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Structural health monitoring system for bridges based on skin-like sensor

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Abstract. Structural health monitoring activities are of primal importance for managing transport infrastructure, however most SHM methodologies are based on point-based sensors that have limitations in terms of their spatial positioning requirements, cost of development and measurement range. This paper describes the progress on the SENSKIN EC project whose objective is to develop a dielectric-elastomer and micro-electronics-based sensor, formed from a large highly extensible capacitance sensing membrane supported by advanced micro-electronic circuitry, for monitoring transport infrastructure bridges. Such a sensor could provide spatial measurements of strain in excess of 10%. The actual sensor along with the data acquisition module, the communication module and power electronics are all integrated into a compact unit, the SENSKIN device, which is energy-efficient, requires simple signal processing and it is easy to install over various surface types. In terms of communication, SENSKIN devices interact with each other to form the SENSKIN system; a fully distributed and autonomous wireless sensor network that is able to self-monitor. SENSKIN system utilizes Delay-/Disruption-Tolerant Networking technologies to ensure that the strain measurements will be received by the base station even under extreme conditions where normal communications are disrupted. This paper describes the architecture of the SENSKIN system and the development and testing of the first SENSKIN prototype sensor, the data acquisition system, and the communication system.

1. Introduction

1.1. Challenge and concept

The project concept is based on the currently limited use of sensors being applied to monitor the stability of civil structures and in particular transport infrastructures. Visual inspections tend to



overwhelm usual inspections in order to collect information to determine the condition of infrastructures. Inspections nowadays can be considered as rather slow in completion, usually requiring (partial or total) closure of the particular network node or link and/or expose inspectors to dangerous working environments and conditions. Detailed monitoring actions and assessments are (a) particularly slow and expensive, (b) usually based on simplistic and conservative models of structural behaviour, and (c) do not provide a rapid, convenient means of determining structural stability following a major incident or other serious event that could potential limit the structural integrity of the structure[1, 2]. On top of this, quality and reliability of the visually extracted information and measurements really depend on the expertise of the inspector (objectiveness factor) and, to add on this, quite often the inspector is unable to gain access to all parts of a structure. State of the art structural health monitoring (SHM) technologies and integrated systems have proved a major role in the management of the transport infrastructure while currently existing and used SHM technologies and methods rely only on the use of dense networks of point sensors to monitor a structure, which is costly (and sometimes not practicable). All at once, conventional sensors also prove to fail at relatively low strains and their communication system is unreliable in extreme service conditions: thus, they do not provide a fool-proof alarm of an imminent structural collapse.

1.2. The SENSKIN Project

SENSKIN is an EC co-funded project that operates in the framework of EC-FP7-Transport (MG-8.1a-2014 - Smarter design, construction and maintenance). SENSKIN includes a consortium with all the expertise needed in the lifecycle from research to innovation, as well as real-life end-users that can provide solid feedback on the project results. The list of partners of the consortium has been presented below:

Table 1. The SENSKIN Consortium.

Partner Name	Short Name	Country
Institute of Communication and Computer Systems	ICCS	Greece
University of Potsdam, Applied Condensed-Matter Physics Group	UP	Germany
Egnatia Odos A.E.	EOAE	Greece
RISA Sicherheitsanalysen GmbH	RISA	Germany
TECNIC S.p.A.	TECNIC	Italy
Democritus University of Thrace	DUTH	Greece
Mistras Group Hellas A.B.E.E.	MGH	Greece
University of Stuttgart	USTUTT	Greece
TRL Limited, Transport Research Laboratory	TRL	UK
State Enterprise State Road Scientific Research Institute	DNDI	Ukraine
Forum Des Laboratoires Nationaux Europeens De Recherche Routiere	FEHRL	Belgium
Teletronic Rossendorf GmbH	TTRONIC	Germany
Turkish General Directorate of Highways	KGM	Turkey

The consortium includes partners that (a) have already developed a first generation of 'sensing skin' with very encouraging results (University of Potsdam), (b) have already developed relevant sensor near electronics (TTRONIC SpA), (c) have developed LCAs and LCCs for construction works (University of Stuttgart), (d) have developed algorithms for the assessment of deteriorating structural systems in the context of several previous research projects (TECNIC SpA, RISA Sicherheitsanalysen GmbH), (e) have developed and implemented relevant wireless sensor network architectures (Institute of Communication and Computer Systems and Democritus University of Thrace) and (f) have particular experience in performing testing sessions of the project prototypes (TRL Limited) in a lab environment. The work in SENSKIN is totally market driven (there are three major end users in the consortium: Egnatia Motoway (EOAE), Karayollari Genel Mudurlugu (KGM) and Forum de

Laboratoires Nationaux Europeens De Recherche Routiere (FEHRL) (including members that belong to Highway Departments)[1].

