MEMSCON PROJECT: WIRELESS SENSOR NETWORK FOR POST-EARTHQUAKE EVALUATION OF CONCRETE BUILDINGS

Matthaios Bimpas
ICCS, Greece

Angelos Amditis
ICCS, Greece

Stamatia Frondistou-Yannas
RISA GmbH, Germany

Vasilis Kalidromitis
TECNIC S.p.A., Italy

Davide Trapani
DIMS,University of Trento, Italy

Daniele Zonta
DIMS, University of Trento, Italy

Yorgos Stratakos
Advanced Microwave Systems Ltd

Anastasios Gkaretsos
Advanced Microwave Systems Ltd

Rapid advances in computation, sensing and data transmission techniques, such as RFID technology, Micro-Electro-Mechanical Systems (MEMS) and low power wireless networking offer hope of a new generation of small and inexpensive networked sensors. These can be distributed on buildings and structures to provide accurate quantitative information on the structure's physical state while in service. The aim of the EU-funded MEMSCON project is to develop MEMS-based sensors for structural monitoring and to integrate them with a Decision Support System that will use the information from the above sensors to aid evaluation of reinforced concrete buildings. This will be done both before and after earthquakes, to aid decisions on improvement and repair. Although today the appraisal of seismic damage is almost exclusively based on visual inspection, measuring quantitatively the response of buildings during and after an earthquake, in terms of acceleration and strain, is an easy task. However structure owners are somehow reluctant to install permanent sensing systems, due to both their high costs and the difficulty of interpreting the data. To overcome these limitations, the MEMSCON project aims to produce a small size sensing node, integrating MEMS-based sensors and an RFID tag in a single package. Such nodes can then be attached to reinforced concrete buildings for life-cycle measurements of acceleration and strain, with data transmitted to a remote base station using a wireless interface. These nodes will allow economically sustainable industrial deployment of structural monitoring systems. This paper presents the development of the first prototypes of strain and acceleration sensors, and their validation in the laboratory.

Corresponding author's email: mbibas@iccs.gr

5th International Conference on
Structural Health Monitoring of Intelligent Infrastructure (SHMII-5) 2011
11-15 December 2011, Cancún, México

MEMSCON PROJECT: WIRELESS SENSOR NETWORK FOR POST-EARTHQUAKE EVALUATION OF CONCRETE BUILDINGS

Matthaios Bimpas[1], Angelos Amditis[1], Stamatia Frondistou Yannas[2], Vasilis Kalidromitis[3], Davide Trapani and Daniele Zonta[4], Yorgos Stratakos and Anastasios Gkaretsos[5]

1 ICCS, Athens, Greece
2 RISA GmbH, Berlin, Germany
3 DIMS,University of Trento, Italy
4 TECNIC S.p.A., Rome, Italy
5 AMS, Athens, Greece

ABSTRACT: Rapid advances in computation, sensing and data transmission techniques, such as RFID technology, Micro-Electro-Mechanical Systems (MEMS) and low power wireless networking offer hope of a new generation of small and inexpensive networked sensors. These can be distributed on buildings and structures to provide accurate quantitative information on the structure's physical state while in service. The aim of the EU-funded MEMSCON project is to develop MEMS-based sensors for structural monitoring and to integrate them with a Decision Support System that will use the information from the above sensors to aid evaluation of reinforced concrete buildings. This will be done both before and after earthquakes, to aid decisions on improvement and repair. Although today the appraisal of seismic damage is almost exclusively based on visual inspection, measuring quantitatively the response of buildings during and after an earthquake, in terms of acceleration and strain, is an easy task. However structure owners are somehow reluctant to install permanent sensing systems, due to both their high costs and the difficulty of interpreting the data. To overcome these limitations, the MEMSCON project aims to produce a small size sensing node, integrating MEMS-based sensors and an RFID tag in a single package. Such nodes can then be attached to reinforced concrete buildings for life-cycle measurements of acceleration and strain, with data transmitted to a remote base station using a wireless interface. These nodes will allow economically sustainable industrial deployment of structural monitoring systems. This paper presents the development of the first prototypes of strain and acceleration sensors, and their validation in the laboratory.

