SMART STRUCTURES RESEARCH AT NTU

ANAND K. ASUNDI
Director, Sensors and Actuators SRP
School of Mechanical and Production Engineering
Nanyang Technological University
Singapore

ABSTRACT

Smart Structures is a rapidly advancing field with the range of support and enabling technologies having made significant advances, notably optics and electronics. Whilst piezoelectric actuators and fiber optic sensors have been accorded the most attention, other techniques such as Shape Memory Alloys, Magneto Restrictive Materials and Electro-Rheological Fluids also have niche applications. Furthermore, aspects such as structural integrity, sensor fusion and data interpretation are being considered. This paper will describe some of the research activities at NTU encompassing this broad range of strategic activities.

1. INTRODUCTION

Smart Materials and Structures, Intelligent Structures and Biomimetics are a new rapidly growing interdisciplinary technology embracing the fields of materials and structures, sensor and actuator systems and information processing and control. These can be brought together in a kind of Venn diagram as shown in fig.1 encompassing the overlap of these base technologies. Rapid advances in each of these fields independently have been responsible for impact of this new interdisciplinary technology.

Nature as always has been the main source of inspiration and thus the term biomimetics has been coined. Early copies considered external features such as DaVinci’s flying machines based on birds of flight, sleek ship hulls from fish features and control stabilizers for airplanes from the turkey vulture. With growth in support technology primarily in the areas of electronics and photonics, mimicry of nature has gone quite a few paces forward with a plethora of new ideas trying to emulate features of the most intelligent of all animals - man.

Expertise in various aspects of these base technologies has enabled the School of Mechanical and Production Engineering at NTU to embark on this Strategic Research Area. While Smart Materials and Structures has been classed under the Sensors and Actuators Strategic Research Programme, it is the driving force behind this group. This article will describe the various activities being undertaken in this area within this Strategic Research Area.

2. THE SENSORS AND ACTUATORS SRP

Sensors and Actuators designs have mimicked nature to a large extent. Similar to our five senses - sight, sound, smell, taste and touch - correspondingly visual/optical, acoustic/ultrasonic, electrical, chemical and thermal/magnetic sensors have been developed. The response from these primary sensors is converted to electrical signals that are transmitted to the brain (central information processing and control unit) for further processing. In addition to the processing, the role of the processor is to make decision based on these inputs. An external human operator in most cases does this. A further development would be to provide the material/structure itself to make the judgment. Thus the information processing and intelligence should be embedded within the structure itself along with the sensors and actuators. With growth in MEMS technology, this development appears to be on the horizon. The final stage in this would be for the processor to decide on the course of action and the actuation mechanism to respond accordingly.

Electronics and Optics have been competing technologies in sensor and actuator system over the years. Indeed, the evolution of electronics and optics has taken similar routes (fig.2). Optical Sensors offer some advantages over electrical sensors, such as use of passive, dielectric and insulating components. No electrical power at the measurement point is required; thus no heat generation, electrical shorting and fire hazard problems. Remote, non-contact sensing and whole-field visual display of the measurand rounds of the positive aspects of optical sensors. However, electrical sensors have a longer industrial history and thus components and devices for these sensors are readily available at relatively low cost. Thus electrical sensors are more prevalent. Optical components such as optical fibers, lasers and detectors are only recently being developed fueled by the applications in the communications industry. The cost of these components is competitive and various off-the-shelf systems are becoming available. Indeed the emergence of Optoelectronics (or Electro-optics) has merged the two competing technologies. Optics has the advantage in the primary sensing capabilities, while electronics is currently leading in the processing and actuating technologies. Thus this marriage has a lot to offer in development of novel sensor-processor-actuator (SMART) systems.

While the scope of sensors and actuators is quite broad, three main sub-programs have been identified - Smart Structures and Materials, Micromechanics and Non-Destructive Testing, Inspection Monitoring and Evaluation. Various research projects within these have been proposed and funded with active participation from industry and overseas collaborators. These are exciting times for Sensors and Actuators with the maturing of the enabling technologies of Photonics and Electronics paving the way for inventive and innovative system designs.

