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FEATURE ARTICLE

MEMS and Smart Systems Development: Indian Scenario

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Abstract

The combination of smart materials and micro-electro-mechanics evolved as a strong platform for developing devices for safe and more comfortable human life. The science and technology evolved from these arenas paved the way for integrating smart electronics and smart mechanics. Globally this technology has already been accepted for developing advanced controls, sensors, actuators, smart systems in regular human life, aeronautics, automobiles and so on. Over the last decade through the two national programs, and internal programs of several Scientific Departments of Government of India, the Micro Systems and MEMS technology has reached a sizable maturity. These programmes have created significant infrastructural facilities and enhanced the human resource appreciably. Several devices have been designed, developed and tested for applications in aircrafts, automobiles and in biomedicine. Present article is a compendium of diversified activities spreading over different applications.

1. Introduction

The history of technology clearly indicates that the 20th century, especially the second half of the century, saw more development during the hundred years than that was seen in the last few millennia. There were several jewels of technology such as the Laser, Supersonic Aircrafts, Satellites, GPS, Computers, World-wide-web, Cell Phone, etc. Without much exaggeration, it can be said that all these were made possible by the developments in electronic technology led by the discovery of transistors and the development of Integrated Circuits. Miniaturization and the ensuing very-large-scale-integration (VLSI) technologies caused this unprecedented technological revolution of the 20th Century. Towards the end of the century, primarily technologies based on silicon miniaturization were extended to mechanical components such as beams, gears, pumps, motors etc. and led to another revolution called, “Micro-machines”. Obviously, the next step was to integrate microelectronics with micro-machines, possibly on the same chip, and the result was Micro-electro-mechanical systems, more popularly known as MEMS. Coupled with the developments that are taking place in Smart Materials, materials that adjust their properties to suit their functional environment, we arrive at the Smart Micro Systems. Smart micro-electro-mechanical systems are combinations of micro sensors and actuators that can sense the environment and can respond intelligently to changes in the environment by using micro-circuit controls. Clearly micro and smart system technologies have immense potential for applications spread over myriad of areas from automobiles to aerospace, from health sciences to environment, from cosmetics to consumer products.

In India though the application of electronic, materials and other technologies resulted in the development of defence, aerospace, automobile and other systems, however, the development of basic microelectronics technologies was rather slow and, indeed, was stymied due to the absence of required infrastructural facilities. Recognizing that certain proactive actions are required to propel the development of Micro and Smart System technologies in India, led a group of Scientists and Engineers to form a Society called, ISSS (Institute of Smart Structures and Systems) and mounted National Programs to develop such technologies. This article briefly presents the collection of developments few selective areas.

2. National Programs

The first MEMS device to be fabricated in India was a pressure sensor developed at IIT, Chennai by Prof. K.N. Bhat. (See Fig. 1.) However, the formation of ISSS following the first International Conference on MEMS and Smart Systems led to the initiation of several activities in this field. One of them was the 5 year National Program on Smart Materials (NPSM) which initiated modest R&D activities in materials and devices besides establishment of basic infrastructural facilities. The available Silicon IC fabrication facilities – using 1 micron technology – were certainly inadequate to cater for the requirements of VLSIs and ASICs and basic MEMS facilities were built around these existing facilities. Several Design Centres with standard MEMS design software were started at academic institutions and the NPSM seriously considered the human resource development as one of its primary responsibilities. The second mainly application oriented national program – National Program on Micro and Smart Systems (NPMASS) – carried forward the initial success of NPSM.

The three basic application areas identified by NPMASS were Aeronautics (to cater for active aircraft programs of DRDO and CSIR), Automobiles (to cater for the successful auto industry in India) and Biomedical as perhaps the most important fields for application of micro (and nano) technologies. As 'Innovation' fundamentally depends on both technology and human resources, the national program continued to concentrate on manpower development and training, besides a few technology development projects through research activities at academic institutions. The entire activities of the National Program was conducted through five Project Assessment and Review Committees. In the remainder of the article covers the technical activities of the National Program (NP).

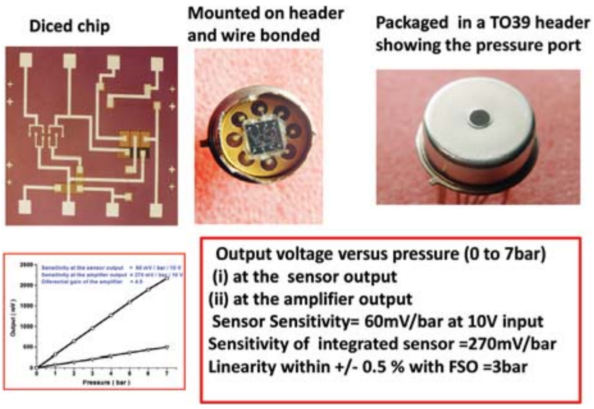


Figure 1. Photographs and characteristics of the first MOSFET Integrated pressure sensor

3. Infrastructure and Human Resource Development

The necessity of infrastructure and human resources in technology development need hardly be emphasized. The NP, thus has made this one of its primary goals. MEMS and micro system designers have now four foundries to choose, namely, SCL (Chandigarh), BEL (Bangalore), CEERI (Pilani) and CMET (Pune). SCL caters for 0.18micron CMOS facility in addition to the standard MEMS facility and is deeply involved with several of the NP projects. The facility itself is run though a separate Society under the Department of Space. Though the BEL facility is an in-house facility, it is accessible to NP projects and commercialization of products. CEERI has both 6" and 3" facilities, the latter being used for training

Figure 2. Micro and Nano Characterization Facility, CeNSE, IISc Bangalore

purposes. This facility is mainly for R&D work. The CMET LTCC (low temperature co-fired ceramic) facility covers most of the requirements towards RF and Microfluidics devices and related packaging needs. These foundries have been augmented with essential equipment so that they meet the future project/product requirements. More recently DRDO's SITAR foundry at Bangalore has established full-fledged MEMS foundry and will shortly have packaging facility for the same. Recognizing the importance and requirements for Bio-MEMs, a new polymer MEMS fabrication facility is being created at SITAR with the help of BIGTEC, a private organization dedicated to medical and biological devices.

Since MEMS device characterization is a specialized task requiring significant infrastructure and expertise, two major test and characterization facilities have been established. 'Mechanical and Materials Characterization' facility (Fig. 2) is located at the Centre for Nano Science and Engineering at IISc. This is a unique facility with a large number of test and characterization equipment located centrally. The equipment include Microsystem analyser, Acoustic microscope, Rate table, Pressure sensor test zig, Field Emission SEMs, Dual beam FIB, and AFM. This facility is being used extensively by a large number of users and is run as an open access facility. The second facility for "RF and Microwave MEMS characterization" has been established at IIT Delhi, with a capability of high frequency characterization up to 110 GHz.

A large number of National MEMS Design Centres (NMDC) have been created in various academic institutes across the country to facilitate manpower development. At present there are 64 such centres partitioned into Resource Centres (IISc Bangalore, IITs at Bombay, Madras, Delhi, Kanpur, Kharagpur), Tier I and Tier II centres. These centres are equipped with Intellisuite, COMSOL Multiphysics and L-Edit design tools. A selected few have access to Coventorware and R-Soft tools. In order to create awareness on Microsystems Technology, several workshops were organized in collaboration with ISSS. The workshops (Fig. 3) held across India (Coimbatore, Pune, Shillong, Kurukshetra), also to provide hands-on design tool demos.

Another important HRD activity under the NP is hands-on training in MEMS devices processing at CEERI, Pilani. A selected group attending the workshops are trained at CEERI 3" facility (Fig. 4) on various MEMS process modules. During this period, the participants fabricate bulk micro-machined MEMS pressure sensors, starting from bare Silicon wafers. The participants also perform

Figure 3. MEMS workshop at NEHU, Shillong

Figure 4. Hand-on training in Progress at CEERI Pilani

post-fab processing – including dicing, packaging and characterized using a pressure calibrator.

Following paragraphs enlist various research and development activities and are selected based on their success status to realize a usable device, for a specific application.

4. Research & Development Activities

The research and development activity in NP is designed to identify projects pertinent to immediate applications of aerospace, automotive and biomedical engineering. Primary aim of this activity is to make rapid strides in developing various applications with improved performance of existing technologies and / or paving way for newer innovations. Few selected projects are listed below considering their maturity towards device development and readiness for immediate application.

4.1 NiTiPt High Temperature Shape Memory Alloys:

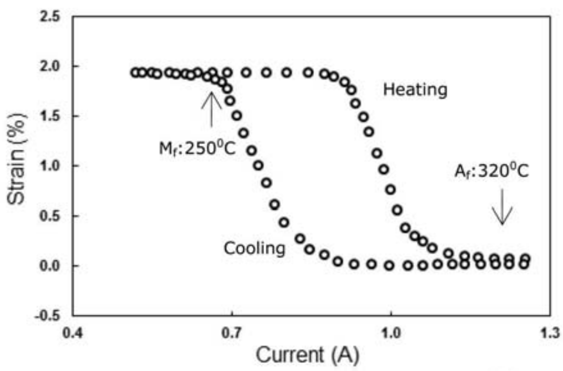
Shape Memory Alloys (SMAs) are used for development of thermal actuators in variety of engineering applications. Among various alloy systems, binary NiTi alloys are the most commercially exploited ones because of their superior shape memory, mechanical and corrosion resistance properties. However, the highest application temperature of binary NiTi alloys is limited to about 120ºC. In recent years, there has been an increasing demand for high temperature shape memory alloys (HTSMAs) for applications in aircraft turbo-engines, automobile engines, power plants, automation, etc. Potential applications of NiTiPt HTSMAs are adaptive (variable area/ geometry) high-speed inlets, various flow control devices, variable area bypass nozzles, fuel nozzles and mixers, active clearance control devices for the compressor section of aero-engines. One of the laboratories/institutes actively pursuing research for the development of HTSMA products for aerospace applications is GRC, NASA, USA in collaboration with Dynalloy, USA.

