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# DEVELOPMENT OF SKIN-FOILS WITH EMBEDDED OPTICAL FIBER SENSORS

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## KEYWORDS

Optical Fiber Sensors, Fiber Bragg Gratings, Fiber Embedding Techniques, Smart Structures.

## ABSTRACT

Optical fiber sensors are increasingly used for monitoring purposes, in which flexible smart structures based in this type of technology have many industrial applications. This paper explores a new approach for integrating optical fiber sensors in flexible substrates that can be mounted in host structures to monitor. This approach combines two well establish components, Fiber Bragg grating (FBG) sensors and flexible skin-foils. A three-layer foil construction based on the spread-coating process was defined, in which the fiber was embedded in the middle layer. Such disposition ensured protection to the optical fiber element without reducing the sensitivity to external stimulus. The functional prototypes were subject to mechanical and thermal tests, in which its performance was evaluated. The smart structure behaves linearly to temperature and strain cycles without affecting the measurement characteristics. The obtained results validated this approach. In addition, the flexibility of the explored method allows custom fiber layouts, finishing patterns and colors, enabling this way a wide range of possible applications.

## INTRODUCTION

Optical sensing technologies have associated advantages that make them very attractive in an extensive range of applications, from biomedical (Wehrle, Nohama et al. 2001) to civil engineering (Ansari 2005), aeronautics (Friebele, Askins et al. 1999) or automotive applications (Norm Schiller 2004).

Sensors based in optical fiber, in particular, deliver low cost solutions with immunity to electromagnetic interference, multiplexing capabilities and a high level of integration.

Currently, optical fiber sensors provide a top performance alternative, in comparison to standard technologies, either for measuring physical parameters like strain, temperature or pressure, or for performing highly sensitive biochemical analysis (Grattan and Sun 2000; Wolfbeis 2006).

Nevertheless, its application *in situ* is still one of their main drawbacks when compared to the competitive technologies. In most of the cases, the fiber optic sensors are attached to the surface, using epoxy resins (Lima, da Silva Vicente et al. 2008) or by welding methods (da Costa Marques Pimentel, Beirao Barbosa et al. 2008), being both a very labor-demanding work without ensuring full repeatability in the overall sensing network.

These approaches allied to the existing fragility concerns of the optical fibers are many times responsible for the low market acceptance.

The solution for overcoming these issues has led research to the integration of sensing devices in substrates that are then connected to the host structure. In addition, in a market vision, such structure should be developed in a ready-to-market format, instead of a laboratorial one. The result would be a sensing “duct tape” style product that enables easy application of the foils modules in the monitored structure, as well as, easy access for replacement.

The smart structure that is described in this paper was designed to be fabricated by already existent industrial processes. Nevertheless, the incorporation of optical sensors creates a few difficulties in eventual sensor maintenance or replacement. Thus, it is proposed the incorporation of optoelectronic instrumentation in standard polymeric foils that can be already found in different products, e.g., automotive and aircraft interior trimmings, wall coverings or in some sports suits.

Furthermore, integrated optical devices are now emerging as the next generation of sensing structures, where virtually any parameter can be determined with high accuracy in a highly miniaturized optoelectronic device (Blue, Kent et al. 2005). Linking polymer-laminates with optical devices and electronics is becoming realistic, enabling its application in any type of surface, being it regular or irregular.

Competitive industries, as the automotive, aeronautics, civil engineering and biomedical one, are keen for smart solutions to gather information from their systems status. In industrial environments, low production costs, wide exploitation and high performance are crucial keywords that were taken into consideration in the development of the smart structure.

## FOIL CONSTRUCTION

One important consideration when designing the smart structure is to consider that functional devices should be integrated in the most discrete and elegant manner, in harmony with the surroundings, without neglecting its functionality performance.