3. SMART STRUCTURES AND MATERIALS

Smart structure systems involve, as shown in fig.1, the synergism of materials with embedded or surface mounted sensors whose information is controlled and processed by intelligent system, which controls the actuator to perform the corrective action. The staffs involved in this programme have varying backgrounds and research expertise, which shows in the diverse range of research activities being pursued. Piezomaterials and Fiber Optic Sensors (FOS) are two of the major sensors being investigated for smart structure application. Piezoceramics, Shape Memory Alloy (SMA) and Electro- and Magneto- Rheological fluids are being exploited as actuators. Neural networks and Predictive Maintenance (Condition Monitoring) are novel approaches for intelligence and control of smart structures. Finally, composite material research that has a long background at NTU is being revisited with embedded sensors and actuators adding to the complexity of the material structure. In addition research activities in MEMS, Non-Destructive Testing, and Micromechanics are seen as technologies which can assist the smart structure development programme. This paper will highlight some of the more current developments in these areas.

3.1. FIBER OPTIC SENSORS

Fiber Optic Sensors are among the preferred sensing material in smart structure applications due to their immunity to electro-magnetic interference, small size, lightweight and compatibility with the host material. In addition remote sensing is easily accomplished where the test specimen with the sensing fiber is placed in a harsh environment and the sensed information transmitted by optical fibers to a remote site for evaluation. Development in fiber optics owes much to the communication industry. Their use as sensors is however still under study, primarily because communication fibers were designed for the information-carrying beam traversing the fiber to be transmitted undistorted over large distances. On the other hand, as sensors it is necessary that the external loading influence the transmitted beam which can then be traced back to cause. As such the sensing part of the fiber is but a small portion of fiber length with the rest still being used to transmit the distorted signal to the processor. An excellent review of fiber optic sensor types and their application in smart sensing is given in Selvarajan and Asundi (1995). Basically fiber optic sensors can be classed according to the light modulation mechanisms. Intensity sensors are the most rugged but the least sensitive as they rely purely on the light intensity and can generally distinguish on/off characteristics only. Interferometric sensors are at the other end of the spectrum providing high sensitivity but with difficult handling characteristics. For smart structure applications, sensors in between these two extremes would be most suitable.

While the birth through health monitoring approach is a longer-term programme, several structure systems are being explored. Amongst them is an on-line Aircraft Structural Health monitoring system using fiber optic sensors. Two avenues are being explored, mimicking nature. The first is a global warning system, where in the entire structural component is monitored. In this the goal is to provide an overall health status of the component. This is similar to our human response of rise in body temperature due to illness. The second is more specific testing, in which quantitative values are analyzed at different locations and the damage then completely identified in respect of size, location and severity. Of course, this stage requires longer examination, but it is envisaged that this could be accomplished without significant downtime. This would provide conclusive evidence as to whether the aircraft needs to the “hospitalized” for a complete check-up repair or removal from service. The methodology, with minor modification, could equally apply to civil structures and roads and highways.

The fiber optic sensor to be evaluated can be categorized as global and discrete. Global sensors include the OTDR (Optical Time Domain Reflectometry), and the FOPS (Fiber Optic Polarimetric Sensor). The discrete sensors the EFPI (Extrinsic Fabry-Perot Interferometric) sensor and the Bragg Grating strain sensor. The principles of these sensors have been demonstrated as regard strain and temperature measurement. Fiber Bragg grating provide discrete yet multiplexed strain/temperature measurement capability by reflecting a specific wavelength which shifts due to a strain induced change in grating frequency. The OTDR system relies on back scattered light from flaws to detect location of fiber breaks and defects. As such its immediate use in locating strain induced brakes in the optical fiber. However, some preliminary work [2] has also exposed some other possibilities, which are being investigated. Finally the Polarimetric Fiber Optic Sensor (PFOS)(Asundi, 1995,1996) provides greater sensitivity than intensity sensors but with higher ruggedness compared to interferometric sensors for continuous health monitoring of the structures. Figures 3-5 shows results of a preliminary investigation on the use of surface bonded PFOS for on-line health monitoring. Figure 3 is the schematic of the set-up, which applies equally to embedded optical fibers as to the surface, mounted ones. Figures 4 and 5 are the static and dynamic response. It has been observed that in the presence of defects and delaminations the response of the sensor changes noticeably and predictably. This thus has the makings of a simple global sensor.

In addition to sensor designs, the effect of the sensing fiber whose diameter is about 5 to 10 times that of the reinforcing fiber embedded within the host material is being investigated both numerically and experimentally. Fiber Optic Sensors is growing area of research with activities being planned in the School of Applied Science and on-going research in the School of Mechanical and Production Engineering and the School of Electrical and Electronic Engineering.