1 INTRODUCTION

Structures which are subjected to the effects of material aging (cracks propagation and reinforcement corrosion), design errors, overloading, unpredicted foundation settlements or seismic events can progressively accumulate damage during their operative life. In order to rationally plan the maintenance actions needed to guarantee an adequate level of safety and serviceability, the regular structural assessment is therefore a key step.

Nonetheless the convenience of installing permanent sensing systems is not easy to prove [1]: the only way to provide economic sustainability is to make use of robust sensors, industrially produced, which can be easily integrated into the construction process of the building and whose measures provide information highly relevant in the reliability assessment. Moreover, as the environmental inside a modern building is usually overcrowded by electrical wires to carry power and signals, the sensing network dedicated to the structural monitoring should not interfere with them: nodes have to be small and links without cables. Radio Frequency Identification (RFID) and Micro-Electro-Mechanical-System (MEMS) technologies offer a set of promising tools to develop a wireless cost-effective system able to fulfil these requirements. The potentiality of MEMS and wireless networking for the monitoring of civil structures is well documented [2,3,4].

The MEMSCON Project (www.memscon.com) is co-funded in by the European Community in the 7th Frame Program; it involves partners from 7 countries. Based on this background, the project is devoted to develop a reliable and cost-efficient monitoring system to be integrated in new Reinforced Concrete (RC) buildings for their defence against seismic events and settlements. The system is made by a wireless network spread inside the building, and a base station linking the building to a remote center for data interpretation. As outlined in Figure 1, the network includes sensing nodes measuring strain and acceleration: strain measurements are collected at the lowest level of the building, permitting to estimate the distribution of the vertical load along the columns and its possible variation to a settlement; horizontal acceleration is to be measured by dedicated nodes at each level, during an earthquake, allowing reconstructing the actual seismic response of the whole structure.

The project is divided in two main tasks: (i) the development of the sensing network and (ii) the development of the software to process remotely the measurements, assessing the structural condition and planning the optimal maintenance operations. The products will be validated both in the laboratory and by in-field applications. Task (i) comprehends the creation of new instruments specifically dedicated to the measurement of strain and others dedicated to the acceleration. Both these devices will be based on RFID in MEMS, integrated into a small-size package and permitting ultra lower consumption. The sensing performances of these nodes have been selected to push up that of the existing technology [4,5].

While the production of the final nodes is scheduled for end-2011, the first prototypes have been already obtained by assembling components available on the market, through a process of design, packaging and programming. These devices do not fulfil the target requirements of the project, but they allow nonetheless investigating relevant features of the system. The prototypes have been tested into the laboratory and the paper reports on this stage of the project.

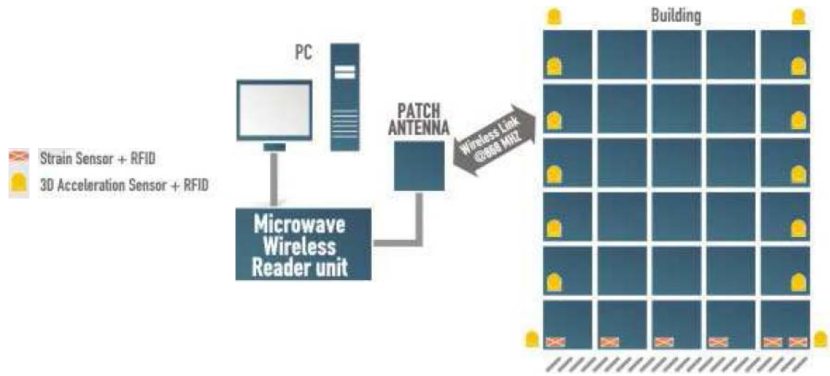

Figure 1: Scheme of the monitoring system proposed in the MEMSCON project.

2 STRAIN SENSOR WIRELESS NETWORK

2.1 Development of the hardware

In this phase of the MEMSCON project, the strain sensors employed are foil gauges available off-the-shelf, produced by HBM GmbH, to be attached on a reinforcement bar. Since the gauge is the only component permanently buried within concrete, the external electronic interrogation node is connected to it via a 2-wire cable and the appropriate connector. The device, which is battery operated, was designed to partially fulfil MEMSCON basic specifications: Ultra Low Power Consumption (no battery replacement ideally for the product life time of 10 years), accurate measurement of strain (20 □□ resolution), and wireless transmission of measurements through the radio network to the base station.

