

# SYNTHESIS REPORT

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TITLE: Manufacturing and miniaturization of low-cost electronic sensors embedded in concrete

PROJECT  
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PROGRAMME

**Manufacturing and miniaturization  
of low-cost electronic sensors  
embedded in concrete**

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**Abstract:**

*A monitoring system for concrete structures has been developed. It is based on the embedding inside concrete of electronic sensors based on very low power dissipation techniques and technologies. These sensors are remotely powered and interrogated with an RF carrier, so that no wires are necessary to transfer commands and data, and the risks of wire ruptures and connector failures are avoided. Partial validations in the field have been made, the limits are shown, and the future industrial prospects of this system are discussed.*

## *I. Introduction*

The monitoring of large concrete structures (tunnels, bridges, dams, highway intersection, ...) is done up to now with three main techniques: strain gauges, vibrating string sensors, and interferometry techniques. These last ones operate externally to the structure, have the advantage of giving the global internal deformation on a wide surface, but are not fully representative of internal (local) strains.

The vibrating string sensors measure the local strains in the more precise possible way, but they are today connected to the outside of the concrete structure by one connector, which also imposes to have electrical cables between the sensor and the connector. The resulting overcost and installation problems limits the use of such a system,

The strain gauges are less used and have the same shortcomings than the vibrating string sensors, adding the fact that they have less precision. A fourth way is sometimes used, in which the relative displacement, of metallic rods anchored in the structure give some information of its behaviour, but it is mainly used in dams. Nowadays, a new technique, based on Bragg-grating optical fibers, seems to emerge. An optical fibre, in which a grating has been engraved by UV light directly at the core level possibly all along its length, is unfolded in the structure, and is made going through places of the structure where some monitoring seems useful. An optical encoded signal is then launched into the fiber, and the retroreflected temporal signal depends of the state of strain all along the fiber. The advantage is to have a fully passive system inside the concrete, and to have a curvilinear representation of the strains in the immediate environment of any point along the fiber.

The drawback are that no data are available today on the evolution with time of both the optical fibers (which are always under stress) and of the UV-induced Bragg-gratings, and that the installation has to be made by experienced personnel.

Another way has been suggested by DE, to embed discrete low power electronic strain sensors, easily positioned, with no electrical or optical cable linking the sensor to the outside. This system should also be compatible with measurements along the three main (directions, and have for this latest configuration a cost 'figure less than 150 ECU. No battery would be "of course included in the sensor, so that the only way to proceed would be to send energy through a RF carrier, and the bi-directional links (activation and commands on one way, data on the other) would also be done thanks to EM waves. To the best of our knowledge, no such system has been tested.' Similar ideas tend to be applied to tags and to some experimental electronic tools on highways, but no sensor is really used in these configurations.

## 2. Technical description

A system of wireless sensors remotely powered and interrogated by modulating a RF carrier would look like the presentation in the following figure:

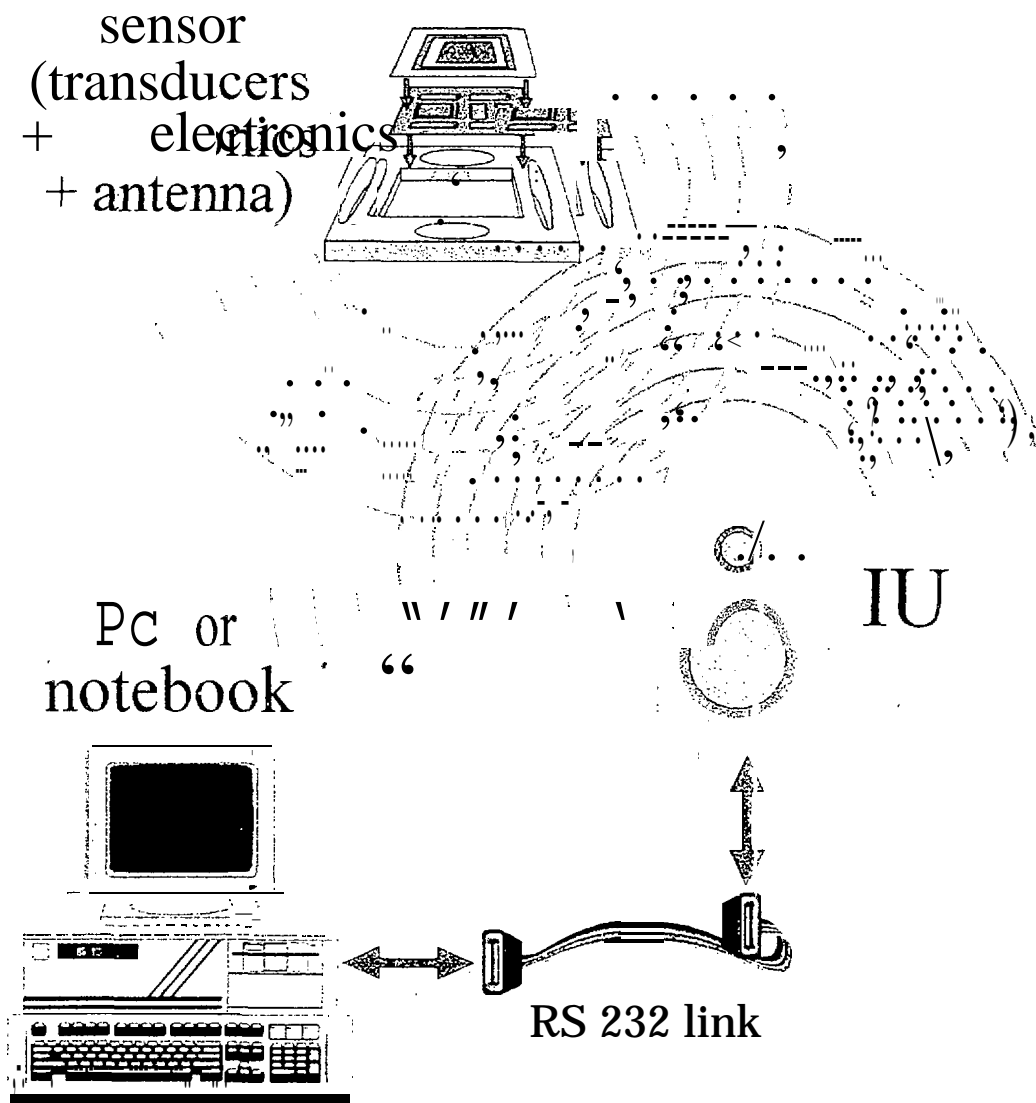


Figure 1

A PC or notebook is sending digital addresses and commands to an Interrogating Unit (IU) through an RS 232 link (the most easily accessible access). This flux modulates a high power emitter (10 W) having in our case a carrier around 1.65 GHz. Part of this power is used to energize the sensor, and part is used to be sent back through frequency translation to get the data issued from A/D conversion back.

Transmission of EM waves through concrete has been made and is still undergoing since the development of wireless telecoms applications asks for an extended coverage of the operational areas of mobile systems, whether local (at the level of a group of offices, like SMEs) or at the regional level. Many publications have been made 'about EM transmission of concrete slabs or walls' in different frequency bands. The subject is quite complex because of the topologies of concrete buildings and office organizations. The main problem is linked with interferences, giving way to dead zones. In our case of concrete monitoring, the problem is quite different as on one side, there is not a real need, at least at the moment, to have ranges more than a few meters, and on the other side, the link budget is limited by the maximum allowed emitted power (in the range of 10 W) and the minimum voltage outgoing a receiving antenna to supply energy to an electronic circuitry (around 1 V for present technologies). The figure obtained is around 40 dB. Two main operational constraints are:

- ◆ the user who wants to get strain data from a sensor does not need to be experienced in EM matters, so that whatever the orientation of the sensor, the budget should not vary too much.
- ◆ metallic wires and meshes are embedded in the concrete, so that if the antenna is too near from the metal, interferences can plague the budget,

The first point means an omni-directional system of antennas is needed at the sensor level (no directional gain). However, the antenna of the user can have some directional gain.

Concerning the second point, for a given distance between the meshes and the antenna, one would deduce that a shortening of the wavelength would be necessary.

However, losses in the concrete increase with the frequency. A preliminary theoretical study, considering mean values for the permittivity and equivalent conductivity of the material, has shown that the compromise on the operating frequencies would be in the range 500 MHz - 2 GHz. For sensors of which antenna would be positioned one wavelength  $\lambda_g$  ahead of the principal plane of the mesh, and near the middle of a unit square mesh (side value between 6 cm and 15 cm), embedded 30 cm from the outside surface, the additional loss would be around 10 dB. In these conditions, the projected operational distance would be 50 cm from the outside surface.