3.2. PIEZOELECTRIC MATERIALS

Piezoelectricity is the ability of a material to develop an electrical charge when subjected to a mechanical strain (direct piezoelectric effect) and conversely, develop mechanical strain in response to an applied electric field (converse piezoelectric effect). The coupled mechanical and electrical properties of piezoelectric materials make them well suited for use as sensors (which use the direct piezoelectric effect) and actuators (which use the converse piezoelectric effect). As a sensor, deformations cause by the dynamic host structure produce an electric charge resulting in an electric current in the sensing circuit, while as an actuator, a high voltage signal is applied to the piezoelectric device, which deforms the actuator and transmits mechanical energy to the host structure.

The two common types of piezoelectric materials are lead zirconate titanate (PZT) ceramics and polyvinylidene fluoride (PVDF) polymers. Piezoceramics and piezopolymers are usually produced in thin sheets with films of metal deposited on the opposite surfaces to form electrodes. Piezoceramics are brittle and stiff, while piezopolymers are tough and flexible. In particular piezopolymers are good candidates for sensing because of their small stiffness, which adds minimum local stiffening to the host structure, while piezoceramics are better suited for actuating due to their greater elastic modulus for effective mechanical coupling to the structure. Piezoelectric materials have been found to be very attractive for smart structure applications. Piezoelectric materials are light and can be readily attached or embedded in structures. They are suitable as distributed sensors and actuators.

With advancement in technology and materials, more and more mechanical systems and components are being produced in miniature sizes, especially in the electronic and computer industries. These mechanical structures or components can be in the millimeter or even micron scale. As mechanical structures and components gets smaller in size, conventional vibration testing techniques are unsuitable and sometimes inapplicable as the mass loading effect of the conventional transducer becomes significant.

One current project involves the use of piezo-electric material for buckling control of structures. Piezo-ceramics bonded to surface introduce lateral forces which can be used to change the initially straight profile of the beam to an anti-symmetrical second mode shape. Both finite element analysis and experimental verification of the effect of boundary conditions, ply orientation and actuator position are being conducted (Chai and Lu Fan, 1998).

Piezoelectric materials are continuing to be among the most widely used and active research within the Sensors & Actuators programme and some details of smart structure systems using piezo-electric material is described in a later section.

3.3. **SHAPE MEMORY ALLOYS**

A shape memory alloy (SMA) is able to memorize and recover its original shape, after deformed by heating over its transformation temperature. During this transformation, large forces or large deformations can be generated which can be used for actuation. Nitinol (Nickel - Titanium Alloy discovered in the Naval Ordinance Lab) is the most commonly used SMA. Nitinol is capable of recovering up to 8% strain, or generating around 500 MPa stress if constrained during recovery, and, if strains are kept below 2%, Nitinol based actuators can survive millions of cycles.

The drawbacks of SMA based actuators are comparatively slow response time. This problem is inherent since these alloys rely on heating and cooling for their actuation. Therefore SMAs are not suitable for high-frequency control, but for low frequency and quasi-static response control.

SMAs have been used in a wide variety of applications. Two quite successful applications are SMA-made eyeglass frame and the antenna of mobile phone. The advantage of using SMA is that after severe deformation, SMA can still fully return its original shape. SMAs have been used in vibration dampers and isolators due to SMAs' high internal friction. For example, SMA wires have been used as passive energy dissipater to increase the hysteresis damping in structure under earthquake. The more advanced applications are in robotics (artificial hand/arm), passive/active control system (buckling control), smart/adaptive structures (vibration control), and composite structures (shape control). Due to its excellent bio-compatibility, Nitinol has also been used in medical instruments (vascular stents and filters). An active endoscope using Nitinol coil spring has been designed and tested. Use of SMA's is a growing field with various staff actively involved in their development and applications.

3.4. **ER and MR FLUIDS**

MR fluids are made of micron-sized particles which under the influence of magnetic field form long chains, which can alter the rheological properties such as viscosity and yield stress of the fluids. The advantages of MR fluids include fast response times, high dynamic yield stress, low plastic viscosity and broad operational temperature range. Electro-Rheological (ER) fluids are also available which behave similarly but under the action of an electrical field. This relatively new research topic at NTU is being exploited to develop a new type of controllable damping unit with potential application in vibration control and hydraulic systems (Li et al, 1997). A brief description of one such smart system is described below (Leng et al, 1998).