SENSKIN aims to: (a) develop a dielectric-elastomer and micro-electronics-based skin-like sensing solution for the structural monitoring of the transport infrastructure that will offer spatial sensing of reversible (repeated) strains in the range of 0.012% to more than 10%, that requires little power to operate, is easy to install on an irregular surface, is low cost compared to existing sensors, allows simple signal processing and includes the ability of self-monitoring and self-reporting. (b) use the new and emerging technology of Delay Tolerant Network to secure that strain measurements acquired through the 'sensing skin' will reach the base station even under extreme environmental conditions and natural disaster events such as, high winds or an earthquake, where some communication networks could become inoperable. (c) develop a Decision-Support-System for proactive condition-based structural intervention under operating loads and intervention after extreme events. It will be based on an accurate structural assessment based on input from the strain sensors in (a) above and will examine the life-cycle economic, social and environmental implications of the feasible rehabilitation options and the resilience of the infrastructure to future changes in traffic demand that these options offer. (d) Implement the above in the case of bridges and test, refine, evaluate and benchmark the monitoring system (integrated a and b) and package (integrated a, b and c) on actual bridges [2].

The practical application of the developed prototypes will significantly enhance structural health monitoring of bridges but could be extended to monitoring of other critical infrastructures like dams, energy related structures, tunnels, concrete pavements (paved or roadway) etc.

2. Elastomer-based sensor for the SENSKIN system

2.1. Soft Capacitive Sensor

The design of the soft skin-like sensor used in the SENSKIN system is shown in Figure 1. The sensor is built around a thin silicone elastomer membrane (1) and can thus detect large reversible strains between 0.01% and 10%.

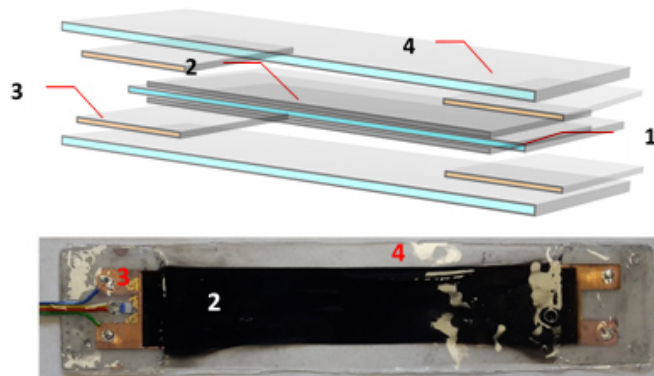


Figure 1. Soft capacitive sensor.

The silicone membrane (1) obtained from Wacker (ELASTOSIL® Film 2030 250/100) is only 100µm thin and coated on both sides with compliant electrodes (2). The top and bottom electrodes are made by spraying a toluene-based solution of the silicone material loaded with carbon nanoparticles (Printex XE-2B) onto the membrane. After solvent evaporation and cross-linking of the silicone, the electrode can be stretched over the whole range of sensor motion with a typical resistance of 8 kΩ across its length (15 cm). Polyester frames (3) are employed to provide electrical terminals and for handling and mounting of the sensor. In a last step, the whole assembly is coated with protective silicone layers (4).

As the active electroded area is $15 \times 3 \text{ cm}^2$, the capacitance without pre-stretching is around 1.5 nF. The resistance of the electrodes changes within $0.02\text{--}0.07 \Omega$ per μstrain . The measurement principle of the skin-like capacitive sensor is based on continuously monitoring the capacitance changes caused by sensor deformation [1, 9, 10]. When the sensor is attached to a component of the transport infrastructure, its deformation will cause a corresponding deformation of the sensor and thus also a change in its capacitance (Figure 2).