The present research work (at NAL, Bangalore) was undertaken with the objective of developing and processing NiTiPt HTSMA in wire form suitable for applications above 200^{0}C. HTSMA of nominal composition $Ni_{30}Ti_{50}Pt_{20}$ (at.%) has been successfully developed and processed into wire form with diameters in the range 263 - 500 mm (Fig.5.(a)). The thermo-physical, mechanical and functional properties of the developed wire (Fig.5 (b) and Table 1) are comparable or better than those reported in literature.

4.2 PVDF based composites films for transducer applications:

Piezoceramics also have a large mechanical quality factor (Qm) and require the addition of damping backings to reduce ringing to an acceptable level. Finally, ceramics are brittle, nonflexible and cannot be formed onto curved surface, limiting design flexibility of the transducers. Polymers such as poly (vinylidene fluoride) (PVDF) and its copolymer exhibit good flexibility which makes them very attractive polymer. Despite having a very high voltage coefficient, the low d_{33} and d_h values and need of an extremely high electric field, which limits

(a)



(b)

Figure 5. (a) $Ni_{30}Ti_{50}Pt_{20}$ shape memory alloy wire of diameter 263 mm (properties in Table 1), and (b) strain vs. current (temperature) at 210 MPa stress

Table 1: Properties of $Ni_{30}Ti_{50}Pt_{20}$ HTSMA wires processed at NAL, Bangalore

Properties	Targeted	Achieved	Literature
Transformation Properties			
Martensite start (M_s) temperature :	>200°C	288°C	285°C
Transformation hysteresis (A_f-M_s) :	25-35°C	27-28°C	11-30°C
Transformation strain :	2.0-3.0%	2.6-2.8%	1.9%
Mechanical properties			
Young's modulus :	30-40 GPa (M*) 60-80 GPa (A*)	31-32 GPa (M) 68-70 GPa (A)	48 GPa (M) 58 GPa (A)
Ultimate tensile strength :	≥ 900 MPa (M) ≥ 900 MPa (A)	1340-1800 MPa (M) 1100-1200 MPa (A)	1550-1670 (M)
Elongation to failure Martensite (fully annealed) Martensite (cold worked) :	10-15% 5-10%	14-16% 8-13%	8.2% 2.7%

* M: Martensite (low temperature phase, A: Austenite (high temperature phase)

the thickness of the material hinder their application in certain areas. Some composite needs to be designed which can utilize the best properties from each constituent phase to create an improved transducer material.

The goal of the present work was to develop a new piezoelectric composite by critically blending the loading of PZT ceramic in the PVDF polymer matrix to serve as a flexible sensor. The primary property for the reliable operation of a sensor would be the electric field generated in a material per unit mechanical stress applied to it i.e. the piezoelectric voltage constant (g_{33}). Figure.6 presents the various PVDF and PVDF-PZT films developed in this program with different silver patterns and different edge connectors for various applications.

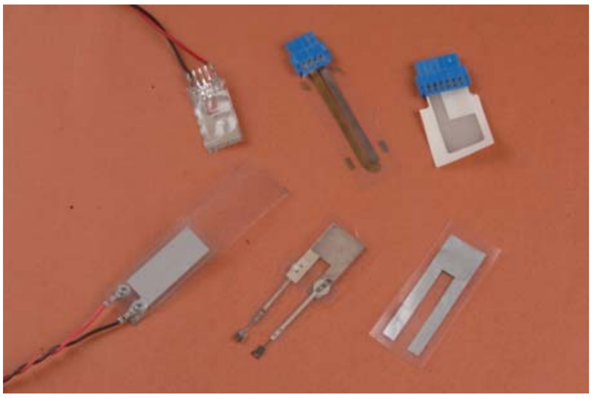


Figure 6. PVDF and PVDF-PZT films with different silver patterns and different edge connectors

The implementation was to focus on three focal areas: tuning the composite properties by controlling the percentage loading of ceramic in polymer matrix, fabrication process to prepare the composites, validate the films for acoustic sensing applications.

A significant portion of the project involved the comprehensive understanding of the variation in the material's intrinsic behaviour while varying the various parameters to finally identify the critical process parameters. The result of this iterative optimization process are PVDF-PZT composite films with the tensile modulus and strength of 1253 MPa and 24 MPa, respectively. Piezoelectric charge coefficient prepared using solvent cast were found to give a d33value of 40pC/N. Using the PZT chips, we could achieve a d_{33} of 100 pC/N. The response of these films for acoustic emission applications was comparable to that of commercial acoustic sensor.

4.3 Acousto Ultrasonic Coating for Structural Health Monitoring

Development of Acousto-Ultrasonic Transceiver on aerospace grade metallic and composite structures by novel technique of insitu piezoelectric coating for Structural Health Monitoring (SHM) is the aim of this research (NAL). This methodology of coating directly on to the test object is found to be superior to the bonded piezo wafer as the ill effect of the intermediate

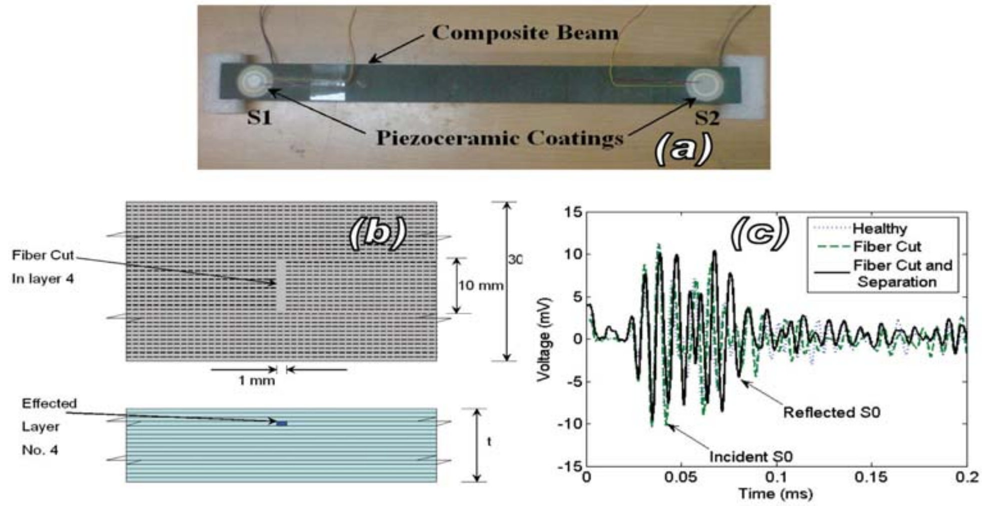


Figure 7. Composite Beam with Piezoceramic Coatings, (b) Defect (Fiber Cut, Fiber Cut + Fiber Separation) introduced in the Composite laminate. (c) Comparison of healthy and damaged signals from piezoceramic coating S1 at 140 kHz.

adhesive bonding is completely avoided.

Ultrasonic transceivers have been developed by in-situ piezoelectric coatings on Aerospace grade Aluminum metal, CFRP and GFRP (regular and irregular surfaces) to function as transmitter and receiver of Ultrasonic wave. The coating has proved its usefulness in field applications by qualifying stringent tests. The performance of Piezoelectric coating as ultrasonic transmitter requiring low voltages (~10V) for excitation is better than that of commercial Piezo Wafer. The developed coating is found to be very promising for damage detection of Composite Structures (Delamination, Fibre separation, Fibre cut) and 2D metal components. Figure 7 (a,b,c) shows a typical composite test object with piezo coating, introduced defect (fibre cut) in the laminate and guided wave signals for healthy and damaged composite laminate employing Acousto Ultrasonic coating.

In recent years, piezoelectric wafers permanently attached to the structure have been employed to generate and detect guided waves for structural health monitoring. The adhesive bonding between wafer and structural substrate is the weak link in the sensory system due to its deterioration with time under environmental attacks. Also need of higher operating voltage (~150 Volts) to excite these Piezo wafers for generating guided waves restrict their application for in-flight SHM. Piezoelectric thin and thick films operating at 10V could have replaced PWAS but for their poor piezo electric performance and need for bonding makes them unsuitable for real time SHM. With the drawbacks associated with PWAS & thick/thin films, the present development of insitu PZT coating is a breakthrough in real time applications and value addition to the field of SHM technology. The present development directly leads to the application of in-flight Structural Health Monitoring. It is useful for Materials Testing viz., porosity and density detection, internal bond strength prediction and revealing anisotropy of composites aiding in Quality and Process control. The developed technology can also be used for Corrosion Detection, Oil viscosity measurement and debris monitoring.