3.5. MICROMECHANICS OF SMART MATERIALS

Following the widespread application of piezoelectric materials in composites, the electro-elastic analysis of such materials becomes one of the most important problems in engineering. When piezoelectric materials are used as sensors, they are usually embedded in non-piezoelectric materials to which external electro-mechanical loads are applied. Due to the electro-mechanical interaction between the sensor and the surrounding material, the properties of the surrounding material may influence the response of the sensor to the external load. According to this phenomenon, the sensor can be used to detect the possible defects in the surrounding material. So it is desirable to understand the interaction between the piezoelectric sensor and the matrix, as well as the defects in the matrix. On the other hand, since piezoelectric composites can take advantage of the beneficial properties of piezoelectric materials, they play an increasingly important role in technology. When piezoelectric fibers are embedded in a polymer matrix, the mechanical strength of the fiber-matrix composite is greatly influenced by the interaction between the fibers and the defects in the matrix. So it is very important to understand such interaction and analyze the electro-elastic stress fields in piezoelectric composites.

A project (Xiao et al, 1997) to investigate the interaction problem of a fiber-shaped piezoelectric inhomogeneity embedded in a non-piezoelectric elastic matrix that contains a crack was conducted. The result can be used to design sensors, which can monitor defects in the material and can also be used to investigate the electro-mechanical properties of piezoelectric composites. The solution to the problem is obtained through the superposition of two sub-problems. The first one concerns a piezoelectric inhomogeneity embedded in an infinite matrix without the crack. The stress distribution outside the inhomogeneity is obtained by the Eshelby's equivalent inclusion method and elasticity theory. The second problem deals with the stress disturbance due to the existence of the crack. In this problem, a set of integral equations in the crack domain is derived through the edge dislocation theory. The expressions for the stress intensity factors are then obtained in terms of the asymptotic values of the dislocation density functions solved from the integral equations. The calculation results are presented graphically, from which the influence of the piezoelectric inhomogeneity and electric loading on the crack can be observed clearly.

Finite Element Methods (Yi et al., 1997, 1998) are also being adapted to solve the acoustic- smart structure-coupling problem. This has potential implication in the development of high-fidelity loudspeakers and electro-acoustic transducers. A finite element formulation for analysis of smart structures including large deformations has been developed. Composite structures with active piezoelectric materials and passive viscoelastic damping layers are considered. Thermo -visco-piezoelectricity is used to formulate finite element procedures to analyze static and dynamic response of such smart composites. Initial results are found to be promising and work on boundary element formulation and an adaptive control scheme for vibration control are being planned.

Many of the smart material systems exhibit a coupling between two different physical phenomena. In piezoelectric solids, the coupling is in between mechanical stresses and electrical potentials and is of first order in nature. In shape memory alloys, thermomechanical coupling exists, with phase transitions occuring as a function of temperature. Smart engineering designs exploit such a coupling for tools which act as both sensors and actuators.

The smart materials micromechanics group at NTU focuses on two specific aspects:

(1) Contact mechanics in Piezoelectric solids. The objective of understanding the mechanical and electrical responses as well as fracture behavior when a piezoelectric solid is indented with variously shaped indentors. Both experimental work and theoretical calculations are being carried out.

(2) Fracture and Fatigue Crack Growth in Shape Memory alloys:
Here, the objective is to understand the micromechanisms of crack growth in Nitonal. Experiments are being conducted to understand effect of transformation plasticity on the thermomechanical fatigue behavior. Both these works are being carried out in collaboration with Prof. S. Suresh, Prof. D. C. Dunand, and their groups at MIT.

4. SMART STRUCTURE SYSTEMS

Sensors and Actuators form the bulk of the current research in Smart Structures and Materials. However the other two categories - Materials and Structures and Intelligence have to be and are being considered as well. Composite materials are the prime targets for Smart Materials in Structural Applications. Damage Mechanics of Composites for predictive maintenance and incipient failure detection and their role in Smart Structural Composite application is being considered. Non-Destructive Testing and Evaluation of Composite Damage provides a wealth of information which can be used to propose a health monitoring chart for these materials based on their response during active life. Most all NDT techniques are being pursued and new methods such as lock-in thermography provide novel solutions to existing problems. This data of current damage mechanisms would also be useful in future design of smart materials and structures with built-in intelligence to adapt to the surroundings as well be aware of its current capabilities. Some of the current work in integrated sensor and actuator for smart structure applications are described here.