With these specifications in mind, the hardware developed for the node includes an analog input management subsystem, with a strain gauge bridge, a programmable amplifier with digital offset and gain adjustments and a low pass filter. The data transmission makes use of a Zigbee Wireless Rx/Tx module, and the node is also endowed with a microprocessor for the global control of the device, the conversion of the analog strain measurements into digital format and with a real-time clock that operates continuously measuring the actual date and time with 1 sec resolution [6].

Special firmware was developed that allows the device to wake up from “sleep” upon specified time intervals, connect to the RF network, take strain measurements and transmitting them to the interrogator and returning back to sleep. This time interval is expected to be 2-4 months, allowing the device to keep battery power consumption at very low levels. It should be noted that during sleep the device consumes only 54µW while when active it consumes 100mW. The electronic system, the battery and the input connector is all included in a small plastic box, dimension 11x8x4cm, with an antenna, as shown in Figure 2.

The base station, shown in Figure 2(b), assigns addresses to the sensing nodes, continuously waits and gives network access to any sensor that asks to transmit data. The acquired data can then be passed to the remote interrogation centre using a 4-element patch antenna array, designed to guarantee a high RF gain to the system. Simulation and validation of the manufactured antenna shows that a reliable link can be expected up to 1 km distance in an urban environment when there is line-of-sight contact.

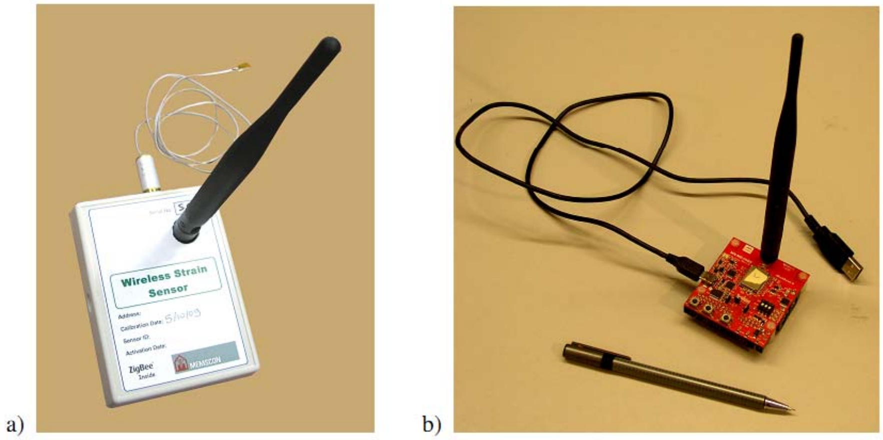

Figure 2. Strain Sensor Node (a) and Base Station (b).

2.2 Laboratory validation

The validating campaign for the strain-gauge nodes aims at reproducing in the laboratory the operational conditions of an RC element in a building, up to an extreme scenario. During settlement and, more often, during an earthquake, the columns can undergo extensive damage including concrete cracks, cover spalling, crushing and reinforcement yield. As we use the wireless network to estimate the damage level during or after these events, we must investigate the network performance and efficiency under the same conditions.

The gauges were attached to ordinary reinforcing bars (steel B450C, 20mm diameter), with a standard cyanoacrylate adhesive and a silicone protective coating. The installation procedure follows the instructions by HBM, and so the time required to fasten a gauge is about 30 minutes. In the first laboratory campaign completed so far, gauge performance was investigated in small specimens, tested in tensile and compression load cycles. The bars and the complete specimens were also instrumented with additional strain gauges wired to a high-precision interrogation unit, to compare in real-time the data flow deriving from the wireless network with reference values. We adopted the same model of foil gauge, so that the difference between the performance of the wired and wireless systems depends only on interrogation and data transmission. Before starting the laboratory tests, both the clock and the voltage sensitivity of the wireless nodes were calibrated, and the sampling frequency set to 3Hz.

The simplest way to check the accuracy of the system is to instrument bare reinforcing bars, not embedded in concrete; this lets us avoid all the uncertainties related to the random behaviour of concrete. Therefore two bare bars, 50cm long, were tested in tensile cycles of increasing amplitude, up to yield and failure. Each bar was instrumented with 1 wired and 2 wireless and gauges, as shown in Figure 3 (upper graph). The same figure reports the outcome of a full test: the strain recorded by the wireless (continuous lines) and by the wired system (dashed line) are plotted against time. The agreement between the two is remarkable, and can be quantified in 20με, of the same order as the resolution of the wireless system. Note that, independently of the acquisition mode (wired or wireless), the gauges become inactive at a strain of about 2300με, which is a predictable value for the fatigue life of a glued sensor.