4.4 Development of a low cost ceramic gas sensor system prototype for monitoring the air quality of automotive cabin.)

The primary aim of this project (IIT,Kharagpur) present proposal is to evaluate the CO, HCs and NOx sensing characteristics of nano-structured composite perovskite: spinel and modified binary oxide to monitor the air quality of automobile cabin. The objective of the present research is to synthesize these sensing materials in the form of nano-powder, thin film and nano-rods or tubes and understand the mechanism that control their sensing characteristics in terms of sensitivity, selectivity, response/recovery times and stability. Finally, using the optimized sensing materials we

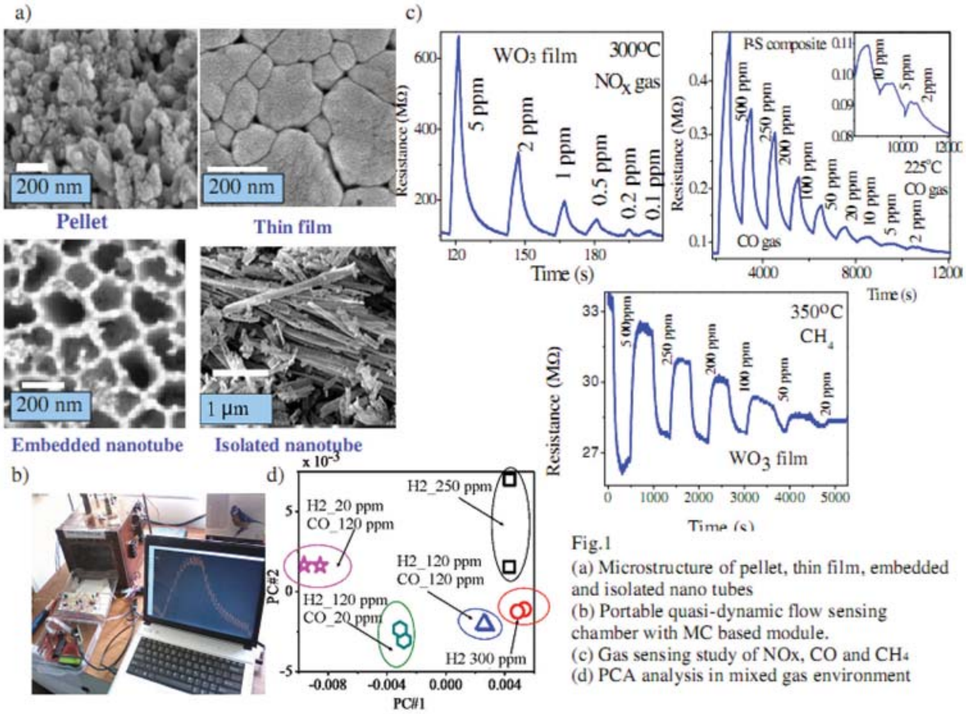


Figure 8. Development of magneto-resistive sensors technology for application in aerospace systems

have proposed to fabricate a microcontroller based prototype gas sensing system.

Significant achievements include, a) Synthesis and characterization of nano-structured thin film and nano-tubes of the proposed sensing materials. Fig. 8 (a) shows the surface morphologies of some of the synthesized oxide sensing elements in the form of pellet, thin film, embedded and isolated nano tubes. b) Development of a portable quasi-dynamic flow sensing chamber, micro-controller based electronic circuit module, data acquisition and analyses software for gas sensing measurements (Fig.8(b). c) As shown in Fig. 8(c) that the developed sensing elements are capable of detecting NO_x (0.1-10 ppm) (using WO_3thin film), CO (2-10 ppm) (with 0.5 $La_{0.8}Pb_{0.2}(Fe_{0.8}Co_{0.2})O_3$ -0.5 $Mg_{0.5}Zn_{0.5}Fe_2O_4$ bulk composite) and C_mH_n (20-500 ppm) (WO_3 film) gases. Sensing of these gases in said concentrations are very important to develop sensing system to monitor air quality in automotive cabin, and d) Fig. 8(d) shows that for H_2, CO mixed gas with different concentration ratios, pattern recognition analyses is very effective for distinct classification.

The present research has three major components namely: synthesizing of sensing material, understanding their gas sensing characteristics, and development of sensing system (consisting sensing element and an micro-controller based electronic module) for selective gas detection. If our approach is professionally developed then this indigenous technology would compete the global leaders (viz. Figaro Inc.) The ultimate application of the proposed research is to make sensing system for monitoring the air quality of an automotive cabin.

The project at NAL aims at the development of Gear tooth (GT) sensor using Giant Magnetoresistance (GMR) based magnetic materials for automobile application. The programme successfully deposited CoFe/Cu magnetic multilayers with varying CoFe thickness and maximum GMR obtained 8 % with CoFe thickness of 1.3 nm and Cu thickness 2.5 nm. The sensitivity of these sensor was found to be 0.08 %/G and the measured hysteresis was negligible (< 10 G). These sensor was found to be stable at 180 ^{0}C in air. We have also fabricated Gear Tooth (GT) sensor on Si substrate using these GMR films. These sensors showed a promising potential for testing to measure the RPM of a rotating shaft and can be used in automobile sector for development of digital speedometer. The highest sensitivity of GMR materials (Ta/NiFCo/ $[CoFe/Cu]_{15}$/Ta) with thermal stability up to 225 ^{o}C was reported by Non Volatile Electronics, USA 0.1 %/G. The results obtained in the present project are comparable to the reported one (Fig.9). These sensors can be used to develop speed sensors for Automobile Applications with Magneto Resistive Element (MRE) Technology.

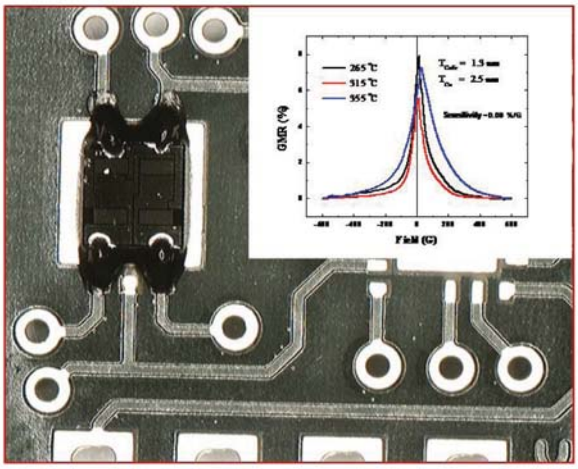


Figure 9. GMR based Gear Tooth sensor fabricated on Si substrate. Inset shows magetoresistance properties of the film annealed at different temperatures.

v) Optical and nano-based devices for bio-medicine

The main goal of this project at Indian Institute of Science was to develop a multidisciplinary approach towards bringing experts from various fields together, namely nanotechnology, biology and photonics, with a special emphasis towards developing modules for sensing minute quantities of bio-pathogens and developing bio-manipulation techniques for measuring micro-rheological properties of single proteins and muscle cells. The proposed bio-sensing modules were optical in nature, in particular those based on nano-photonics concepts, such as localized surface plasmon resonance (LSPR).

Significant progress has been made in developing a low cost, wafer scale technique in developing SERS (Surface Enhanced Raman Scattering) substrates, which have a very high limit of detection. The key innovation in the present method has been to use multiple layers of plasmonic nanoparticles in porous films, which results in a very large number of hot spots with high electromagnetic field enhancement. The resultant substrate has a large available surface area, as well as a high EF (Enhancement Factor), within the illumination volume. Preliminary measurements in these substrates show an EF of 10^7-10^8 with an effective surface area that is orders of magnitude higher than a regular 2D substrate. As a result, the performance of the SERS substrate is unprecedented with respect to all other SERS (3D or 2D) substrates (Fig. 10). Interestingly, this substrate is unique in which both fluorescence and Raman signal were found to be enhanced, which can have major implications in sensing applications. Present findings towards the development of a low cost SERS biosensor, specifically targeted towards bio-pathogens like Salmonella, as well important bio-molecules like Thrombin.

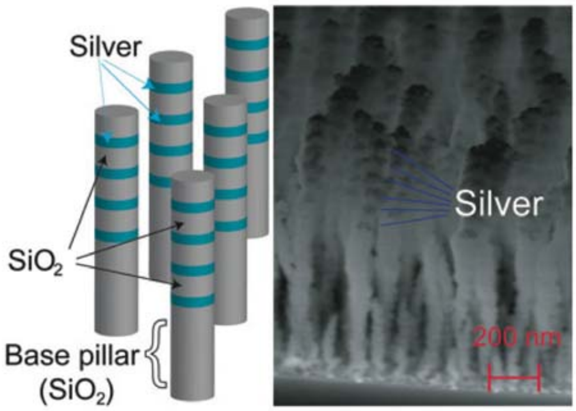


Figure 10. (Left) Schematic of a 3D porous array of plasmonic nanoparticles, here Ag, separated by dielectric rods, here SiO_2. (Right) SEM image of the fabricated array.