In micro-modal testing, which refers to the modal testing of micro-mechanical structures, the advantages of piezoelectric materials as sensors and mechanical actuators are being exploited. Piezoelectric actuator is used to excite the structure into vibration and the piezoelectric sensors pick up the response of the structure. The excitation and response signals are then analyzed to obtain the modal properties of the structures. These piezoelectric sensors and actuators are small, light and can be readily attached or embedded in the structure without significantly affecting the modal properties of the host.

One completed project (Lin et al, 1997) demonstrates the feasibility of using piezoelectric materials as sensor and actuator in modal testing. Experimental modal testing on a small cantilever beam was performed. A small patch of thin PVDF film was surface bonded on the beam as sensor and another patch of thin PZT layer was bonded on the beam as the actuator. The analyzed results of modal properties obtained were satisfactory when compared with finite element analysis results.

Another study involves development of active sensors and actuators for self-monitoring and control in structural design. A simple system is a cantilever beam with surface bonded piezoelectric sensor and actuator for vibration suppression. In understanding smart structure technology, the modeling of such structures is essential. A three dimensional finite element formulation is employed for the elastic cantilever beam with surface bonded piezoceramic sensor and actuator. A series of finite element analyses were performed to study the dynamic behaviour of the structure and the level of response control provided by the active devices under different feedback methods. Two different feedback control algorithms are considered, constant-gain velocity feedback control and constant-gain displacement feedback control. With velocity feedback, the sensor signal was amplified and phase-shifted by 90 degrees and then fed back to the actuator. As for displacement feedback, the sensor output voltage was amplified before feeding back to the actuator. The change in damping ratio and change in vibration amplitude were evaluated when comparing the control effectiveness. The feedback gain was varied in the study. In the velocity feedback control algorithm, the damping ratio increases as the feedback gain increases. The beam oscillation is damped out much faster at higher feedback gain. Velocity feedback control is therefore effective in vibration suppression. In the case of displacement feedback, a stiffness change is observed resulting in a shift in natural frequencies. Depending on the sign of the feedback gain, the natural frequencies can be increased or decreased. At excitation frequency near the resonance of the structure, shifting of the resonance frequency can significantly reduce the vibration amplitude of the structure. Experiments were performed on a cantilever beam with surface bonded piezoceramic sensor and actuator. The two feedback control methods were implemented and the experimental modal testing results obtained verified the conclusion from the finite element modeling.

Another study proposes the use of an optical fiber sensor and Electro-Rheological (ER) fluid actuator for active vibration monitoring of smart composite structures (Leng et al. 1998). Intensity modulated fiber optic vibration sensor with higher sensitivity for vibration frequency determination is developed. Also the elastodynamic response of a beam fabricated with ER fluid is evaluated. Finally the vibration of smart composite beam with an embedded fiber optic vibration sensor and ER fluid actuation is demonstrated for detection and active control of vibration.

5. CONCLUSIONS

A brief review of the current research activities in the School of Mechanical and Production Engineering at NTU is described. The primary initial focus is on Sensor and Actuator designs for Smart Composite Materials, Vibration and Noise Control. Some basic understanding of the sensor and actuator systems is also being studied, as is the effect of embedding sensors and actuators on the structural integrity of the structures. Piezo-electric and Fiber Optic Sensors have a larger contingent of researchers due to their longer histories, however MR and ER fluids as well as Shape Memory Alloys have their own niche applications and are also being investigated as complementing techniques. In addition research at NTU in the areas of Advanced Materials and Processing, Non-Destructive Testing, MEMS, etc. will have a bearing on the future of Smart Materials and Structures. It is our wish to develop a well-rounded facility at NTU and towards this end we would welcome any input and collaboration from interested parties.

6. ACKNOWLEDGEMENTS

I would like to thank Dr. Chen Guang, Dr. Du Hejun, Dr. Huang Weimin, Dr. Lin Rongming, Dr. Ong Ling Seng, Dr. Seah Leong Keey, Dr. U. Ramamurthy, Dr. Yi Sung for providing me with outputs of their research activities. Also I would like to acknowledge, A/P Ling Shih Fu for sharing their research proposals in Smart Structure Applications. Finally, thanks to the Dean, Prof Lim Mong King; Vice-Dean for Research, A/P Lye Sun Woh and the Head of Engineering Mechanics Division, A/P Ling Shih Fu for their support.