To investigate the performance of the gauges in concrete, three instrumented reinforcing bars were embedded in a concrete cylinder (length: 50cm, diameter: 13cm). The sensors were placed at the middle of the bar and protected by a Butyl rubber sealant with aluminium foil. When the concrete was poured, the mould was weakened, to induce a crack exactly at the instrumented cross section. The specimens were also instrumented with external sensors to measure the crack opening. Figure 3 (central graph) reports the strain time history, as for the previous test type. Two wireless gauges and two wired were arranged along the same cross section, where a crack is expected. The test shows that the sensors keep working up to the same level of strain as that applied to the bare bar, and the difference between the time histories can be easily attributed to the random behaviour of concrete under tension. In fact, during the test, asymmetrical cracks appeared along the specimen, which altered the load eccentricity and, consequently caused variation of the strain along the rebar cross section. The evolution of the load eccentricity during the test was consistent with the measurements derived by the external sensors.

The last tests were devoted to analysis of the behaviour of the gauges embedded in concrete under compression. Three concrete specimens (length: 33cm, diameter: 13cm) were produced, reinforced by the instrumented bar surrounded by a spiral stirrup to reproduce the effect of confinement. External long-base strain gauges were also applied to the concrete surface, to record the behaviour of the cover during the test. The specimens underwent cycles of increasing magnitude, up to spalling of the cover and crushing of the concrete core. Four gauges were arranged so that 1 wired and 1 wireless sensor were on both sides of the rebar; Figure 3 (lower graph) shows the measurements obtained against time, for both systems. The strain, now in compression, again reaches 2000-2500$\mu\varepsilon$, and the agreement is of the same order as the resolution.