### Optical Fiber Sensor Selection

There is a large variety of optical fiber sensors used for monitoring purposes. However, Fiber Bragg Grating (FBG) sensors have caught attention in the last decade, due to their distinguishing advantages when compared with other sensors. First, they are not sensitive to the light source amplitude fluctuations, since the readout mechanism is based on wavelength instead of light intensity. Second, the Bragg structure is directly written into the fibers core, keeping the overall fiber structure unaffected. Third, it is a type of sensor that can be mass produced at low-cost, ensuring this way a competitive sensing solution. Finally, for quasi-distributed sensing applications, the FBG inherent multiplexing characteristic makes them a practical solution (Yun-Jiang 1997)

FBGs are periodic changes in the refraction index of the fiber core made by adequately exposing the fiber to intense UV light. The gratings produced typically have lengths of the order of 10 mm (Glisic and Inaudi 2007). When an optical beam is injected into the fiber containing the grating, the wavelength spectrum corresponding to the grating pitch will be reflected, while the remaining wavelengths will pass through the grating undisturbed, as exemplified in Figure 1 (Rizvi and Gower 1995; Kersey, Davis et al. 1997). Since the grating period structure is sensitive to strain and temperature, these two parameters are measured by the analysis of the reflected light spectrum.

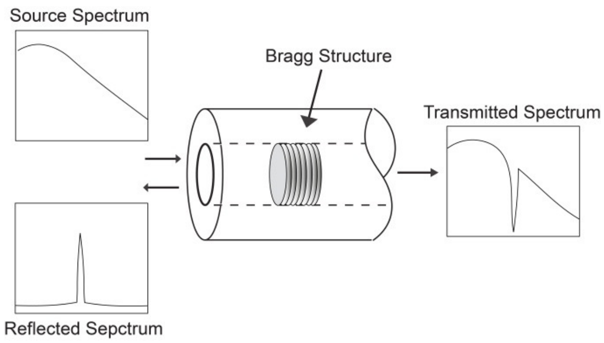

Figure 1: Illustration of a Bragg Sensor Principle

A resolution in the range of 1 με (micro-strain) and 0.1 ºC can be achieved with the best demodulators (Glisic and Inaudi 2007). Since we are dealing with optical sensors that are sensitive to temperature and, in this case, also to strain by the same manner, a few issues may appear when measuring both parameters simultaneously. In this case, it is necessary to use a strain free reference grating that measures the temperature alone, in order to compensate the temperature error from the sensor network and measure the correct strain values.

A main advantage to use Bragg gratings is their multiplexing potential (Kersey, Davis et al. 1997). Many gratings can be written in the same fiber at different locations and tuned to interfere at different wavelengths. This leads to the possibility for measuring strain at different locations along a single fiber. However, since the gratings have to share the spectrum of the light, there is a trade-off between the number of gratings and the dynamic range of the measurements on each of them.

### Material Selection

Flexible skin-like foils can be made of a lot of different polymers.

Polyurethane (PUR) may be one of the "noblest" materials, feeling like leather, with very long durability and high performance in regard to abrasion resistance and flexibility. However, PUR-based artificial leather is one of the most expensive skin materials for automotive interior trimming (Hepburn 1992; Špírková, Strachota et al. 2009).

Polyolefin based artificial skins are a suitable alternative for the required objective, but their flexibility and performance related to softness, abrasion and flexibility is in general more difficult to adjust (Collina, Braga et al. 1997; Holden, Kricheldorf et al. 2004).

As the research is focused on the development of a generic manufacturing technology for a flexible optical sensing foil, it was decided to choose a polymer matrix with an acceptable average quality and price. The choice was set on plasticized PVC, for its general good cost/performance ratio and ease of use during manufacturing processes. PVC certainly is one of the most versatile plastics, still playing a major role in the building, packaging and automotive market. Furthermore PVC exhibits many advantages like highly competitive production cost, high versatility in interior trim applications, high resistance to ageing, ease of maintenance (Seki 2008).

### Technology Selection

Another interesting aspect of PVC is that it has possibly the widest range of processing techniques compared to all other polymers. Extrusions, calendering as well as paste techniques like spread coating, slush molding and dip molding are predominantly used for PVC.