5. Aerospace Applications and Structural Health Monitoring

MEMS (sensors and actuators) and Smart systems find wide application in aircrafts, space vehicles, especially in Structural Health Monitoring (SHM) Systems. Indeed , one of the earliest application of MEMs was in Indian Satellite Program. Several initiatives like DISMAS of Aeronautical Development Agency (ADA), MEMS program at ISRO, and work on SMAs (shame memory alloys) of National Aerospace Laboratories of CSIR addressed certain aerospace applications. The main aim of the NP in aerospace was to complement the work in the earlier initiatives and gravitate towards products for current and future national activities in aerospace and simultaneously look at SHM systems for both aerospace and civilian structures. Specifically NP addressed the requirements of:

- MEMS Device Development- Pressure sensors, Accelerometers and Gyroscopes;
- RF MEMS devices Development for switches, varactors, phase shifters and their integration in T/R modules;
- Smart actuator development using Piezo stacks;
- Smart application for vibration and noise control, morphing of wings;
- Rapid NDE techniques for SHM
- Integrated Vehicle Health Monitoring

One of the major differences the current NPMASS program has over other Government funded projects is the involvement of Indian private industries and foreign universities in the technology development. The sanctioned projects include four private industries (Cranes Software, Mahindra Satyam, Tata Consultancy services and Astra Microwave Products Ltd. (AMPL)) and one university from abroad (Georgia Institute of Technology, Atlanta, USA). .

In the area of device development, MEMS Accelerometer is being developed at IIT Kharaghpur, Inertial MEMS (Gyroscopes) at IISc and CEERI Pilani, RF switches for phase shifters at AMPL(IIT-Delhi), IIT Chennai and CEERI Pilani, while RF Veractors development is taken by IIT Kharagpur. Though the device designs is undertaken by the academic institutes, device fabrications is being undertaken by SCL, CEERI, and SITAR. M most of the devices would cater for the requirements of ADA and RCI Research Centre Imarath). Recently a subsystem development of Air data probes for India's Light Combat Aircraft has also been initiated. Gyroscopes and Inertial sensors are very important in aerospace and development of these have been undertaken in the NP. Fig. 11 shows the first four natural frequencies of a 4 beam proof mass accelerometer developed at IIT Kharaghpur. To cater for the requirement of Defence laboratories specific Pressure sensor projects have also been initiated. Tables 2 to 4 indicate their specifications.

Table 2

(1)TECHNICAL SPECIFICATIONS: MEMS PRESSURE SENSORS for RCI

Salient specifications

Pressure Range :50 Bar to 400 Bar
Measurement mode :Gauge Pressure
Proof pressure: 1.5 times FS
Burst pressure : > 2 times FS
Non Linearity : < ±0.50% FS
Hysteresis : < ± 0.15 % FSO
Supply Voltage:28 V (from 12 V to 36 V)
Output Voltage : -2.5V to 2.5V (typical)
Temperature Range: -30 C to + 125 C
Insulation Resistance: > 100 M ohms @ 50 V DC
Electrical Connector: 5 pin push-fit locking connector with cable
Pressure Port :M10 X 1 – 6g (Male)
Pressure Transducer Body: SS 316L
Media compatibility : All fluids compatible with SS 316L
Weight :< 90 grams
Burst pressure: 2 times FS for 10min (burst limiting pressure)

Table 3

(2) Technical Specifications : MEMS Pressure Sensor (P50) for Cabin Pressure in the aircraft for ADA

Sensor Range : 0 -1200 mbar
Output signal : 0.25 to 5 V dc
Sensor Accuracy: +/-15% of PSR
Power Supply :16-32 V dc.
Current <50mA at 28Vdc
Response time : < 10mSec
Weight : < 150 gm
Experimental : Temperature Range: -55°C to 80 °C
Acceleration: -3.5 to 9 g
Altitude : 18kmabove sea level
MTBF : 20,000 hrs

Table 4

(3) Technical Specifications : MEMS Based Pressure Sensors For Pressure inside Backup Oxygen Cylinder (BOS) for DEBEL

Specifications:

Pressure Range : 0- 5000psi
Burst Pressure (diaphragm) : 20000 psi
Full Scale Output : 500 mV (Typical)
Zero Pressure Output : < 25mV
Case material : Stainless Steel
Weight : < 15gms
Mill grade or Industrial grade

Under smart application area, some of the applications being are:

- Active Vibration Control of SARAS (NAL project) aircraft Engine mount
- Development of Active noise controlled Helmet for TEJAS (LCA) aircraft cockpitt
- De-icing methodology using Smart piezo actuation

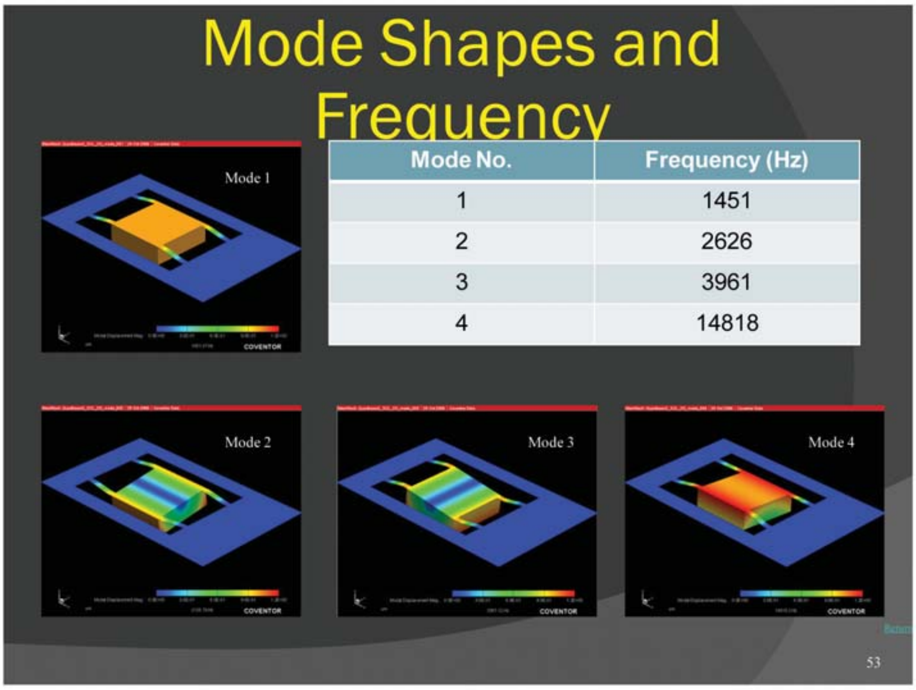
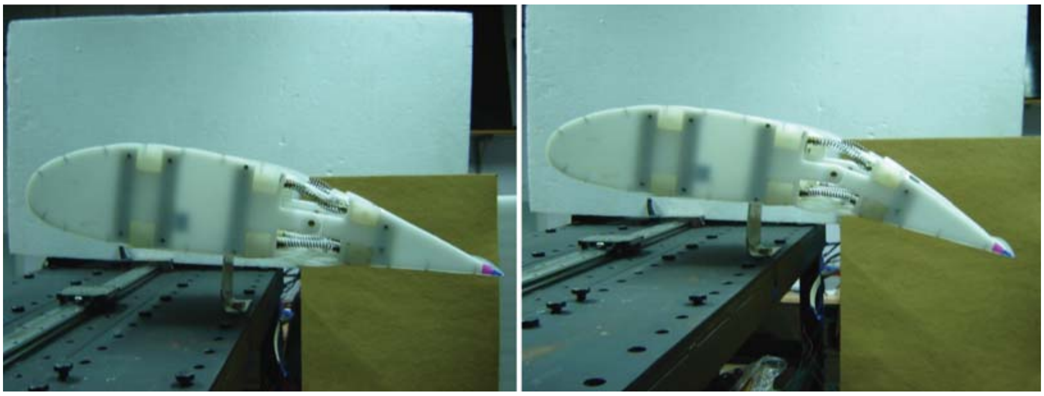


Figure 11. First four natural frequencies of a 4-beam proof mass accelerometer



(a) Before Morphing (b) After Morphing

Figure 12. Wing Morphing demonstration of NACA 4421 airfoil

- Aircraft wing morphing using smart actuation, and
- Trailing edge flap actuation for exterior noise control for Advanced Light Helicopter (ALH) developed at HAL

Figure 12 shows the experimental demonstration of morphing of the NACA 4421 airfoil using Peizo stack actuators. This work is currently done at Indian Institute of Science,(IISc) Bangalore while the peizo stack actuator development is undertaken by NAL and CGCRI, Kolkata. A class actuators developed by these institutions have a range of block force (400 N-8000N) and a range stroke lengths (10 μm to 90μm).

