ability to contain sensors and sample their environment even when these are not in communication with the interrogator. However, for the communication ranges required by GEMS, it appears that RF-ID tags will not be a feasible communication technology[3].

In Project GEMSTONE, RF communication was not considered because with probes of this size RF communication is not practical over the distances of several kilometers as their linear dimensions are too small in comparison to radio wavelengths[2].

4.3.1.1 Antenna Design

The simplest antennas that can be envisioned for use in GEMS are quarter-wave monopoles and half-wave dipoles, consisting of a straight piece of wire. However, power-loss due to resistance change with temperature renders this type of antenna unsuitable.

Other options for small antennas for GEMS probes are fractal antennas and metamaterials. Fractal antennae is a proven technology which gives modest improvement in antenna performance. Metamaterials are a new class of engineered materials with remarkable RF properties. It has been shown that periodic arrays of normal materials can create artificial materials with effective permittivity and permeability that is negative. Such materials have remarkable properties, including the fact that Snell's law operates in reverse, and waves entering the material are bent away from the normal rather than toward the normal, meaning that focused beams can be generated from sub wavelength antennae[1].

4.3.2 *Optical Communication*

Using optical frequencies from airborne probes can have some advantages over using RF due to the high antenna gains available when the wavelength is small. This high antenna gain is the basis for interest in optical communication for GEMS.

Considering an optical communication system based on free space optical communication, in which the transmitter will have three parts: (a) laser source, (b) collimating optics, and (c) beam steering system will be a very narrow beam of energy radiated from the transmitter will be needed to aim this beam at the receiver. For an airborne probe, that will most likely not be stable, this will necessitate an active beam-steering system[1]. This optical communication system will not be operable due to clouds and fog that will block any optical communication signal.

In the GEMSTONE Project, the GEMS probe used the Axonn STX2 satellite transmitter (SATCOM) which provided one-way communication to the Global Star network. Each transmission was accompanied by three backup transmissions to get over 90 per cent success rates[2].

4.4 Networking

The available power and distance of separation of the probes will decide the viable communication and networking solutions. The probe separation distance as well as power constraints and communication range will determine if each probe can transmit to a remote receiving station (aircraft, LEO satellite, or both) or if mobile networking via multi-hop routing will be viable.

The network design issues to be considered would be fault tolerance, scalability, production costs, operating environment, network topology, hardware constraints, power consumption, communication protocols, networking strategies, data structures, and determine how many bits of data must be exchanged per unit time and at what power cost, given requirements of accuracy and sampling rate. It might also be useful to consider an optical communication system where the airborne probes communicate with one another to form an ad hoc, peer-to-peer, wireless optical network[1].

For developing a worldwide network the following can be considered:

(a) *Satellite constellation* – where the probes will directly send discrete data packets to LEO satellites for collection.
(b) *Mobile adhoc network* – where the data packets hop through a mobile network to distributed nodes.
(c) *Hybrid* – a combination of the above two can also be used depending upon probe location and conditions.

4.5 Sensors

Microfabricated devices for sensing temperature, relative humidity, and pressure are well developed today. These sensors-integrate on a single platform by MEMS will be ideal for the GEMS probes. The velocity can be extracted from the positional data of the probes. Sensor selection would be based on accuracy, dynamic range, size, calibration, noise suppression, self-test, and activation procedures along with the amount of data that can be stored and processed onboard the probes given the expected advances in microprocessor technology and available power.

In the GEMSTONE Project, the sensor package was equipped with an Intersema MS5401-AM analog pressure sensor and a Sensirion SHT14, 14-bit temperature/relative humidity sensor[2].

4.6 Geo-location

As the atmospheric wind velocity will be measured based on changes in probe position, it will be necessary to assess whether miniaturisation of accelerometer, gyroscope, and GPS technology will provide viable opportunities for navigation.

The present GPS does not appear to be suitable because of weak GPS signal, requirement of several minutes for cold start and several seconds for warm start, and more power consumption. If a future generation of GPS satellites is launched to broadcast a stronger signal, a substantial improvement in the power budget to acquire position can be envisioned.