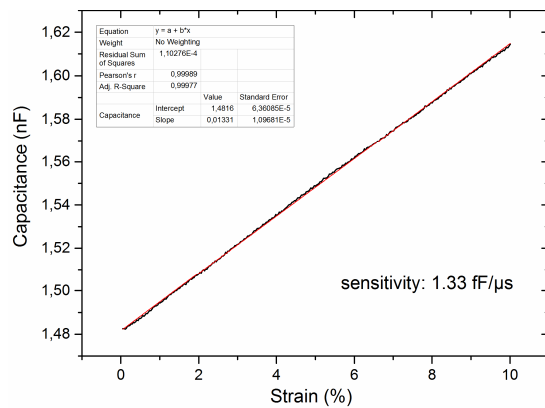


Figure 2. Strain dependence of the capacitance measured directly with an LCR meter.

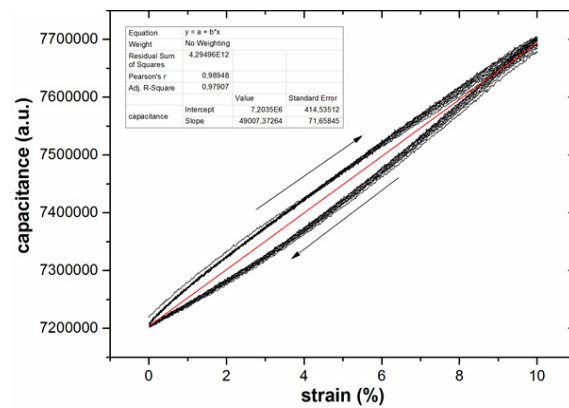


Figure 3. Sensor output as measured via the DAQ (see subsection 2.2 below).

The data shown in Figure 2 were obtained with a linear testing machine (Zwick/Roell Z005) for the controlled deformation of the sensor and with a precision LCR meter (HP 4284A) for measuring the sensor capacitance. The capacitance-strain dependence is linear over the whole range of motion with a typical sensitivity of around 1.3 fF per μstrain . When the sensor output is measured with a SENSKIN Data Acquisition (DAQ) module (see section 1.2 below), the capacitance behaviour becomes more complicated (Figure 3). There is some drift in the measured values at higher strains as well as a hysteresis-like behaviour for the overall curve. The nonlinearity is due to the fact that the PCap system inside the DAQ module actually measures RC times during charging or discharging of the soft capacitor. Even if the capacitance changes linearly (Figure 2), the resistance of the electrodes can change nonlinearly over the range of 10% deformation.

2.2. Data Acquisition (DAQ) from the monitoring sensor

The DAQ is part of a complex sensor NODE situated between the sensing element based on stretchable elastomeric material and the microcontroller for signal pre-processing and communication control. From a measurement point of view, the sensor is a capacitance that must be monitored very precisely. There are three main challenges for the measurement electronics:

- The sensor being used has a mean capacitance of about 1.5 nF in the prestressed state. However, the sensitivity of the sensor is as low as only 1.33 fF per μstrain . Therefore, a capacitance of approx. 1.5 nF with a noise-limited resolution of ca 40 fF must be determined for the desired resolution of ca. 30 μstrain at a sampling rate of 50 Hz.
- The compliant electrodes of the stretchable sensors have relatively high internal resistances between 3 and 10 kOhm, and the resistance is also strain-dependent.
- The strain-dependent capacitance is highly sensitive to temperature. Therefore, the data acquisition system contains a temperature-measuring chip with a resolution of 24 bit for calibration purposes.

For the capacitance measurement, a Charge to Digital Converter (CDC) PicoCAP02 from ACAM electronic is used. It was developed by ACAM Elektronik and adapted by Teletronic to meet the measuring requirements of the project. The operating principle is illustrated in the equivalent circuit:

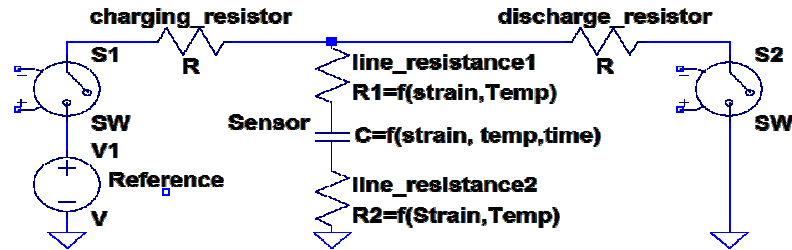


Figure 4. Equivalent Circuit for the PicoCap02 Measuring System.