Spread coating technology allows the manufacturing of foils for a broad range of applications, such clothing, footwear, home decoration, waterproof tablecloths, tarpaulins, conveyor belts, wallpapers, floor mats and among many others, of course also for artificial leather and automotive interior trimmings (Seki 2008).

Spread coating (Figure 2) is a process that consists of depositing one or more layers of plastisols (viscous paste obtained by suspension of polymer resins in plasticizers) on a support such as natural or synthetic fiber mats, textiles or paper (release paper). Afterwards, the deposited layer is gelated in ovens. Because of its versatility, this technique constitutes an optimal choice for the development of flexible optical sensing foils.

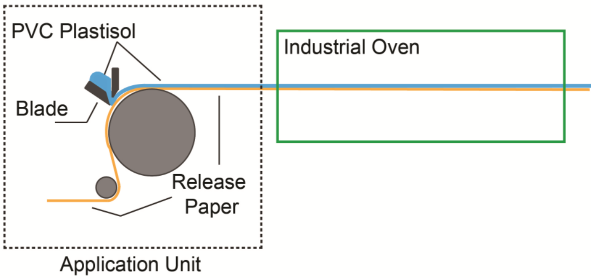

Figure 2: Spread-Coating Process

## Foil Layout

When developing a flexible sensing structure, the need for an easy to apply product becomes evident. In this context, the sensing product should be handled, avoiding damaging the integrated optical sensing elements.

By other hand, it is important to ensure a good bonding between the sensor and the foil substrate to ensure the minimum sensitivity loss by the polymeric component. Also, the thickness of the whole structure should be the minimum possible, or at least, the distance between the integrated sensor and the host structure should be minimized. This ensures that, the existent polymeric layer between the host structure and sensor is reduced, guarantying the transference of the structure behavior stimulus with the minimum interference.

Other requirement for the structure is its ability to be applied in regular and irregular surfaces, enabling a broader application field. This feature requires flexibility and dimensional stability from the sensing structure to sustain some application methods as thermo or vacuum forming.

Consequently, optical fibers and sensors integration should be done by inserting them directly in the carrier matrix. This approach guarantees a better bonding of optical fiber with the polymeric matrix, and subsequently a better transfer of stimuli from the host material to the sensor. For this purpose, a multilayer structure approach is chosen (Figure 3).

The layer #1 plays the role of a protective skin for the optical fiber. Optical fibers are flexible and can be easily bent but they always tend to recover their initial shape. It is therefore mandatory to bond the fiber to the substrate over which it is deposited. The use of adhesive polymers is avoided by an intermediate layer (layer #2). The density and, especially, the whole formulation of this layer are responsible for the fiber adhesion to the carrier and for keeping it steady in its place. Finally a third layer is applied as cover layer.

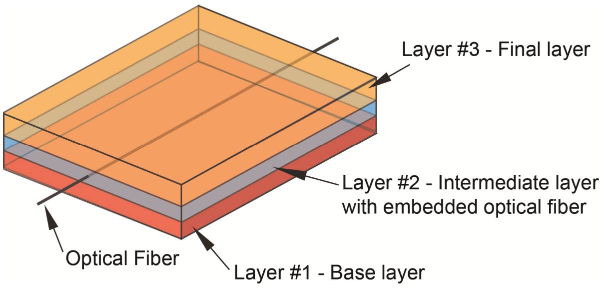

Figure 3: Foil Construction

## FABRICATION

A *Werner Mathis* coating equipment was used for the production of laboratory scaled flexible PVC foils with embedded optical fibers (Figure 4). This lab equipment allows the direct scale-up to the industrial machines, since it reproduces the industrial machine process but at a smaller scale.

Figure 4: Integration Example

The FBGs utilized in these prototypes were produced by *FiberSensing* company. The gratings were written in hydrogen loaded standard telecommunication fiber (SMF-28 type) using the phase mask technique and a pulsed *Excimer Laser*. The length of the gratings was 8 mm and the resonance wavelengths 1541.168 nm, corresponding to a refraction index modulation period of the core in the half-micrometer range.

Table 1 describes the manufacturing procedure used to produce the prototypes.