A long-term solution using a GPS-aided inertial vavigation system (INS) appears to be a viable option for GEMS. All components of a GPS-aided INS can be fabricated with MEMS as part of the probe. A complete navigation system would include 3 accelerometers, 3 gyros, and GPS or other location-determination device[1]. Navigation and filtering software would combine data from all sensors to provide optimum determination of position and attitude.

Another option for navigation could be network localisation. With this solution, only few probes (or remote nodes such as unmanned aerial vehicles (UAVs) would have knowledge of their locations and the remaining probes would estimate their positions dynamically using an onboard algorithm.

In the GEMSTONE Project, the Navman Jupiter 30 GPS receiver board was used for its small size, weight, and performance characteristics[2].

5. POTENTIAL DEPLOYMENT STRATEGIES

A large number (>106) of GEMS probes may be deployed at any time and at any latitude, longitude, and altitude within the 3-D model domain[6].

Probe deployment can be envisioned for numerous scenarios where high spatial and temporal resolution data are required to assess the development of environmental phenomena like tornadoes, thunderstorms, and hurricanes, or to support military operations in data-limited or data denied-regions. Deployment patterns to be explored include release from:

- High-altitude (stratospheric) balloons
- Rawinsonde (weather) balloons
- Surface release with positive buoyancy
- UAVs
- Commercial aircraft, and
- Directly from spacecraft during planetary missions.

6. GEMSTONE PROJECT

In the GEMSTONE Project, free-flight tests were designed to examine the GEMS system functionality and robustness in the relevant environment, record sensor data, and document satellite transmitter reliability. Two free-flight tests were attempted during the last week of March 2007 with little success. Problems with the GPS unit for not updating position and the balloon having insufficient buoyancy to lift the payload, caused premature test failures. The third and the final free-flight test in April 2007 successfully demonstrated system functionality and robustness in the relevant environment including capability to acquire and transmit useful data in real time.

7. USE OF GEMS IN INDIAN SCENARIO

As it is clear that GEMS weather observation system is a viable solution for *in situ* measurement of weather parameters over all regions of the earth, India should also be ready for use of the system in the near future. It is necessary that the various parameters like the weather phenomena for which GEMS would be used, cost, the number of probes required for each term of usage, the frequency of usage etc. should be analysed prior to the commercial launch of the GEMS system. Three applications, viz., cyclone forecast, monsoon prediction and urban air pollution measurements, for which GEMS system could be extremely useful in India, are highlighted:

7.1 Cyclone Forecast

A cyclone is an intense vortex or a whirl in the atmosphere with very strong winds circulating around it in anti-clockwise direction in the northern hemisphere and in clockwise direction in the southern hemisphere. *In situ* information of cyclonic parameters will help in the following:

- Forming effective cyclone disaster prevention and mitigation plan
- Better cyclone forecast and warning services
- Rapid dissemination of warnings to the government agencies, marine interests like the ports, fisheries, and shipping and to general public
- Knowing cyclonic parameters at particular region will help in constructing better cyclone shelters in the cyclone-prone areas.

Andhra Pradesh and Orissa are the most tropical cyclone-prone states in India. It has been observed in India that due to lack of reliable forecasts of cyclones, much more reason are utilised on relief after the event rather than proactive preparedness before it[7].

Although in recent decades, people in these regions have become aware of the need to be prepared for future tropical cyclones, but an accurate and fast forecasting system is still needed. For example, the phenomenal damage and deaths resulting from the super cyclone (defined as an event with maximum sustained surface wind in excess of 62 ms^{-1}) which struck the Indian State of Orissa with 72 ms^{-1} surface winds in October 1999 may be largely attributed to lack of preparedness[7,8].

Deployment of GEMS through UAVs would be a good solution to make *in situ* measurement of cyclonic parameters like wind speed, wind direction, pressure within the cyclone, and related parameters so that the nature and the path of the cyclone could be predicted well in advance for the safety of life and property. The place and time of deployment of the probes could be determined by observing the creation of low pressure points analysed through satellite pictures. Also, a database of the cyclonic parameters, over time, would help in deciding the design and type of constructions in the cyclone-prone regions.

7.2 Monsoon Prediction

Monsoon is sources of rainfall for India. Being an agricultural country, monsoon plays a pivotal role in Indian economy. Any variation in the monsoon can lead to floods or droughts, and when the Indian agriculture suffers, it will also affect a lot of secondary industries, which depend on agriculture. Likewise, a wrong prediction of monsoon can ruin the life of many farmers, thus affecting the agro and related industries and ultimately the economy of the country.