6. REFERENCES

1. Selvarajan, A. and A. Asundi 1995. "Photonics, Fiber Optic Sensors and their Application in Smart Structures" Non-Destructive Evaluation, J. 15(2)

2. Asundi,A. 1996. “Polarimetric Sensors for Strain Measurement and Damage Detection, Smart Structures, Materials and MEMS: Bangalore, India
3. A.Asundi, 1995.Workshop on Fiber Optic Sensors, Hong Kong
4. Leng J.S., Asundi,A and Liu, Y.1998 "Active Vibration Control of Smart Composite beam with Embedded Optical Fiber Sensor and ER Fluid", ASME Conference.
5. Li W.H., Chen,G and Yeo, S.H., "Magnetoreheological Fluids: Mechanisms, Materials, Propoerties and Applications", 1997, Journal of the Institution of Engineers, Singapore, 37(6).
6. Lin R.M. Lim, M. K. and K. M. Nyang. 1997 "Vibration Control Using Smart Sensors and Actuators" Asian Pacific Vibration Conference: Korea
7. Xiao Z.M. and Bai J., " Electro-elastic stress analysis on piezoelectric inhomogeneity-crack interaction, NTU Internal Report, 1998.
8. Yi, S., Ling, S.F., & Ying M., 1998 "Nonlinear Finite Element Analysis of Smart Structures with a Solid Element with Allman’s Rotations International Journal for Numerical Methods in Engineering: to be published
9. Yi, S., Ling, S.F., & Ying M, 1997 "Finite Element Analysis of Composite Structures with Smart Constrained Layer Damping" Advanced Engineering Software: in press
10. Yi, S., Ling, S.F., & Ying M, Hilton, H. H. & Vinson, J. R., 1997. "Finite Element Formulation for Anisotropic Coupled Piezo-hygro-thermo-Viscoelasto-dynamic Problems", International Journal for Numerical Methods in Engineering, (submitted).