SHM development is mainly oriented towards development of off-line technology, which are required for reducing aircraft maintenance significantly. Some of the technologies developed include development of non-contact Laser Doppler Vibrometry (LDV) based SHM, Rapid NDE methods such as air coupled ultrasonics, Piezo array based damage detection method, the development of FBG based interrogation system for high frequency SHM applications and more recently, the development of SHM centric software that

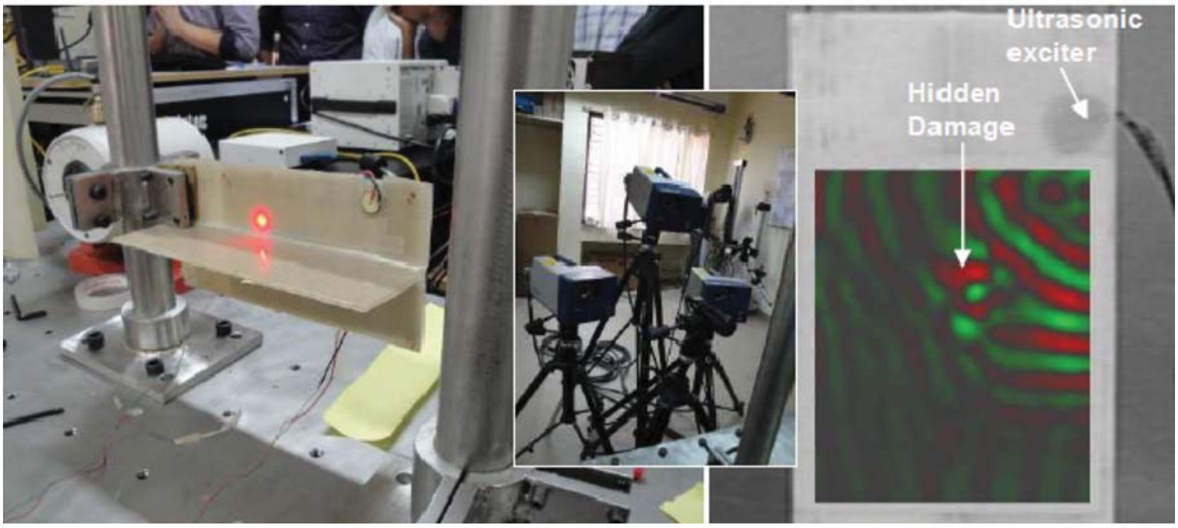


Figure 13. SHM of a composite t-Pull Joint using LDV

integrates both NDE and SHM protocol. This software package development is being undertaken jointly by Mahindra Satyam, IISc and IIT, Madras. When developed, this software will be the first of its kind in the world that will be completely centric to off-line SHM, which will include all NDE methods of damage detection and will completely integrate with MRO operations of aircraft fleets with SHM.

Figure 13 shows the presence of delamination and debonds in a T-composite joint using LDV. This work, undertaken at Indian Institute of Science has Georgia Institute of Technology, Atlanta, USA, as its collaborator.

NP has initiated a project on developing a Micro systems software module for MEMS structure analysis and design. This software is expected to have all features of other MEMS software such as Coventerware, Intellisuite etc. This software module will use NISA finite element software developed by Cranes Software, Inc. as its engine.

6. Automitive Applications

Since 1980, there has been an ever increasing penetration of electronic control systems and electrical components in automotive products. These systems can be categorised into areas of powertrain and chassis control, comfort and convenience and communications. Each of these systems requires specific set of low-cost sensors and actuators. Most of the commercial automotive activity for MEMS technology has been in the sensors area. Actuators having MEMS parts are starting to emerge as ways to fabricate intricate parts. The projects taken up under the NP fall into three categories: Pressure Sensors, Gas Sensors and Hall Effect based Sensors. The MAP (Manifold absolute pressure) sensor falls in the first category.

6.1 MAP Sensor:

Here the main aim was to develop both MAP and TMAP Sensors for Automobile Applications and package it for its ultimate use in automobile instrumentation systems. With a view to productionise the same, Pricol Ltd. Of Coimbatore was inducted in to the project at the beginning itself. Pricol is already producing various variants of Pressure Sensors, Speed Sensors, Temperature Sensors, Temperature Switch cum Sensors and Pressure transducers, Cam & Crank Position Sensors, Throttle Position Sensors & Actuators etc. The development of MEMS pressure sensor elements, integration with required ASIC for MAP and integration of temperature sensor for TMAP were done by SCL; while Pricol's responsibilities were development of Sensor housing and adaptor with requisite span and offset and temperature compensation, packaging and testing. .

The sensor, in its various stages of fabrication, is shown in Fig. 14. Table 5 gives the specifications of the sensor.

The development work is now complete and industrial prototypes have successfully undergone

Table 5: Sensor Specifications

Pressure range	13.332 to 119.99 kPa
Over pressure	490 kPa
Supply voltage	5 ± 0.5 V
Output voltage	1 to 4.2 V
Body material	PBT 30% GF
Input voltage	5 ± 0.25 V

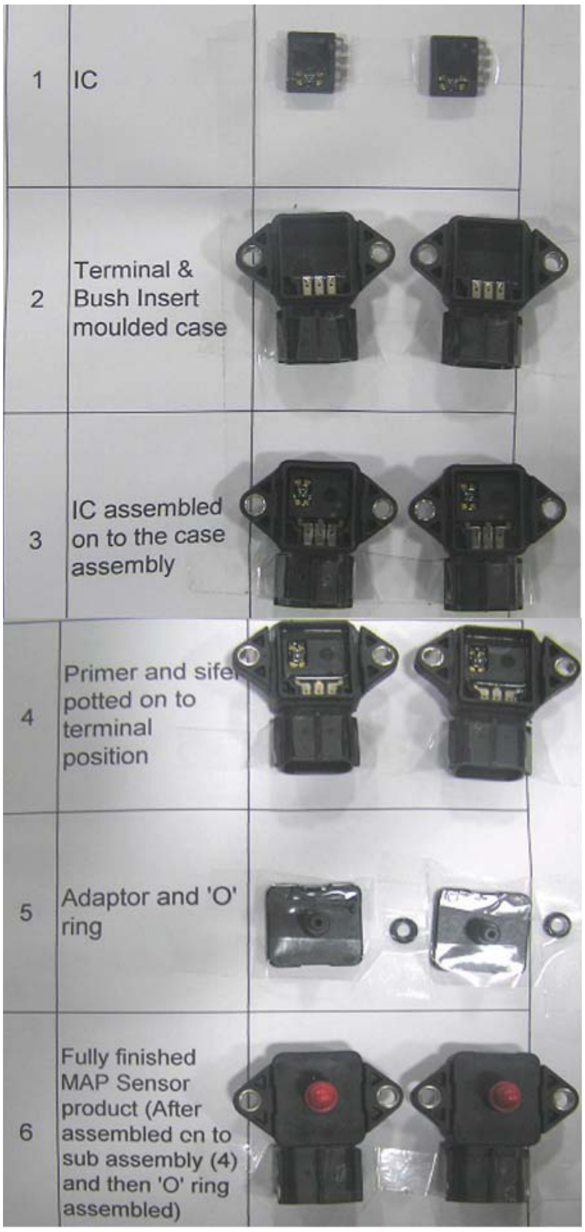


Figure 14. MAP Sensor Fabrication Stages

the all the required - general performance, excessive pressure, gasoline resistance, high temperature high humidity storage, low temperature storage, drop, thermal cycle, High temperature, high humidity operation, high temperature operation, thermal cycle operation, high temperature storage, low temperature operation, vibration, water resistance, salt spray and exhaust condensed water test. Actual commercialization is just round the corner.

6.2 Gas Sensor Platform

This multi institutional project aims at the development of Zinc and Tin Oxide film based sensor for exhaust gas monitoring in automobiles. The various features of the sensor are shown in Fig. 15.

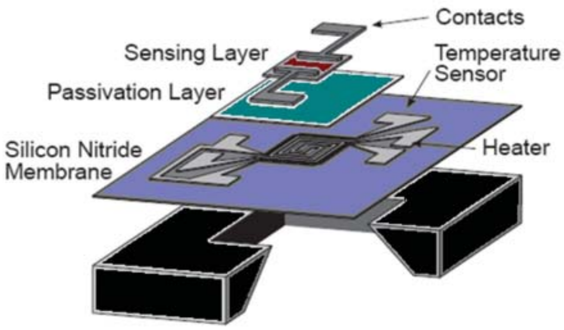


Figure 15. Gas Sensor

Various subsystems being developed for this platform are:

1. Design of micro-heaters and synthesis and characterization of SnO_2 and mixed oxide films with specific dopants for methane and hydrogen gas sensing.

This project is being done at IISc Bangalore and it aims at (i) Development of Tin oxide films with dopants for Methane and Hydrogen sensing (ii) Development of MEMS based micro-heaters at the Proof of Concept level. Three designs have been developed and ten prototypes for each design have to be delivered (iii) Selective synthesis and characterization of SnO_2 nanostructures in the form of thin films (iv) Exploring the effect of substrate temperature, deposition rate, carrier gas pressure and annealing on the yield and growth of nanostructures of SnO_2 (v) Demonstrating the effect of surface functionalisation on gas sensing properties of SnO_2 thin films (vi) Optimize process parameters for required sensitivity and selectivity;

2. Growth and characterization of composite matrices of Zinc oxide thin films with dopants- CO_2,NO_2 and SO_2.

This project is being done at the University of Delhi and it aims at (i) Development of Sensing composite matrix of ZnO thin film with suitable catalyst (ii) Selective synthesis and characterization of ZnO nanostructures in the form of thin films (iii) Exploring the effect of substrate temperature, carrier gas pressure and annealing on the yield and growth of nanostructures of ZnO (iv) Demonstrating the effect of surface functionalisation on gas sensing properties of ZnO thin films (v) Obtaining optimized process parameters for required sensitivity and selectivity;

3. Fabrication of MEMS Microheater for Automotive Gas Sensor.

This project is being done at CEERI Pilani and it aims at up-scaling and development of batch processing of the "proof-of-concept microheaters" developed at IISc Bangalore in the first project. The deliverables are 25 wafers of Microheaters for gas sensor fabrication (in the form of processed 4" dia. wafer or chips);

4. Design and Development of Microsystem Platform for Gas Sensors Using General Purpose ASIC Devices.

This project is being done at IISc Bangalore and its objective is to develop a Gas Sensor with commercially available sensing element chip and ASIC. It is expected to deliver ten prototypes of fully built sensors for one target gas;

5. Miniaturized Gas Sensors for Hydrogen and other gases.

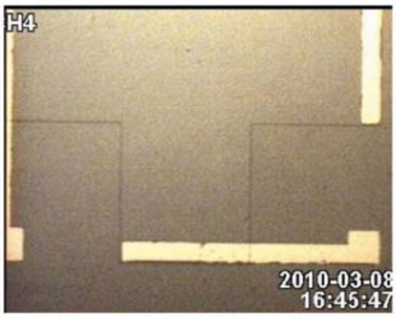
This is a futuristic project being done at IIT Kanpur on nano silicon sensors for gas sensing.