A first layer in applied in a substrate (support for the fabrication) and layer-by-layer, the structure passes through a gap between the “blade” and counter cylinder to ensure the desired thickness.

As the coating and substrate pass through, the excess is scraped off. At the end, the layer goes to the inside of the oven to cure and become a solid state structure.

The second layer suffers a partial cure in order to increase the viscosity and facilitate the insertion of the optic fiber.

Table 1: Polymeric Foil Fabrication Procedure

| **Step** | **Operation** | **Condition** | | |
|---|---|---|---|---|
| | | Gap [μm] | Temp [ºC] | Heating time [s] |
| 1 | PVC-layer 1 Application | 200 | - | - |
| 2 | PVC-layer 1 Cure | - | 200 | 60 |
| 3 | PVC-layer 2 Application | 300 | - | - |
| 4 | PVC-layer 2 Partial Cure | - | 200 | 5 |
| 5 | Optical fibres insertion | - | - | - |
| 6 | PVC-layer 2 Full Cure | - | 200 | 60 |
| 7 | PVC-layer 3 Application | 400 | - | - |
| 8 | PVC-layer 3 Cure | - | 200 | 60 |
| 9 | Cooling + manual release | - | - | - |

## RESULTS

Figure 5 shows the result of the fabrication process previously presented. The polymeric foil has optic fiber based sensors embedded in it. By visual inspection, we can conclude that the fabrication process has run successfully. Figure 6 presents the reflected spectrum of the FBG sensor. The side lobes come from the grating fabrication process, resulting from the radiation transmission function, and can be smoothed by apodization function. As the foil is stretched, the Bragg pitch shifts, maintaining the optical spectrum shape and amplitude.

### Structure characterization

It is also vital to evaluate the performance of the overall structure and infer its sensitivity and integration level. For such purpose, the prototype was tested over a setup (Figure 7) composed by a *Instron® 4302* testing machine, while the optical signal was being measured by the *BraggMETER*™ 4200 unit.

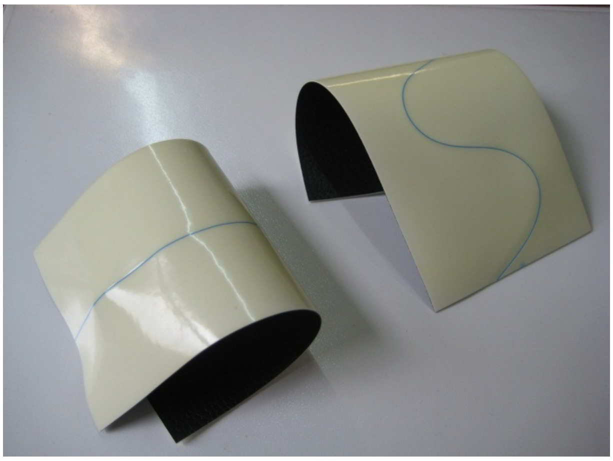

Figure 5: Developed Prototypes

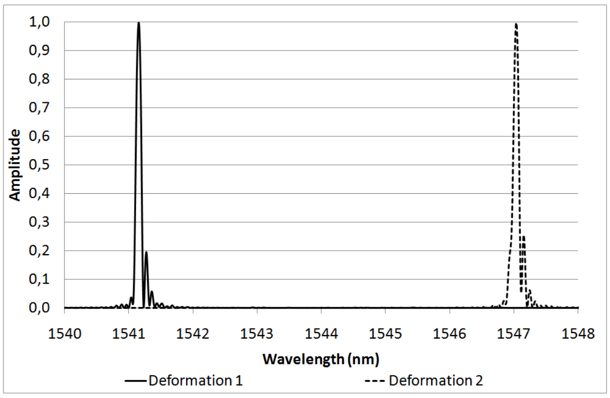

Figure 6: Reflected Spectrum from the Developed Foil for Two Distinct Tensile Forces