An internal voltage reference charges the Sensor represented by the Capacitor C across the internal charging resistor R and the compliant-electrode line resistances $R1$ and $R2$. The capacitance of the Sensor as well as the two line Resistances depend on both strain and temperature, and the charging process is controlled by the switch $S1$. The detection process is completed by measuring the discharge time across the discharge resistor controlled by the switch $S2$. The measuring principle implemented in the application of the PicoCap02 CDC is radiometric, *i.e.* the capacitances are compared to a fixed reference, and the ratio of the discharge times is directly proportional to the ratio of the capacitances, as the discharge time is determined by the respective capacitance and the selected discharge resistor.

Both circuits, the CDC as well as the temperature measurement chip, communicate via the SPI bus with the microcontroller for averaging and data management. Both have internal processors for controlling the measuring process. Measurement of capacitance and temperature may be done in parallel so that an associated temperature is determined for each strain value. In order to compensate for the temperature-dependent internal resistance, as well as for the temperature coefficient of the capacitance, each sensor is calibrated individually. In practical applications, the EMI influence of any nearby 50 Hz power lines is significant because of the length of the sensor and its small capacitance. Up to now, the measuring process is synchronized with the power-line frequency for suppressing the interference. In future developments, the influence may be suppressed via higher sampling rates for the capacitance and by the use of a 50 Hz notch filter.

3. The SENSKIN Communication system

3.1. Why Delay-/Disruption-Tolerant Networking technology is necessary?

WSNs (Wireless Sensor Networks) deployed in open environments are prone to intermittent connectivity due to power scheduling, channel fading, node failure, and severe packet losses from unpredictable external factors, such as interference. On top of that, the connection of the Gateway to the Internet might also present its own challenges, as it is not uncommon for bridges to be located at places where communication infrastructure to the Internet is only available intermittently (e.g. remote places where only a satellite link is available) or it is not sufficient to cover monitoring needs due to the employment of low-capacity links (e.g. GPRS links).

In this context, SENSKIN communication system utilizes DTN (Delay-/Disruption-Tolerant Networking) protocols [3, 4, 5, 6, 7], which synergistically with mesh networking, address the majority of the aforementioned problems. In particular, DTN communication protocols provide reliable data communication across failure-prone networks by employing various purpose-specific network mechanisms, including store-and-forward data forwarding, multi-path routing and hop-by-hop reliability.

3.2. The SENSKIN Communication System

SENSKIN communication system, depicted in Figure 5, constitutes a fully distributed and autonomous WSN that is able to self-monitor and report itself.

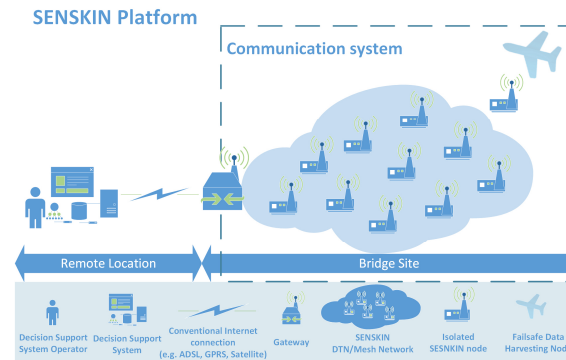


Figure 5. SENSKIN communication system network architecture.

It is composed by three different elements: SENSKIN, Gateway and Failsafe nodes.

3.2.1 SENSKIN nodes. These are essentially SENSKIN devices placed at different locations of a bridge site. Each SENSKIN device is equipped with a communication module. Each communication module implements the network stack presented in Figure 6.

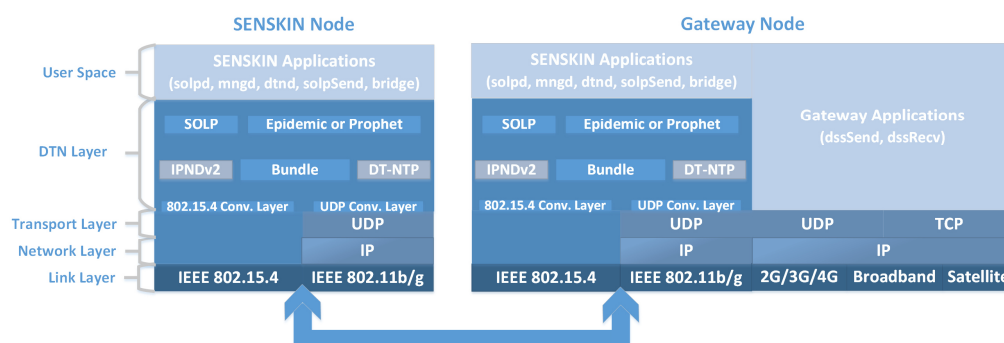


Figure 6. SENSKIN and Gateway nodes network protocol stack.