6.3 Hall Sensor Projects

Hall Effect based sensing with the final aim of position and speed measurement have been undertaken.

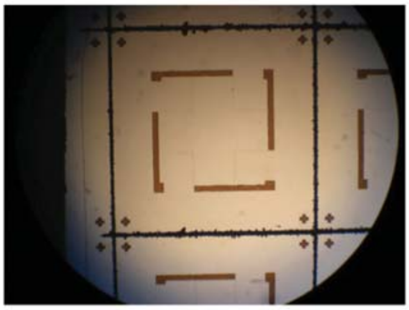
1. Development of GaAs Based Hall Elements at Chip Level for Automotive Applications

It aimed at development of the fabrication protocol for Gallium Arsenide element chips on Alumina substrate. Activities involved Layout Design and Mask fabrication, Reactive Ion etching, Development of Ohmic contacts and Testing at various levels. The chip is shown in its various stages of fabrication in Fig. 16.

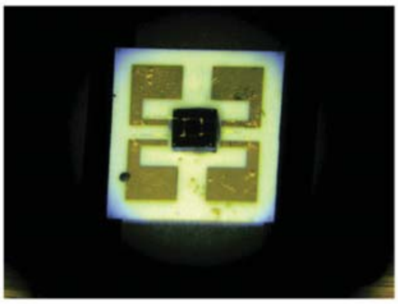


(a) Hall Chip after MESA etching and ohmie contact

(b) Gold patterned alumina substrate



(c) Hall Chip after electroplating and scribing



(d) Hall Chip mounted on alumina substrate

Figure 16. GaAs Hall Effect Chip

2. Hall Sensors for Automotive Applications

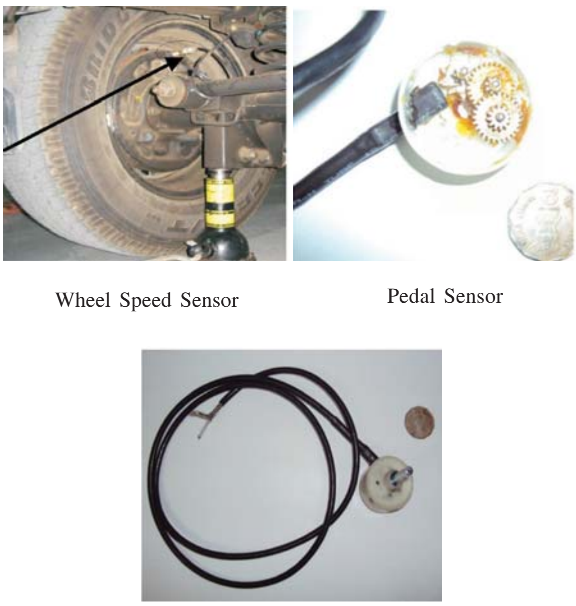
This project successfully completed at IIT Kanpur involved using commercially available, off-the-shelf sensor chips and to develop (i) RPM/ Speed Sensors, (ii) Crankshaft Sensors and (iii) Pedal Position Sensors for automotive applications.

The following components (Table 6) were used

Table 6: Hall Elements

No.	Component Name	Description
1	Hall Sensor	ATS643LS (2 pin)
		ATS667LSG (4 pin)
2	Hall Element	SJ 119 (GaAS type hall element)
		TY101A (InSb type hall element, smd)
3	Magnet	Rare earth type

Electronics and Packaging for the sensors have been developed and calibration has been carried out on different automobiles. The sensors are shown in Fig. 17.



Wheel Speed Sensor　Pedal Sensor

Crankshaft Sensor

Figure 17. Hall Element Sensors

6.4 IVHM Projects

In addition to the three sensor platforms discussed here, several projects on Integrated Vehicle Health Monitoring (IVHM) have been taken up for application in aircrafts and automobiles. The aircraft based projects are just underway, while the automobile based projects have progressed satisfactorily.

This goal of the Integrated Vehicle Health Management (IVHM) program is to equip vehicles with on-board and off-board smart sensors and algorithms to enable diagnosis, prognosis and isolation of faults. The challenge associated with IVHM is the poor observability in vehicles, both in the automotive and aerospace industry. This is mainly due to the lack of durable and affordable, high performance sensors. The IVHM program will develop a set of vehicle and sub-system level test stands that will enable development, testing and ruggedization of smart sensors that can meet the needs of the automotive industry. In addition, the program will develop algorithms that compliment these sensors to develop an end-to-end, smart sensor based prognostic solution for vehicle health management. The primary focus of the smart sensor based IVHM program is to improve the following vehicle performance metrics: (i) Fuel efficiency (ii) Emissions (iii) Safety (iv) Maintenance Cost.

The following sub-systems of an automobile have been initially taken up – (i) Brake system (ii) Steering system and (iii) Engine. Projects on Brake and Steering System are being done by IIT Kanpur and the Engine System project is being executed at IIT Kharagpur.

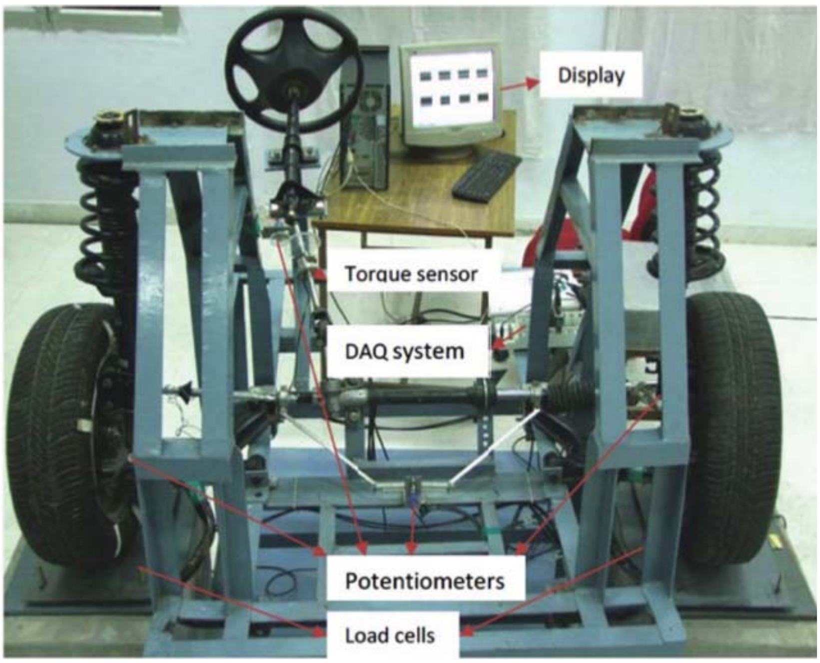
The Steering and Brake System Test Beds developed at IIT Kanpur are shown in Figs.18(a), (b) and the Process-in-Loop Tests and the Harnessing activity schemes are shown in Figs. 19(a), (b) respectively. Work is currently, in progress at both IITs on instrumentation and algorithm development.

The development and implementation of IVHM is gaining momentum and it is anticipated that it may be a standard fit in the coming decade.