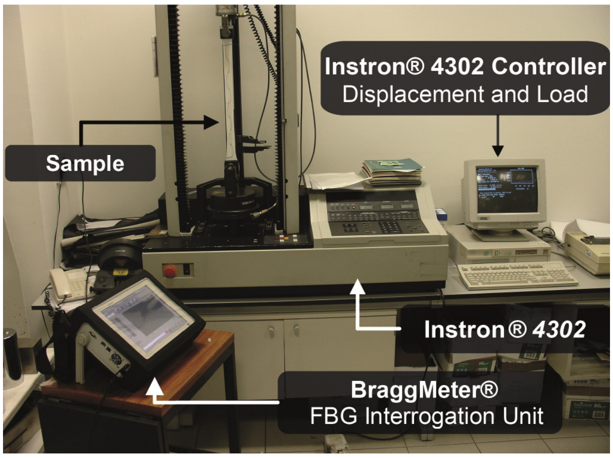

Figure 7: Mechanical Testing Setup

The prototype was cut to a 50x100 mm size strap and two tests were made over the model.
In the first test, a displacement was applied at a constant increment rate of 16 μm/s, until the prototype break. As it is demonstrated over the graph (Figure 8), the wavelength deviation had a linear behavior above the 0.5 % elongation state. Under 0.5 %, the non-linearity was mainly due to initial stretch state of the sample.
Besides this fact, the model was able to sustain the 1.62 % stretching, which is 1.62 mm of displacement in this case. At this time, the fiber was subject to a load of 9.691 N. This displacement of 1.62 % is followed by a wavelength deviation of 9.207 nm, defining the present model sensitivity to 6 nm per 1 % of elongation. If this structure was applied to one meter long steel beam that had been stretched one millimeter, the wavelength deviation that would be measured is 0.6 nm. The determined sensitivity value provides a qualitative measurement about the integration quality.

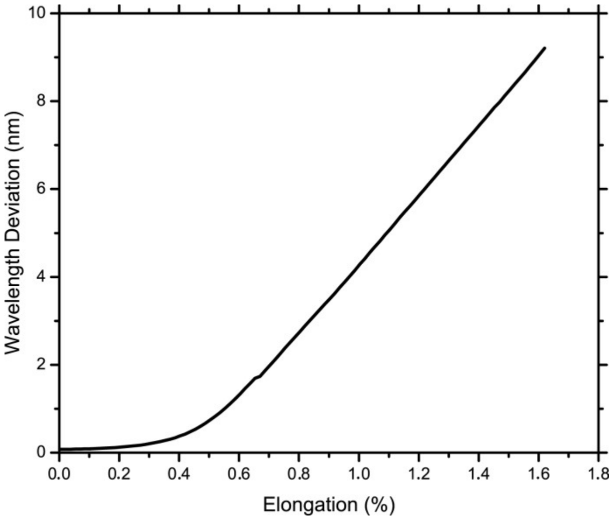

Figure 8: Smart Foil Response to Applied Displacements

Finally, a displacement was applied in steps of 0.2 % (200 µm) and kept at that state during a period of time, in order to evaluate if the fiber slipped over the polymeric foil (Figure 9). If that happened, the optical signal should decrease while keeping the displacement constant. In Figure 8, it can be seen a little bump after each step, but in seconds the optical signal stays constant. When stopping the displacement, the vibration of the claw was observed and detected by the FBG sensor due to its high sensitivity. The preservation of a constant value ensures that the fiber did not slip and that it was well embedded in the foil.

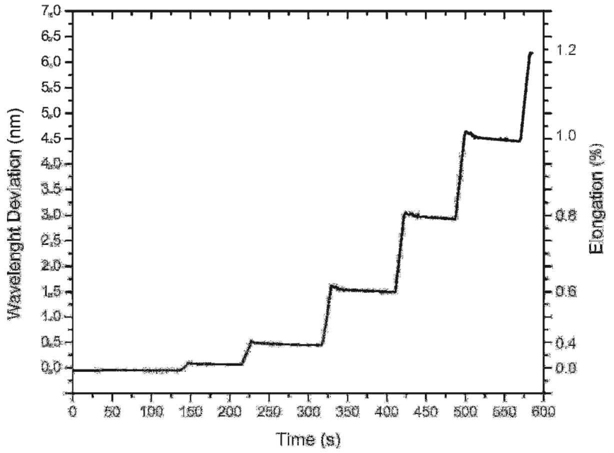

Figure 9: Smart Foil Response to applied Displacement Steps

The resistive behavior to mechanical stretching of the flexible sensing foils is altered due to the presence of optical fibers. This behavior is dependent of the configuration of the optical fibers or on the optical fiber path in the PVC matrix. To better evaluate these dependencies, several prototypes were produced with different paths of the inserted optical fibers.