At link layer, communication modules adopt a dual interface approach, by employing in particular the IEEE 802.11 and 802.15.4 standards on an as-needed basis. This approach helps to increase communication robustness and data delivery reliability, as well as, to balance out the trade-off between performance and energy consumption. Bundle Protocol (BP) runs on top of them [3]. BP constitutes the basic protocol through which a DTN architecture can be established among the nodes of a network. Through appropriate convergence-layer protocols, BP runs directly over IEEE 802.15.4. The same does not stand true for IEEE 802.11, where a UDP/IP stack is employed to allow BP pass its data over IEEE 802.11. Custom-tailored networking solutions for supporting SENSKIN system operation logic, such as the SENSKIN Operation Logic Protocol (SOLP), run at the Bundle layer. Finally, all SENSKIN communication applications used for sending and receiving data (i.e. solpd, solpSend), along with a panic communication mechanism that is implemented as an extension of the node's management application (i.e. mngd), run at the application layer. Panic communication mechanism is triggered under certain network circumstances (e.g. low signal quality, loss of neighbour nodes, extreme weather conditions). In particular, it allows network self-recovery and in extreme cases, (e.g. major catastrophic event like an earthquake) it enables data from potentially isolated

SENSKIN devices to be flushed to external ad-hoc nodes. These ad-hoc nodes essentially act as failsafe data-harvesting elements.

3.2.2. Gateway(s). As depicted in Figure 6, Gateway nodes employ a dual network protocol stack that allows them to serve as a middleware platform for interconnecting the deployed SENSKIN nodes network with a remote administration facility. The first network stack is identical to the one employed by the SENSKIN nodes, while the second one employs mobile telecommunications, broadband or satellite link layer protocols, along with conventional Internet protocols, such as TCP, UDP and IP.

3.2.3. Failsafe node(s). Failsafe nodes are similar devices to Gateways in terms of operational capabilities with their basic difference being that they are mobile.

3.3. PCB Design and Interfaces between the Application MCU and the Communication System

The Application MCU exchanges information with the Communication MCU using a Universal Asynchronous Receiver/Transmitter (UART) serial communication interface. The SENSKIN node provides the functionality to update the Application MCU's firmware remotely. The Application MCU includes a simple, ROM-based bootloader which communicates with the Communication MCU over the serial interface. The Communication MCU uses two digital I/O pins, in addition to the serial communication interface, to take advantage of ROM-based bootloader. One I/O is used to control bootloader's backdoor functionality and one for resetting the Application MCU, in order to force a ROM bootloader entry upon reset of the Application MCU. The hardware interfaces between the Application MCU and the communication system are presented in Figure 7 [8].