Indian summer is famous for its atrocious nature. The months of May and June leave the Indian soil dry and baked and the people thirsty and panting. The first raindrops of the season bring relief from the heat and also replenish the dropped underground water level.

It is, therefore, extremely important that such a vital phenomenon be accurately forecasted, and that also well on time. It seems that at present, GEMS is the most suitable system for *in situ* measurement of monsoon parameters. Deployment of GEMS can be through weather balloons, UAVs, etc. *In situ* information of monsoon parameters will help in:

- Forming effective water management plans
- Better weather and agricultural forecasts
- Prediction of floods, famines, and hence, better disaster management
- Tourism
- Though *in situ* data of monsoon parameters are available but due to the sparse spatial distributions of weather monitoring systems, the data is not sufficiently good to obtain accurate predictions from the NWP models.

7.3 Urban Air Pollution Measurement

In India, the pattern of economic growth that we are adopting is becoming increasingly associated with environmental pollution. Chronic noncommunicable diseases such as cancer, cardiovascular diseases and respiratory disorders, etc. are becoming dominant. A study comparing the rates of economic growth and the rates of growth of vehicular pollution and industrial pollution shows that during 1975-1995, the Indian economy grew by 2.5 times, but the industrial pollution load grew by 3.47 times and the vehicle pollution load by 7.5 times[9]. Indian cities are being exposed to high levels of air pollution and people living in these cities are paying a price for the deterioration in air quality, causing a number of diseases.

Therefore, there is an urgent need for comprehensive epidemiological studies to show how ambient air pollution is affecting people's health and quantify this information to provide policy tools for air quality planning.

The GEMS probes can be used for monitoring and predicting the dispersion of particulate emissions, organic and inorganic pollutants, ozone, carbon dioxide, and chemical, biological, or nuclear contaminants in the urban environment. GEMS are capable of locating and characterising the ambient air and peak concentrations resulting from a pollutant released[6].

The Government can set up national atmosphere level institutional mechanisms for medical research and monitoring in the areas of air pollution using GEMS with a view to control urban air pollution and also to keep a check on the numerous chronic diseases due to the polluted air, to which the people living in the cities are constantly exposed.

7.4 Support in Military Operations

Defence is the most sensitive, critical, and important issue for any country. Logistics and strategy have always posed serious challenges to every defence operation that has occurred which further requires the knowledge of geographical information. Hence, the knowledge of geography is the key that benefits defence services. Information on the question like, position of the enemy, location of own assets, and what lies between the enemy and themselves, are very important for any defence strategy[10].

Equally important is accurate weather information that would increase effectiveness of military operations. Weather has always been a significant, and sometimes, decisive factor in military operations throughout history[11]. As military operations, equipment, and weapon systems have become complex and costly, accurate weather information has become increasingly important for their effective and efficient deployment.The future will depend more and more on enlightened weather advice to increase the effectiveness, and at the same time, decrease the costs of their operations.

The GEMS system appears to be the most-suited system for catering these needs during military operations. The advancements in MEMS technology have resulted in the development of the first silicon MEMS digital auto-focus camera with a focus range of 10 cm of infinity and the size in millimeter[12]. In the near future, it is expected that size of digital still and video cameras is going to get even smaller without having to compromise on the optical performance. These cameras and the MEMS sensor packages could be used in the GEMS system for acquiring accurate weather and terrain information during military operations. The probes could be deployed by UAVs in the enemy territory during war or during tactical operations. The GEMS system will definitely give any military force an edge over its enemy.

8. CONCLUSIONS

The GEMS concept leverages technological advancements in the field of communication and micro- and nanotechnologies for a new *in situ* weather observation system based on an ensemble of self-contained, low-cost, disposable probes. Besides gathering meteorological data, these probes could be used for environmental monitoring of particulate emissions, pollutants, and contaminants.

India can use GEMS for understanding and predicting vital environmental phenomena like cyclones and monsoon, measurement of urban air pollution, and as an aid during military operations. It is only the beginning, once GEMS are operational, their use will revolutionise every aspect of civil and military communication and measurement.

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