7. Biomedical, Food and Environmental Sciences

It is believed that the micro (and nano) have

(a)



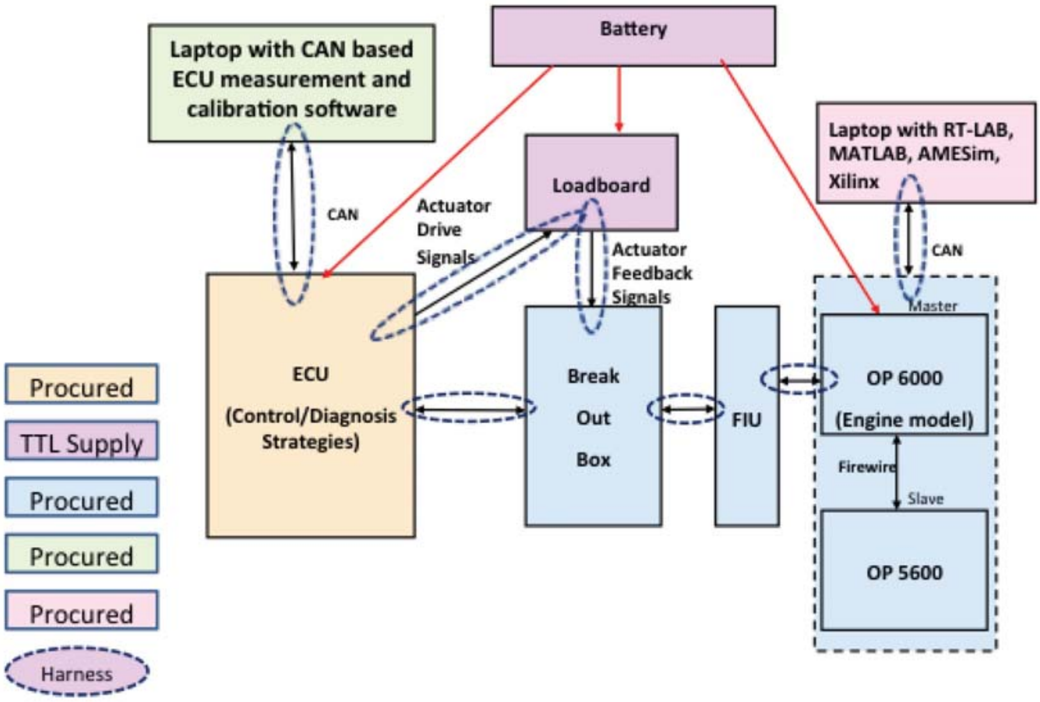
(b)

* Overall dimensions: 1m wide x 3.6m long x 1.5m tall
* Total weight: 220 kg
* Tests right-hand side front and rear wheels
* Bracketry mimics car body mounting points using actual suspension parts

Figure 18. (a) Steering System Test Bed and (b) Brake System Test Bed

greatest potential for application in biomedical field covering diagnostic (especially point-of-care diagnostic) devices, drug delivery systems and patient health monitoring systems. Also micro fluidic and lab-on-a-chip devices are more applicable in this area. Devices for food and environmental monitoring are similar in nature and share large commonality with biomedical devices. Recognising the importance of this area, the NP has mounted several programs in development of such devices.

(a)



(b)

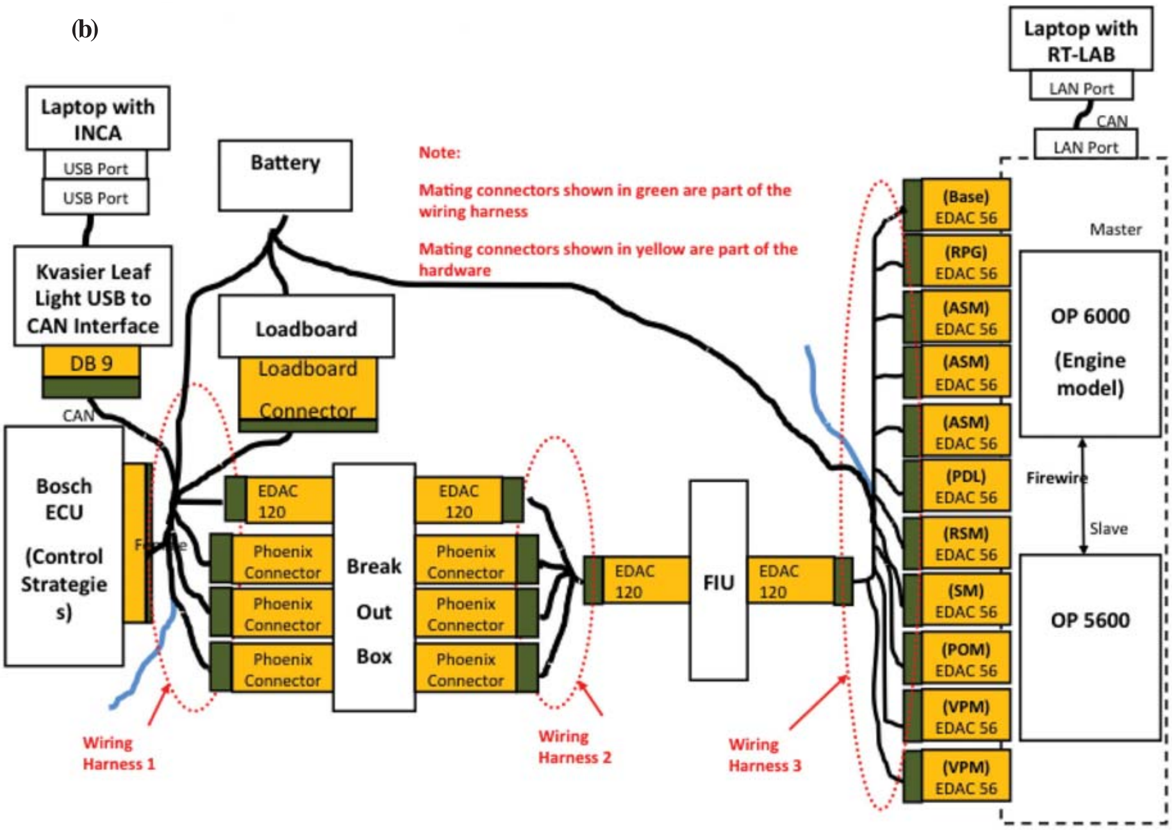


Figure 19. (a) PIL Scheme for Engine and (b) Harnessing for Engine-ECU

One of the earlier devices attempted for lab on Chip for cardiac diagnostics. The current understanding on the biomarkers for acute myocardial infarction (commonly called heart attack) is the liberation of fatty acid binding protein (FABP), troponin and myoglobin within 1 – 3 hours of the potentially fatal incident. Diagnosis on the basis of biomarkers assumes significance as the patient cannot be subjected to stress or any invasive procedures at that juncture. The development (at IIT, Bombay) is ready for field tests.

The technology consists of use of micro-cantilevers coated with the antibodies to the above proteins and a drop of serum on this cantilever initiate reaction culminating in the deflection of cantilever. The changes include surface charge, intermolecular energetics, molecular density and conformational changes. The deflection of cantilever produced by these changes is measured piezo-resistively using appropriate electronics. After initial experiments on silicon micro cantilevers, the device is now made on polymer (SU8). These micro-cantilevers have the advantage of lower Young's modulus, less expensive fabrication procedures, compatibility for integrating sensor with micro-fluidic components.

Fig. 20 shows the functional architecture of the device, and the schematic representation of micro-cantilever deflection is given in Fig. 21. At present, the researchers have demonstrated the effect of biomarkers troponin and FABP, the experiments on myoglobin is in progress and tested the device (Fig. 22) in the laboratory and awaiting clinical trials.

As part of this project, another device based on surface Plasmonic resonance principle was also developed at the same institution.. The phenomenon was demonstated with typical results as shown in Fig. 23, with various concentrations of Sucrose. This device basically can be used for teaching and experimental purposes (Fig. 24).

Development of a bio chip for testing antibiotic sensitivity of pathogens of urinary tract" is also under way (BITs, Pilani). The project is of great significance to our country as many women suffer from urinary tract infections. The gold standard for testing the antibiotic sensitivity is by using culture method and the standard procedure takes 36-48 hours for a final result. This project is an efforts at finding quicker solution. The approach is to concentrate the urine samples using disposable 0.2