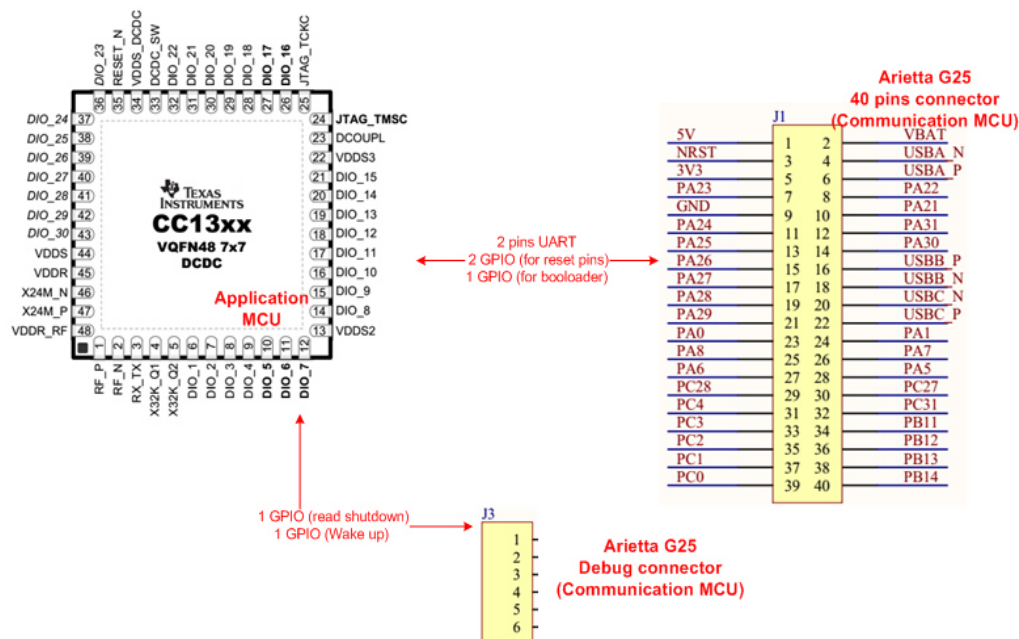


Figure 7. Hardware interfaces between Application MCU and communication system.

The Application MCU handles the power source of the communication module, in order to reduce the power consumption, increase SENSKIN integrated device's lifetime and maintain all the benefits of the communication system without compromising its operation and functionality. If there is no incoming or outgoing information to or from the SENSKIN node, then the Application MCU turns off the power source of the communication module. The application MCU turns on the power source of the communication module incoming or outgoing data needs to be transferred.

The printed circuit board (PCB) of the initial version of the SENSKIN integrated device hosts the Application MCU, the power supply, the necessary physical interfaces for connecting the DAQ and the solar panel, a Ferroelectric RAM (FRAM) for storing measurements and information regarding the operation of the Application MCU and the low power wakeup receiver, which allows the on demand functionality of the SENSKIN node [8].

4. System integration

The SENSKIN integrated device is composed of the following components following an integrated approach:

- Sensor Device: a skin-like sensor capable of measuring strains over a surface area
- Data Acquisition System (DAQ): a capacitance to digital converter unit which will digitize the sensed strains
- Communication Module: the part of the SENSKIN integrated device that is responsible for transmitting and receiving all data related to the operation of the SENSKIN system, as well implementing the communications operational logic
- Processing Module: the computational core of the SENSKIN integrated device
- Low Power Wakeup Receiver: a promising energy-saving approach for on demand wireless network operations
- Power Management, Energy Harvesting and Energy Storage Units: the hybrid power supply of the device
- Packaging: the enclosure of the device

A block diagram of the SENSKIN integrated device is presented in Figure 8.