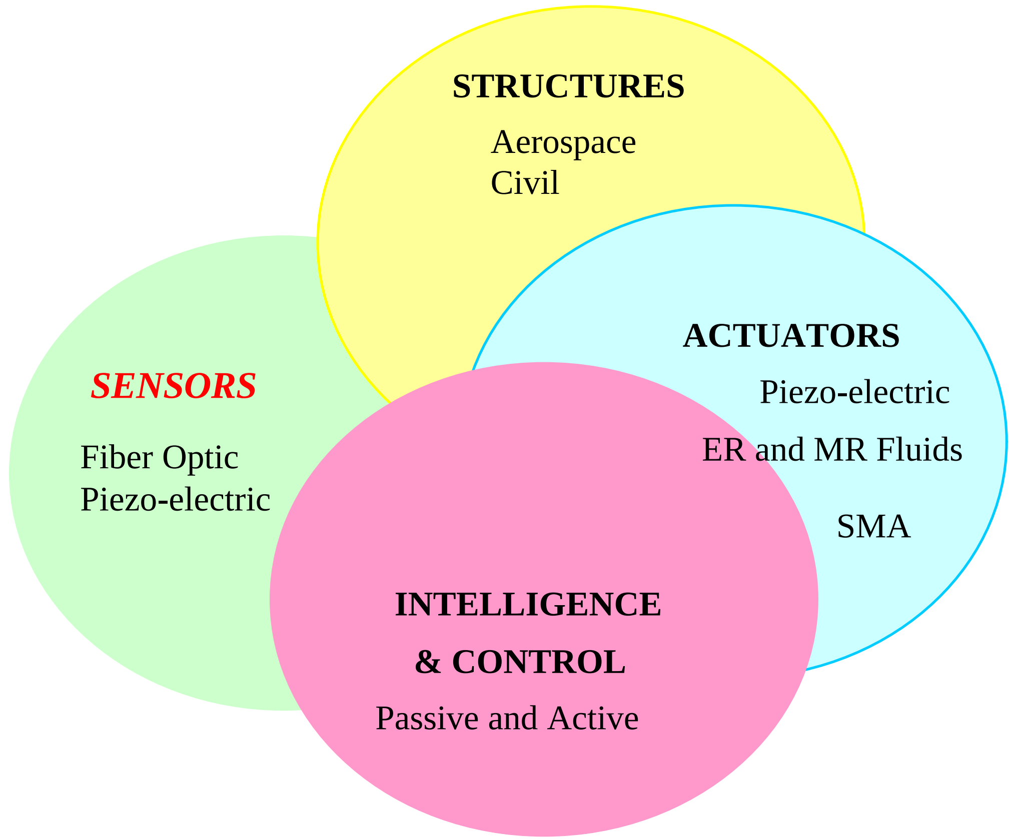

Figure 1 Synergy of Smart Materials and Structure Systems

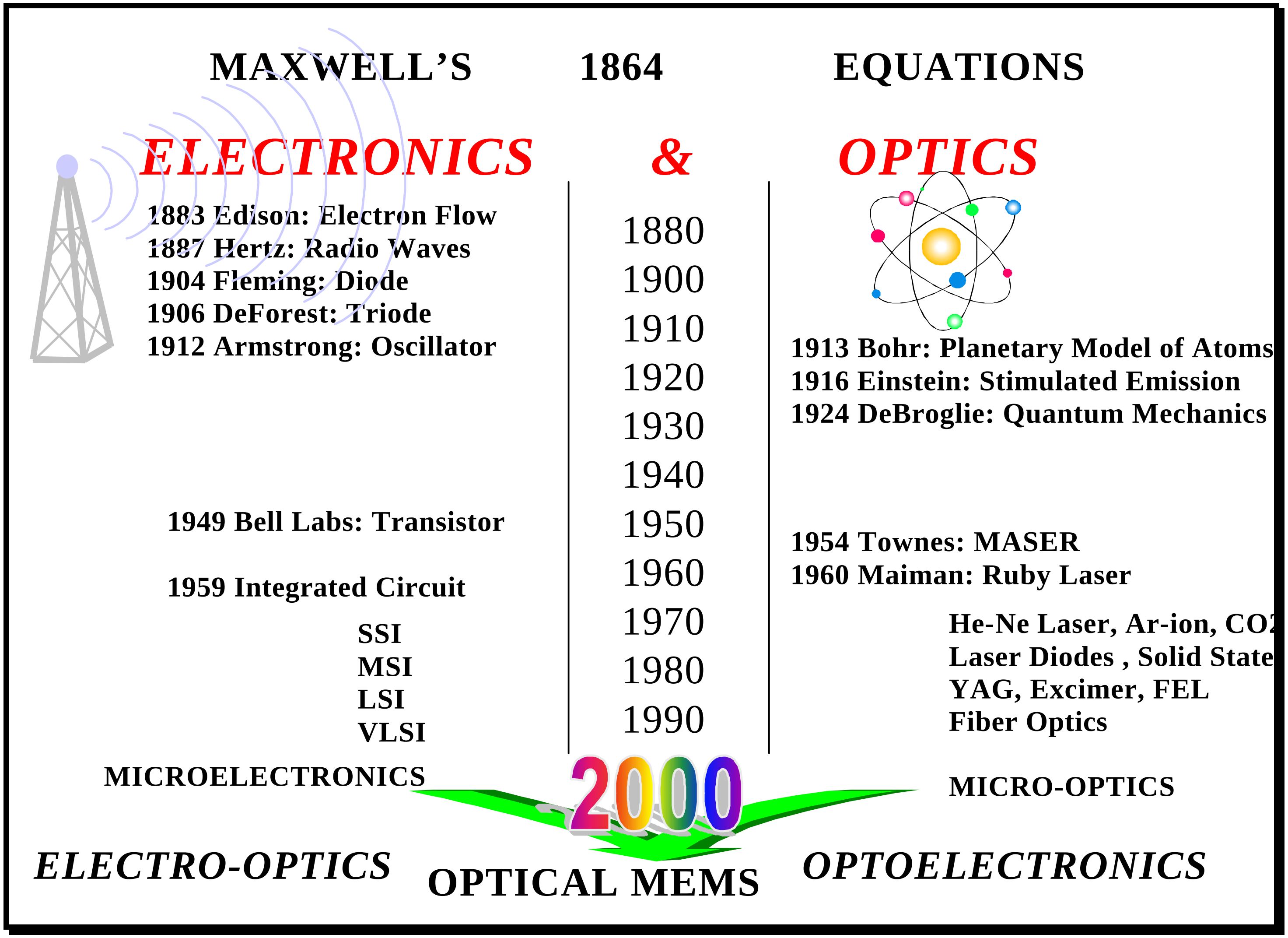

Figure 2 Electronics/Optics Tree

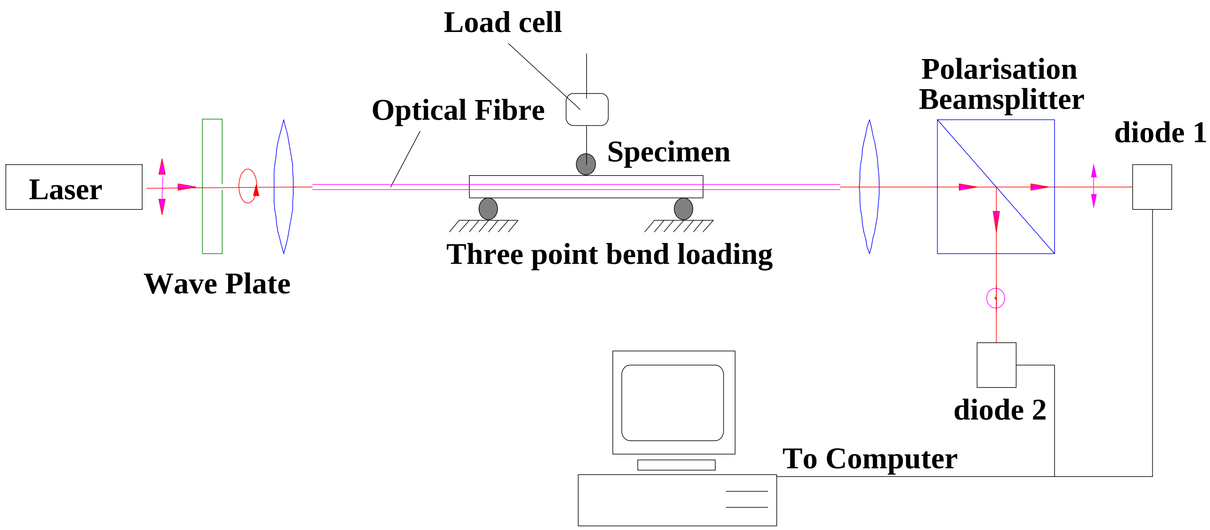