When stretching the samples, it was possible to detect a good integration level, since all the samples had the expected behavior for an excellent level of integration. The curve behavior for a good integration level is composed by an increasing load along the elongation increment until the fiber snap. At this moment, the load decreases, since there is no more fiber resistance. Then the resistance in only due to the PVC matrix and the load start to increase again until the full collapse of the PVC matrix. Another important detail during the elongation is the break of the fiber without seeing it appearing in the exterior. This means that it was well embedded and was not able to cut the PVC matrix.

Looking to each plot in the Figure 10, it is clear that the variability is very low. The curves in each group are very alike, changing only in the fiber snap instant. Even though, the variation is 10 % in the worst case.

Comparing now the two set, the samples with more curves were able to sustain a higher elongation, which is the expected behavior. Higher number of curves for the same sample length means lower radius of the curves. Thus, the distance between the further spot of the fiber from the elongation axis is lower and consequently, the shear stress inside the mid-layer will be also lower, allowing a higher elongation with lower applied loads.

The final test was performed to characterize the smart structure thermal behavior. The samples were glued to a metal plate, 0.8 mm thick, which was placed over a hot plate. The heat source was programmed to achieve a temperature of 175 ºC at a rate of 1 ºC each 3 seconds.

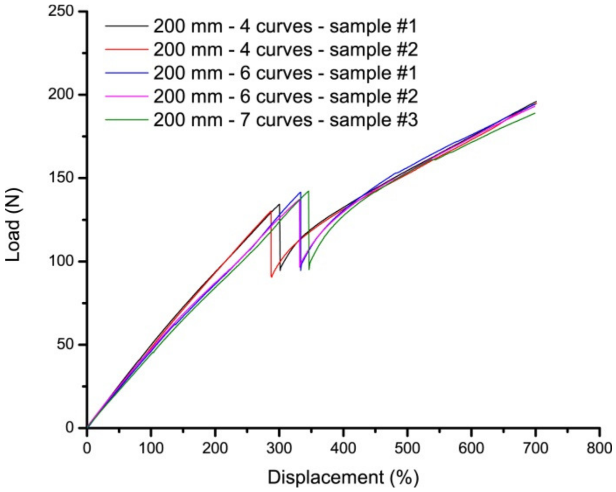

Figure 10: Elongation-at-break Of PVC Foils with "S" Pattern Fiber

As the metal plate, with the sensing foil attached to it, was being heated, the FBG wavelength shift was recorded, and the result is plotted in Figure 11. The temperature rising is followed by a positive deviation of the sensor reflected wavelength. The obtained data tends to follow a linear fit with an R-Square value of 0.99789. The prototype responded to temperature changes with a slope of 0.1 nm/ºC.