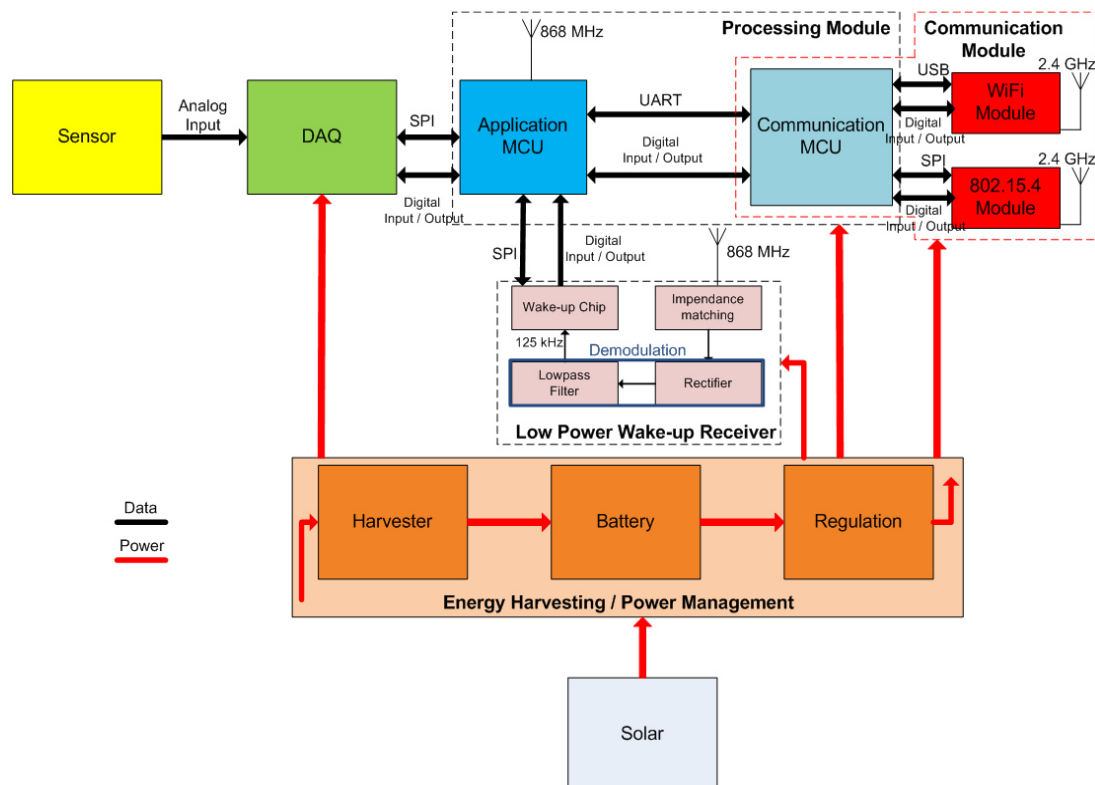


Figure 8. SENSKIN node block diagram.

5. System Experimental Evaluation

The findings of a review showed that it was necessary to (a) design and fabricate purpose-built test rigs for undertaking calibration tests, and (b) that an off-specimen camera-based system was the only practicable means of calibrating the sensor. The calibration tests are undertaken using uniaxial test rigs (in the main) and a flexural rig (see Figure 9). Both types of rig can accommodate steel and concrete test coupons.

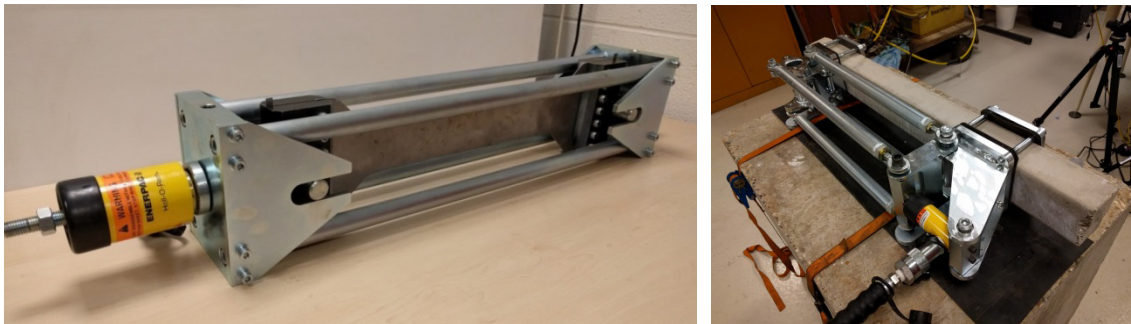


Figure 9. View of uniaxial test rig (left) and flexural test rig (right).

The strains applied to the test coupons, and sensors, are measured using an off-specimen camera-based system obtained from iMETRUM. The variation in the output of two sensors with ambient temperature is investigated using the environmental cabinet at TRL. Prior to undertaking the calibration tests it was necessary to undertake proving tests of the equipment and calculation routines to establish a reliable standard reference procedure.

Tests on the prototype sensor showed that the application of a uniaxial load generated differential movements within the silicone encapsulation. And, as shown in Figure 10, a highly non-uniform strain field was developed around the end-blocks of the sensor.