Figure 3 Schematic of the Polarimetric Fiber Optic Sensor System

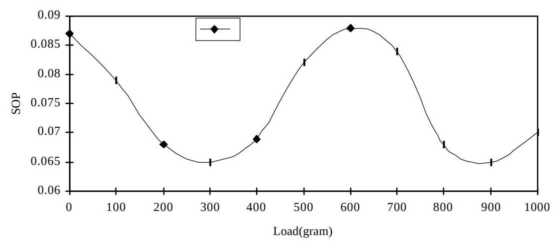

Figure 4.Static response of fiber optic polarimetric sensor

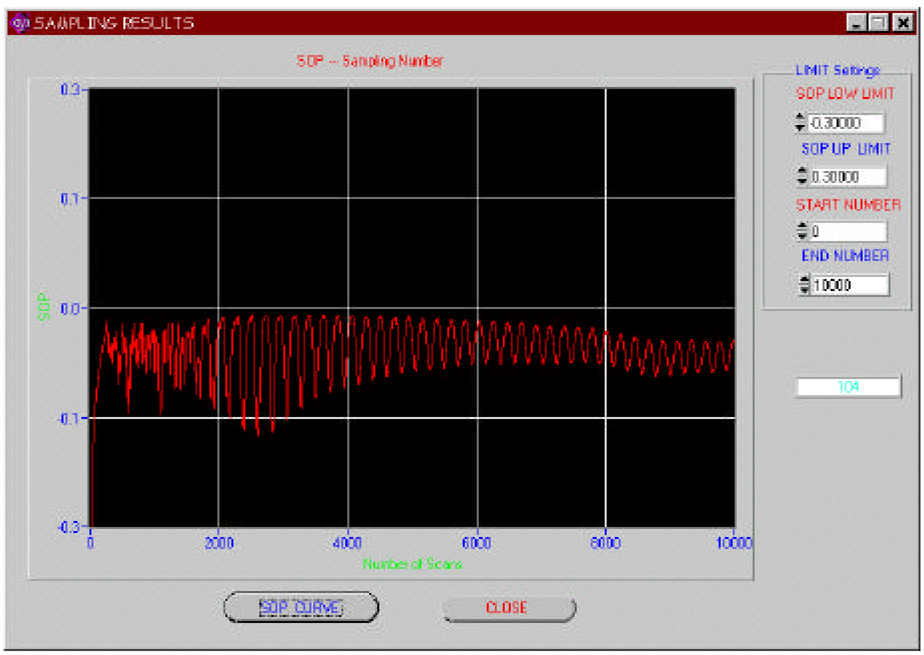

Figure 5. Dynamic response of fiber optic polarimetric sensor