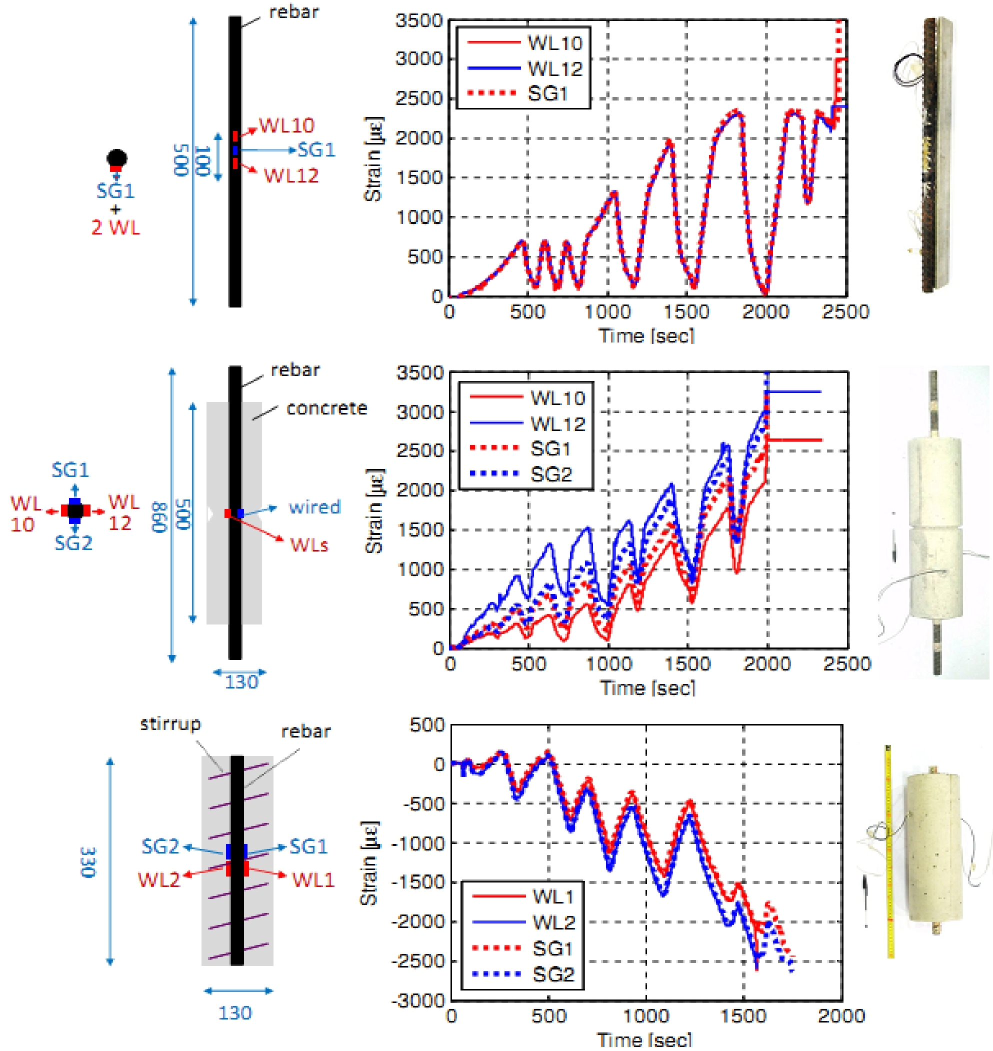

Figure 3. Outcomes of a test on a bare bar (upper graph), a test on a bar embedded in concrete and tensile test (central graph) and a test on an embedded bar tested in compression (lower graph).

The network was validated with only two nodes working simultaneously, however additional tests prove that the network can easily manage many more sensors. The nodes are activated by a switch and continuously record and send measurements to the base station, which is connected to a PC via USB. The measurements were acquired using Microsoft Hyperterminal and post-processed via Mathworks Matlab. The whole system is user-friendly and stores strain data in a database with a timestamp and sensor identification tag. Over the entire campaign, the network had no problem in data acquisition or transmission.

To better couple with the needs of in-field applications, the sampling frequency can be also set by the user, and the strain data can be sent on demand.

3 ACCELEROMETER SENSOR WIRELESS NETWORK

3.1 Development of the hardware

Each accelerometer node measures, records and transmits on RF network 3-axis acceleration data, using a MEMS-based sensor commercially available from Analog Devices Inc [7]. It is a completely digital output device that communicates with the system through an SPI interface, endowed with a serial EPROM memory and a micro vibration sensor. The firmware developed allows waking up the device upon activation of the micro vibration sensor, a fast setup of the node (accelerometer and Zigbee transceiver) from the microprocessor, and the recording of the measurements into the EPROM. The power consumption of the unit is similar to the strain sensor unit. Special algorithm have been developed to minimize activation of the unit by false alarms (vibrations caused by other reasons than earthquakes)

3.2 Laboratory validation

To test the performance of the network, three wireless nodes were mounted on a shaking table, back to back with high precision, wired piezo-electrical seismic accelerometers, and they underwent several vibration tests, using excitations of various shape, frequency and amplitude. The aim of the campaign was to investigate the accuracy and reliability of the wireless sensing system in condition similar to that experienced in field during a seismic event.