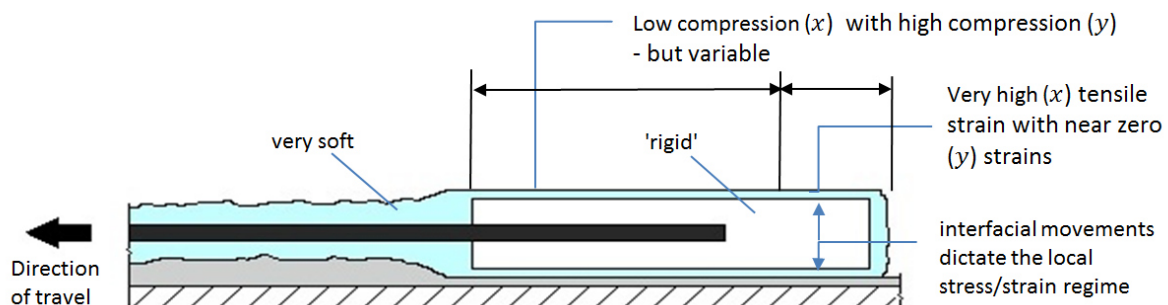


Figure 10. Cross section through the end-block of a sensor

The results of preliminary tests on the prototype sensor showed that the output of a sensor varied non-linearly with the ambient temperature; this was expected. However, more importantly, the temperature sensitivity of the output of the prototype was higher than would be accepted for most structural health monitoring applications.

The findings of the tests show that the prototype needs to be refined to meet a few key target requirements for bridge monitoring: in particular to (a) improve the reliability of the relationship between the applied strain and the output of the sensor, and (b) reduce the temperature sensitivity of that output. The findings also provided suggestions for effecting such refinements.

6. Conclusions

This publication has presented the challenges and system concept of operation as well as the system modules of the SENSKIN monitoring solution that is being developed in the framework of the SENSKIN EC co-funded research project. The project is currently at the first integrated version where the second version of the sensor has been developed followed by the development of the first version of the data acquisition system (DAQ). The first integrated version of the system has been also implemented and tested including the design of the system electronics, interfaces and data considerations. The next steps of the project will be a set of simulated environment testing of the prototype device that will be executed by the partner TRL (TRL Limited) that will provide direct feedback to the technical activities towards the final implementation of the SENSKIN system. In turn the final system prototype will be validated in the actual bridges of Egnatia Motorway (Greece) and the Bosphorus Bridge (KGM). SENSKIN is expected to provide high impact to monitoring and management systems increasing infrastructure capacity and optimizing maintenance costs for all transport modes, new construction and maintenance techniques that enhance the performance and reliability of infrastructure, innovative and cost effective approaches to use Green Infrastructure for transport, extension of the life span of ageing transport infrastructure, development and application of effective and efficient materials, technologies and tools to meet cost-effectiveness and sustainability goals, reduction of multi-modal infrastructure construction and maintenance energy intensity and subsequent CO₂ pollutants and noise emissions, support the transition towards zero traffic disruption from inspection, construction and maintenance by 2030 and boost the overall performance of the European transport infrastructure and reduce nuisances generated by transport. The first steps towards the system commercialization have already started though a draft exploitation strategy identifying the SENSKIN market opportunity, initial partners' IPRs as well as a concise strategy for the SENSKIN commercialization.

Acknowledgements

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References

- [1] SENSKIN [635844] Annex 1 (part A) Description Of Work
- [2] Loupos K et al 2016 Skin-Like Sensor Enabled Bridge Structural Health Monitoring System *8th European Workshop on Structural Health Monitoring – EWSHM (Bilbao)*
- [3] Scott K and Burleigh S 2007 Bundle Protocol Specification RFC 5050 (Online) <https://tools.ietf.org/html/rfc5050>
- [4] Morgenroth J 2015 *Event-driven Software-Architecture for Delay-and Disruption-Tolerant Networking* (Technische Universität Braunschweig)
- [5] Ellard D et al 2012 DTN IP Neighbor Discovery (IPND) draft-irtf-dtnrg-ipnd-02 (Online) <https://tools.ietf.org/html/draft-irtf-dtnrg-ipnd-02>
- [6] Lindgren A et al 2012 Probabilistic Routing Protocol for Intermittently Connected Networks, RFC 6693 (Online) <https://tools.ietf.org/html/rfc6693>
- [7] Lindgren A, Davies E and Doria A 2013 Epidemic Routing Module for Generic Opportunistic Routing Framework (Online) <https://tools.ietf.org/html/draft-lindgren-dtnrg-gorf-epidemic-00.html>
- [8] SENSKIN [635844] D2.3 SENSKIN Integrated Device Initial Version
- [9] Kolloosche M, Stoyanov H, Laflamme S and Kofod G 2011 Strongly enhanced sensitivity in elastic capacitive strain sensors *J. Mater. Chem.* **21** pp 8292-94
- [10] Carpi E F 2016 *Electromechanically Active Polymers: A Concise reference* (Springer International Publishing Switzerland) p 798