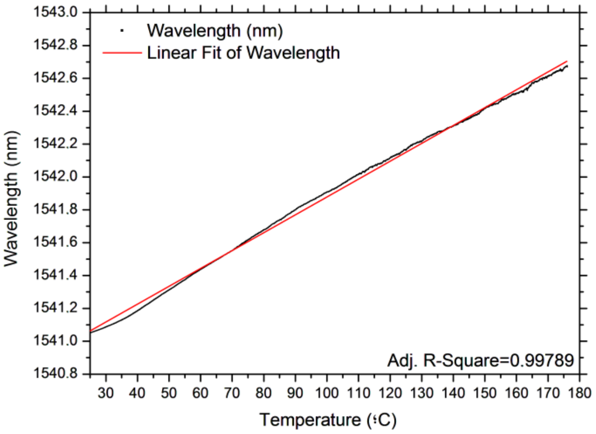

Figure 11: Smart Structure Response to Temperature Cycles

## APPLICATIONS

The developed smart structure can be compared to a thick (900 µm) paper foil with the capability of sensing temperature, strain and related measurands. Since it can be provided in a coil, at the application site, it is unwounded and mounted as it was a wallpaper cover. This enables the covering of a full structure with a non-complex sensing network due to the sensor's multiplexing characteristic. The interrogation of such network can be done from a far site from the sensing network by an optical fiber connection cable.

### Automotive Application

The automotive industry, among many others, is already benefiting from the potential of optical sensing technologies. The number and sophistication of optoelectronic systems found in modern cars is increasing at an unprecedented level. Presently, electronics and photonics account for nearly 25 % of total vehicle manufacturing costs for luxury models (Norm Schiller 2004). Linking textiles or textiles-polymer-laminates (artificial leather) with optical devices and electronics is more realistic than ever. An emerging new field of research that combines the strengths and capabilities of electronics, optics and textiles is opening new opportunities. Therefore, for automotive makers and insurance companies, a powerful diagnostic tool as an inner smart flooring for monitoring the chassis deformation in case of collision, car accident or in crash tests would be a breakthrough. A sensing network can be incorporated in the car chassis for monitoring of its structural integrity. However, direct incorporation creates some difficulties in eventual sensor maintenance or replacement. Alternatively, the developed foil can work as a usual car flooring, taking advantage of the fact that this item is typically interconnected with the car structure, and can easily be substituted or applied to different automobile models.

### Biomedical Application

The prognostic, diagnostic and therapeutic treatment can be greatly improved by the correct, accurate, non-invasive and long-term monitoring of vital signs such as respiration, cardiac activity, and blood pressure, among others (Kanellos, Papaioannou et al. 2010). The majority of commercial sensors widely used in medicine are electrically active and, hence, not advisable for use in a number of medical applications, as during MRI exams, high microwave/radiofrequency fields or laser radiation procedures (Chong, Leija et al. 2001). Consequently, sensing foils as the one developed can be applied as a wearable device to monitor vital signals of the patient.
Furthermore, the developed smart structure can be applied for monitoring of the human kinematics. This can be very useful in physical-therapy, for assessing an accurate motion range in order to define the appropriate rehabilitation plan and monitor the patient evolution.

### Civil Engineering

Integration of optical fiber sensors in civil structures is the most active research field on this type of sensors, where several applications have been already implemented, leading to their maturation (Glišić and Inaudi 2007). The main goal of using optical fiber sensors in this application field is to detect, prematurely, possible damage or deterioration; provide real-time information for safety assessment in case of adversities and extreme events; and plan, prioritize and monitor inspection, rehabilitation, maintenance and repair (Ko and Ni 2005).
The designed sensing foils can be applied as a wall cover or a carpet. Since it is fully customizable, it not only can be fully discrete but also be able to sustain harsh condition and still monitor with success the building, bridge or tunnel.

## CONCLUSIONS

There is a great interest in FBG sensors and, in more recent years, in the development of distributed strain and temperature sensor systems for application in smart structures systems. Nevertheless, it has been identified a lack regarding the automated methods for manufacturing smart-structures. The chosen process, described through this article, takes advantage of flexible skin-foil structures manufacturing method by meeting its requirements and embedding fiber Bragg grating sensors. Functional prototypes have been produced without neglecting the sensor performance. Moreover, the sensing fiber integration was a success. The bonding between the fiber and the PVC matrix ensured the correct transference of mechanical and thermal stimulus. The integration of fiber optic FBG sensors was successfully achieved with a direct fiber deposition technique. The developed process was modified in order to be run in line during the normal manufacturing process for flexible laminated foils by spread-coating. The selected direct deposition of optical fibers during the spread-coating process for PVC foil manufacturing demonstrated to be practical for an industrial and automated production of flexible sensing foils.

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