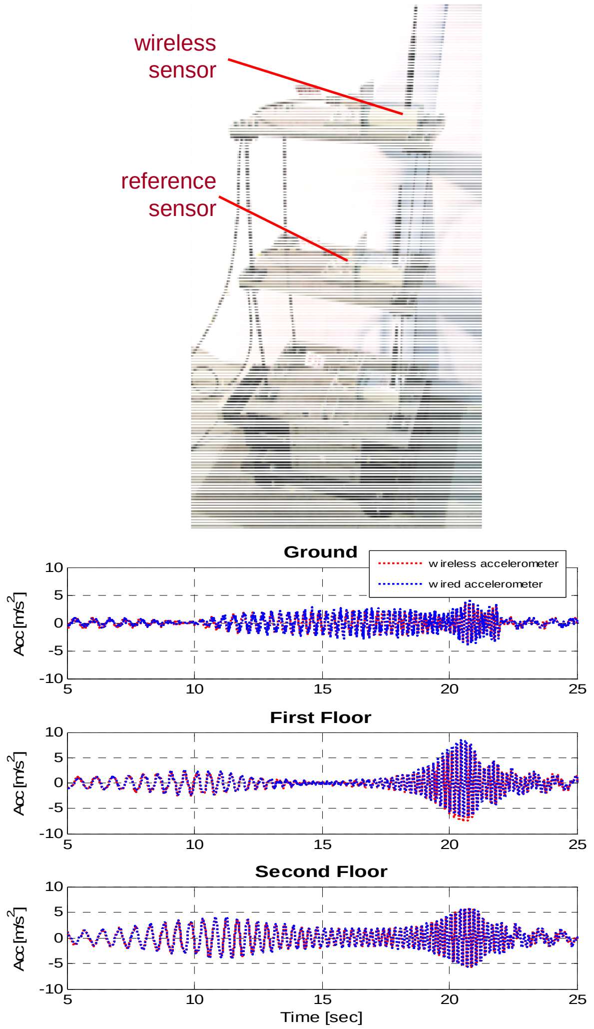

Figure 4: instrumented metal frame on the shaking table (left). Example of a test outcome (right)

Two types of tests were performed: in the "calibration tests", the nodes were mounted in parallel on the table, and each axis was tested with harmonic excitation at different frequency in the range 1-20Hz. Then, to better simulate the operative conditions, the wireless sensors were mounted on a two-storey metal frame, again back to back with the wired instruments, as reported in Figure 4. The same figure shows the comparison between the vibrations recoded by the wired and the wireless systems, at each floor, during a sweep. Agreement in very good, in the same order of the resolution of the wireless system, which is equal to 18mg (=0.18m/s^2).

4 CONCLUSIONS AND FURTHER STEPS

Both the strain gauge and accelerometer networks prove to be reliable in the operative conditions to be expected in an in-field application. The performance in stain measuring permits to follow the beginning of the yielding branch of the reinforcing steel, which is a usual limitation for sensors applied to civil structures, and it is suitable for assessing the occurrence of settlements. In the next months, additional tests will be done of fullscale specimens of columns, to investigate the behavior of a larger wireless networks in a more complex environmental and in a seismic scenario.

The accelerometer network proves to be reliable in the frequency range relevant to the seismic analysis, with a sufficient accuracy, and several three axial nodes can be employed simultaneously. The acquisition is automatically triggered by the overcoming of a vibration threshold, and this allows a long-span monitoring, recording all the relevant seismic events.

The final products the MEMSCON project, expected for end-2011 will try to push these performances up. Particularly, the further steps in the development of the sensing nodes will reduce the size of the packaging, improve the measurement range and reduce the power consumption, while the progress in the development of the accelerometer nodes will be related to the improvement of resolution, the real-time synchronization of the nodes, allowing acquiring a reliable time-stamp years after installation and the adoption of more sophisticated algorithm to reduce the number of false alarm.

ACKNOWLEDGEMENTS

The MEMSCON project is founded by the European Community with Grant Agreement n. CP-TP 212004-2. The authors wish to thank all the people involved in the project, particularly Stavros Tsakiris and Dimitris Plotas from ICCS.

REFERENCES

1. Pozzi M., D. Zonta, W. Wang and G. Chen. 2010. “A framework for evaluating the impact of structural health monitoring on bridge management”. *Proc. "5th International Conf. on Bridge Maintenance, Safety and Management (IABMAS2010)"*, Philadelphia, 11-15 Jul 2010.
2. Lynch, J.P. and K.J. Loh. 2006. “A summary review of wireless sensors and sensor networks for structural health monitoring,” *The shock and vibration digest*, 38(2):91-128.
3. Zonta, D., M. Pozzi, and P. Zanon. 2008. “Managing the Historical Heritage Using Distributed Technologies,” *International Journal of Architectural Heritage*, 2:200-225.
4. Kruger, M., C.U. Grosse and P.J. Marron, 2005. “Wireless Structural Health Monitoring Using MEMS”, Key Engineering Materials 293-294: 625-634.
5. Ferrar, C.R., Park, G., Allen, D.W., Todd, M. D., “Sensor Network Paradigms for Structural Health Monitoring*”, Journal of Structural and Health Monitoring*, 13 (1), 210-225, 2006.
6. Jiang, X., et al, “Wireless sensor networks in Structural Health Monitoring based on ZigBee technology”, Anti-counterfeiting, Security, and Identification in Communication, 2009. ASID 2009, pp 449 – 452.
7. Selvarajan, A. 2003. “MEMS and photonics technologies for structural health monitoring.” *SPIE: Smart Materials, Structures, and Systems*, 12-14 December, Bangalore, India, Vol.5062, 10-17.