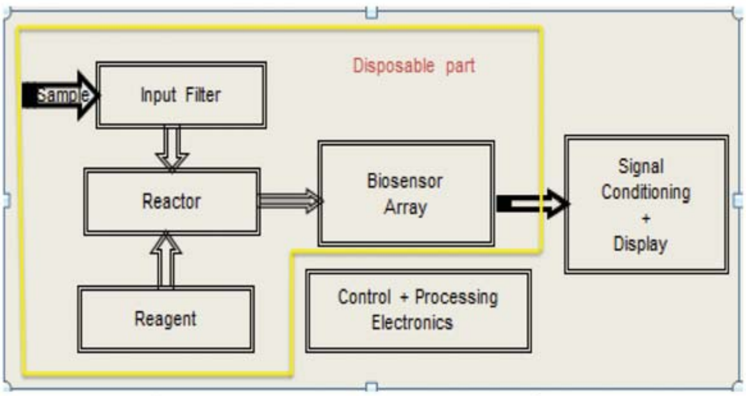


Figure 20. Functional architecture of the device

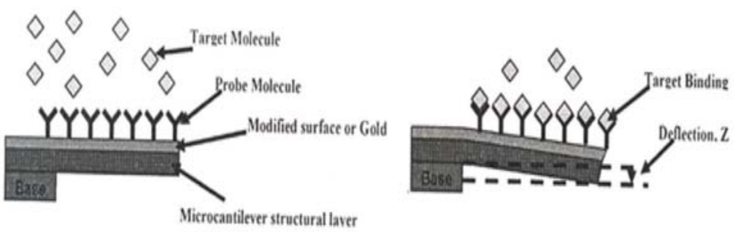


Figure 21. Schematic representation of microcantilever deflection

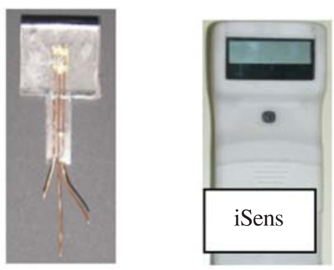


Figure 22. Reaction Chamber & Hand held Device

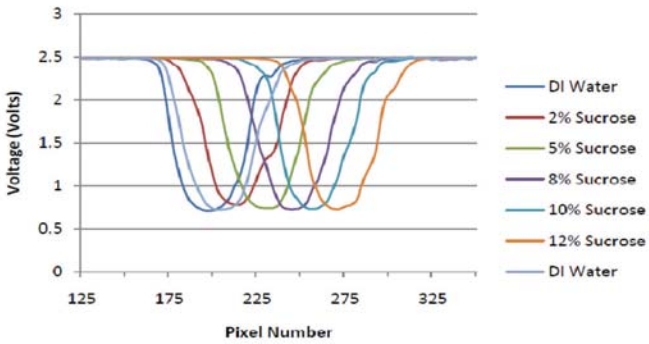


Figure 23. Sensing Changes in Refractive Index

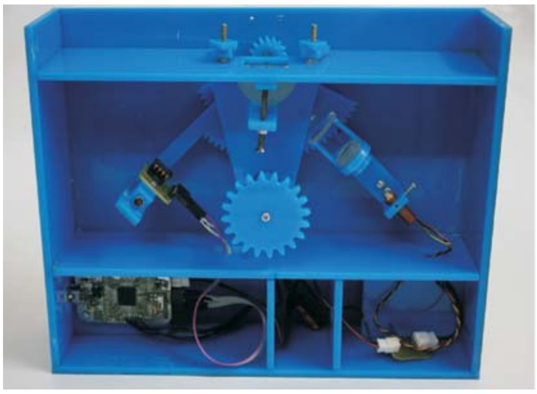


Figure 24. SPR based device

micron cartridge leading to a loading trough, which is then connected to a disc containing 10 growth chambers of 2 mm diameter and 8 mm height, through micro-fluidic channels of 50 and 100 microns respectively in two separate discs (Fig. 25). In these chambers of 30-50 micro-litres volume, the urine sample will contain 200-300 bacteria. The point-of-care device being developed, comes with a ready to use kit for rapid culture of pathogens present in the human urine sample and tests a panel of antibiotics for their bactericidal /bacteriostatic effect on the pathogens present. This device offers ease of operation and analysis of results, rapid results at the bedside or in doctors' chambers/lab in less than two hours, reliable comparable to conventional disc assay and affordable cost per test.

The growth of the bacteria is monitored using dissolved oxygen sensing, which is done by an optical fibre probe dipped into each growth chamber. Within an hour, doubling of bacteria takes place in chambers where the bacteria is not susceptible to the antibiotic, thus the sensitivity of the specimen can be diagnosed. However, to be on safer side, one can wait one or two more doubling, and a very accurate result can be made within 2-3 hours. The clinical isolates of suffering women were tested for commonly used antibiotics such as penicillin, ampicillin, gentamycin, kanamycin, cefuroxime and ciprofloxacin.

The device provides for growth of pathogens in a specially designed medium ensuring rapid growth with release of a product linearly related to the number of bacteria present. In the instance of the bacteria being sensitive to any given antibiotic the chromogen is not released. The released chromogen is read out using a specially fabricated readout-machine(Fig. 26), based on a color to frequency conversion, giving both an alphanumeric display on a screen and a print out for permanent record of the report.

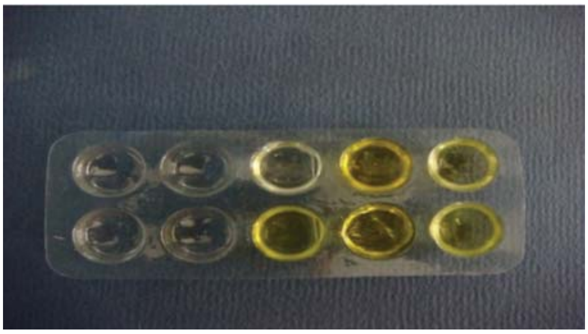


Figure 25. Loading trough containing growth chambers for bacterial multiplication

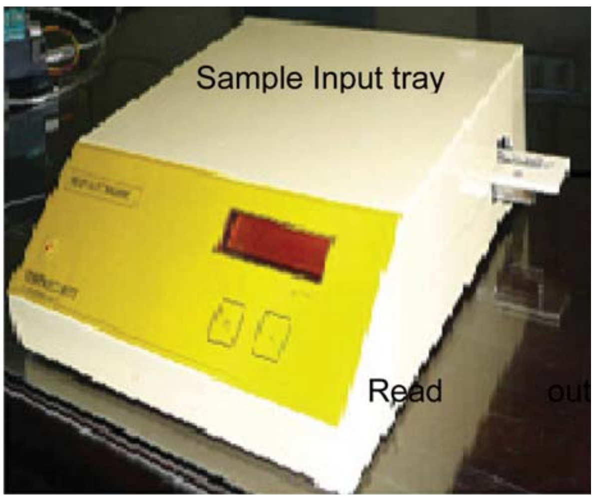


Figure 26. Prototype device -Uro Pathogens sensor

The microfluidic liquid assay has been tested on more than 200 patient urine samples collected from various hospitals in Pilani and Hyderabad. Device is being developed in two phases. The first phase, which has already been completed, consisted of lab scale testing of the engineering version of the device.

During the second phase a multi-centric trial is planned at 3-4 locations for final validation of the assay.

A device for explosive detection has been crying need for quite some time. This chemical device is developed on the same basis of gas sensors but by using amplified fluorescent polymers, a new route (IIT, Bombay). The device has been tested at HEMRL (DRDO Establishment) at Pune. More devices are under fabrication for multicentre trials. This devic can detect RDX and TNT, within a metre, without any direct contact. The The device uses a AFP's (Amplified Fluorescent Polymers) as the sensing element. It consists of an excitation source (LED: Light Emitting Diode) emitting light in wavelength range of 380 to 440nm. The LED source is focused on to a thick walled glass capillary tube coated with the AFP. The polymer emits light in wavelength range of 450 to 490nm. A miniature pump samples vapour through the capillary. The fluorescence from the polymer is detected by a photomultiplier tube (PMT) with an appropriate optical filter. An amplifier circuit amplifies the output signal from the PMT. This device consists of three major modules – the sampling/detection module, detection electronics and a controller running embedded software controlling all functions of the device including display.

First set of prototypes (Fig. 27) are being modified by replacing PMT with photodiode and appropriate amplifier circuit for fluorescence detection (Fig. 28). This includes the modification of detection/optics module to improve the flow of vapour through the capillary to improve the performance, Incorporation of a flow sensor for detection of blockage in the air flow path through the capillary and replaced fan based suction mechanism with a miniature pump.

Figure 27. First prototypes of BEAGLE

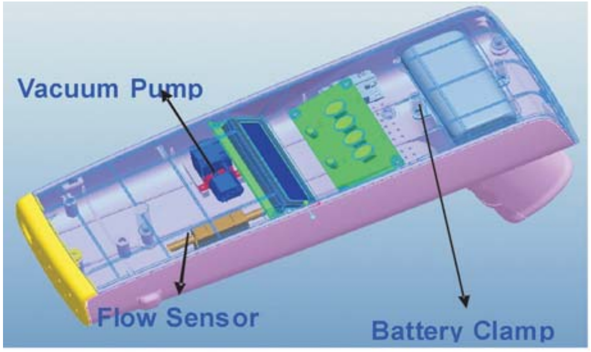


Figure 28. Second set of prototypes- BEAGLE

8. The Way Ahead

Over the last decade through the two national programs, and internal programs of several Scientific Departments of Government of India, the Micro Systems and MEMS technology has reached certain maturity. We have created some, although insufficient, infrastructural facilities and enhanced the human resource appreciably. Several devices have been designed, developed and tested for applications in aircrafts, automobiles and in biomedicine. A few private industries have joined academic groups and national laboratories in producing prototypes. It is expected that some of the devices will be packaged and commercialized in the coming months. Yet, the efforts are insufficient to make any appreciable impact. For this to happen it is essential for many more industries to recognize the importance of this highly application oriented technology and for the academic institutions and National laboratories to enhance their efforts in R&D resulting in devices and subsystems at the same time increasing the human resources. Of course, government has to make substantially increase funds for R&D and infrastructure.

Acknowledgements

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Dr Aatre worked in India's Ministry of Defence in the Department of Defence Research and Development as a Principal Scientific Officer (1980–1984), Director of Naval Physical Oceanographic Laboratory (1984–1991), Chief Controller (1991–1999), and Director General of DRDO and Scientific Advisor to Defence Minister (1999–2004). During this period he designed and developed sonar suites for surface ships, submarines and the air arm of the Indian Navy. He was also instrumental in the development of integrated electronic warfare systems for the Indian Army, Navy, and Air Force, and he established GaAs MMIC fabrication and VLSI design centers for Ministry of Defence. Dr. Aatre is the founding president of the Institute of Smart Structures and Systems (ISSS) and has been running national programs on smart materials and MEMS. He has published over 60 papers in the fields of active filters, digital signal processing, and defense electronics, and has written a book entitled Network Theory and Filter Design published by John Wiley & Sons. He is a Fellow of the IEEE (USA) and the National Academy of Engineering (India), a Distinguished Fellow of IETE (India) and several other societies. Dr. Aatre is the recipient of the prestigious Padma Bhushan Award of the Government of India.