This pre-dimensioning was confirmed with some lab experiments, in which concrete blocks could be inserted into one another, like Russian dolls, to verify the theoretical figures. The agreement was rather good, however, a deeper analysis has shown to us that traditionally, some additives are mixed with concrete, which may have a high ionic content, and so introduce higher losses. These additives are helpful according to different criteria: accelerate the drying, or plasticize the concrete, reduce the probability of appearance of cracks, . . . The partial conclusion is that, in these conditions, the dispersion of the concrete properties, on the EM point of view, should be assessed by more experimental set-ups to assess quantitatively the influence of each additive, whether alone or not.

The possibility of transferring EM power to an antenna embedded in a concrete block being assessed, we had to design both an adequate packaging taking into account the chemical activity of the concrete mainly at its drying stage, the addition of at least an omnidirectional antenna, and a sufficient sensitivity of the packaging to the external stress. The transducers have been chosen to be strain gauges of high electrical resistance (5 k $\Omega$ ) to minimize their power dissipation. This value cannot be too high because of stability problems with time.

Three types of packaging have been developed:

- ♦ type I was first intended to include (internally) the sensor electronics made with CMS components. This necessitated a relatively high internal volume, and considering a maximum stress of 800 bars, the deflexion of the walls would have been around 0.5 mm on each side for a width of 3 mm. This was considered a limit to avoid crushing the electronics, and this also explains partially its lack of sensitivity compared to the others. To increase the influence of concrete deformations, two squares have been added on three of the four corners. The strain measurements can be made on the two directions of the principal plane.
- ♦ type II was not designed to include electronics, so that its volume was minimized. Strain measurements can be made along three orthogonal directions. It is more sensitive than type I (ratio  $\cong 6$ )
- ♦ type IV was designed to ultimately include an ASIC, and issue measurements along 1, 2 or 3 main directions. It is nearly  $2 \frac{1}{2}$  orders of magnitude more sensitive than type I, and is the more versatile of our designs.

Type I II has been omitted, although more interesting than type I, because the only advantage was due to the ultimate hypothesis of an ASIC realization. According to simulations, it could have been around 5 times more sensitive than type I.

The electronics associated with the system consisted in two parts:

- + the Interrogating Unit (IU) in charge of addressing the different sensors to send them commands
- + the proper sensor electronics, including the RF uplink

All these functions have been implemented using commercially available components

Two main versions of the sensor electronics have been implemented, the difference being in the digital sequencer, for which the first version was considered too power consuming. Presently, the diagram is shown as below:

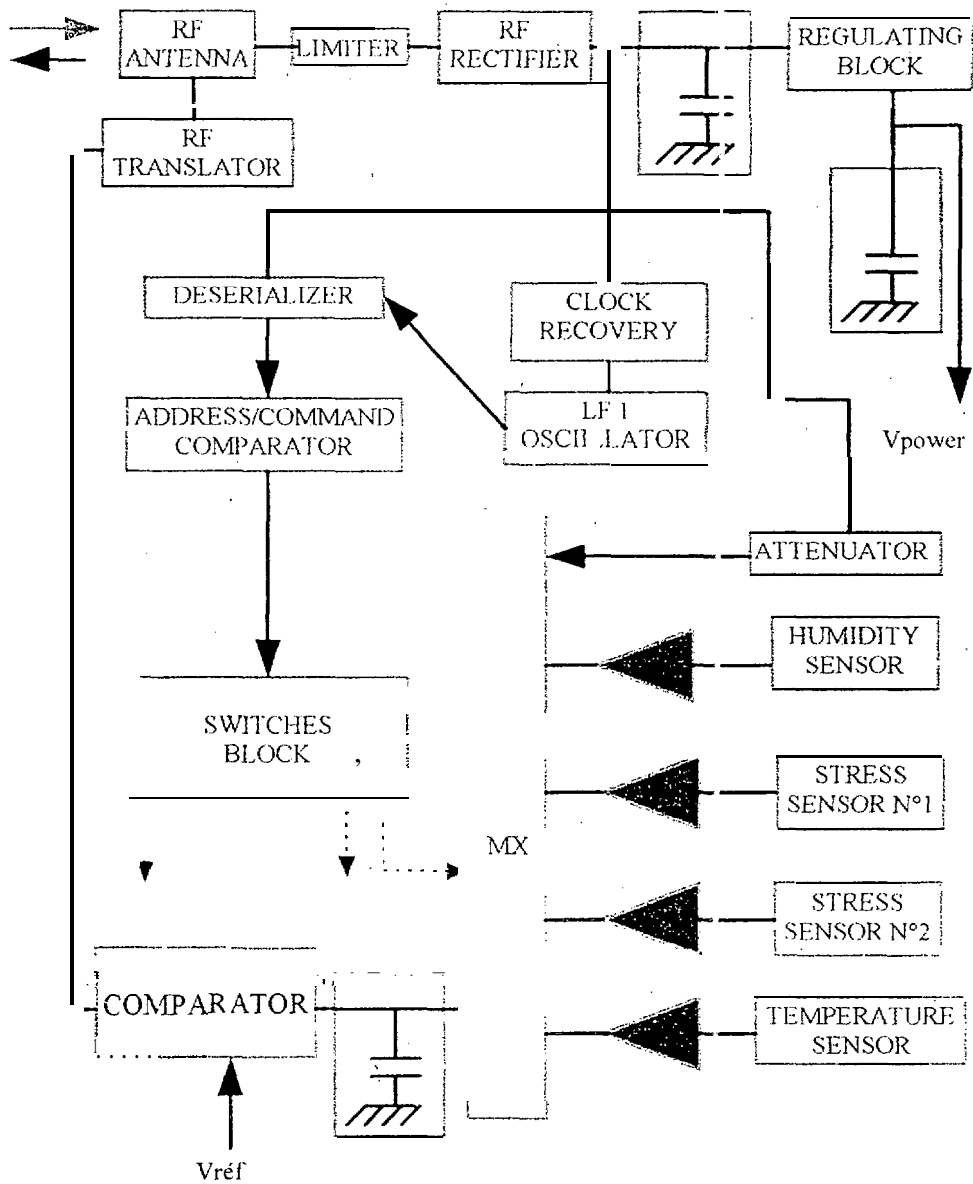


Figure 2

The A/D conversion is made with a very low power comparator and judicious signal processing at the software level. This solution was drawn after many evaluations of other solutions. The developing technologies of switched capacitors will give way in a very near future to higher performances and more versatile architectures.

### **3. Results**

The system had to be validated by different steps. First, a RF power amplifier operating at 1.65 GHz with an output power of +40 dBm has been connected on one side with a synthesizer delivering 0 dBm, and on the other side with a patch antenna ( $G \cong 1$  dB) with virtually no rear emission. Cubic concrete cells with walls having 5 cm widths were made with decreasing square lengths, such that they could be included one into another, like Russian dolls. For the particular "standard" concrete used to make them, an approximate value of 0.3 dB/cm for the linear attenuation (excluding diffraction) was observed at 1.65 GHz.

The voltage outgoing the rectifier part was around 1.5 V for +2 dBm, which was "the minimal voltage to start the DC-DC converter.

The whole system was then made fully operating in free air, but with no applied stresses to the "ears" of the packaging, and operated correctly for the temperature data.

In a last step, two items of type I and two of type II were embedded in a concrete beam. The type II, without electronics, acted as a reference.

Although the signals were of course weak (around 600  $\mu$ V at the strain gauge level for a maximum of 16 bars applied longitudinally to the beam), they were sufficient to be amplified and finally processed. The amplifier of the associated electronics was given a gain of only 10, which of course is not the limit. However, the operation has led to the conclusion that, specifically in the field of low power electronics, which was the main core of our project, higher gains would have led to higher time constants, and above all to resistor stability problems. This is the reason why the tests are now oriented towards capacitive measurements of the strains, leading to much lower power dissipation (factor 1:20) and much higher sensitivity (at least two orders of magnitude).

New tests have been planned for the end of November for the final version of the sensor (type IV)

### **4. Conclusions**

Only partial validations have been made. The system operates correctly in free air and uses commercially available components.

An original system, energetically efficient, has been designed to solve the problem of the wireless data return.

The experiments with the sensor embedded in concrete have shown that the actual version is too sensitive to the presence of metallic wires.

A new version is now being developed that will first increase the energy transfer, and above all, the voltage outgoing the sensor antennas, and secondly increase the sensitivity to strains in the three orthonormal directions by at least two orders of magnitude,

The main advantages of this system are the easiness of installation, the survivability of the network to major cracks, the reliability, stability, and lifetime associated with the design and the operational mode, and, if a Silicon ASIC is developed, the low cost/unit.

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