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# Fiber optic river navigability monitoring system

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Abstract: Fiber Bragg Grating (FBG) sensor systems are widely used to monitor mechanical parameters for structural health monitoring (SHM) of civil engineering structures. Among many applications, FBG technology allows the development of weighing pads with a fully passive optical working principle, with no need for electrical power at the measuring point.

In this contribution, a technical solution for monitoring the navigability of the "Po" river, proposed in the framework of the European project CRISTAL (Climate resilient and environmentally sustainable transport infrastructure, with a focus on inland waterways) is investigated. The preliminary laboratory test to assess the feasibility of a procedure based on FBG technology to monitor sand accumulation on the riverbed is exposed, by using a weighing pad instrumented with FBGs. Indeed, its design and prototype realization are under development in the ENEA FOS (Fiber Optic Sensor) laboratory.

Keywords: Instruments for environmental monitoring, food control and medical use; Overall mechanics design (support structures and materials, vibration analysis etc); Real-time monitoring; Detection of defects

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## 1 Introduction

As part of the HORIZON Innovation Actions program, the ENEA FOS [1] laboratory participates in the EU CRISTAL project [2].

Currently, to detect possible accumulation of sand and debris along the riverbed, scheduled campaigns with vessels equipped with bathymetric devices are used, which is a costly and a time consuming procedure, particularly complex to be activated after unexpected and potentially offending natural events. Bathymetric monitoring to control the depth of the river occurs using a multibeam sonar. Having a permanent and remote monitoring system of the height of the accumulated debris would overcome this inconvenience. As a matter of fact, FBG technology provides a potentially effective technique for that monitoring, through the measurement of the weight of the accumulated debris.

FBG sensors are efficient fiber optic strain sensors [3–5], they can be used as sensing element of a bending plate scale, to measure the elastic deformation of a metal plate burdened by a weight. In the application of interest, the weight of the debris accumulated on the weighing pad is measured to work out the height of the column of the debris itself staying on the scale. The deformation is ideally and linearly correlated to the weight above.

## 2 FBG technology

FBG sensors are intrinsic sensors: their mode of operation is based on the disturbance of the light occurring inside the fiber.

The sensors are embedded in the core of the optical fiber as diffraction gratings located in a short segment of optical fiber itself (figure 1). The diffraction grating consists in a periodic variation of the refractive index in the core of the optical fibre, with no evident alteration of its dimension and appearance. The rest of the fibre stays pristine and operates for the transmission of sensor's signal. If broadband light propagates along the fibre, a specific peaked narrowband back-propagating signal originates at the FBG by diffraction. The back-propagating wavelength's peak is linearly dependent on

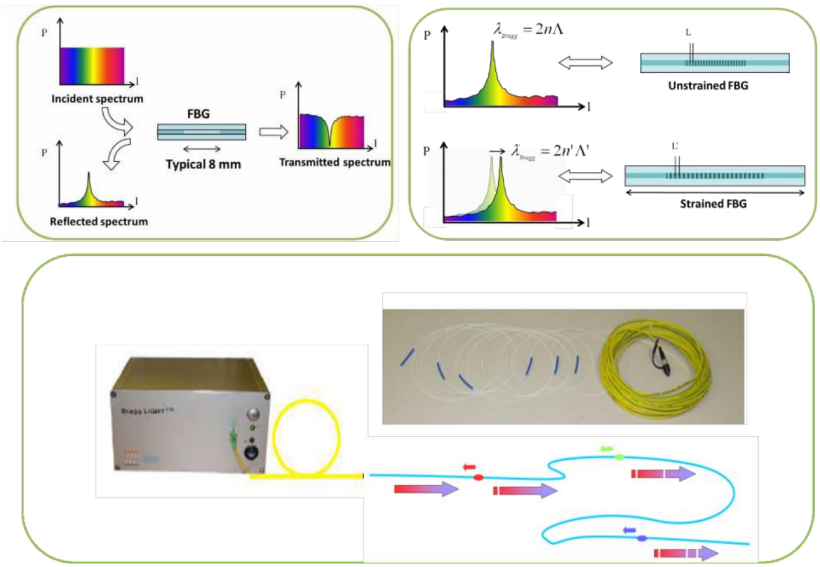



**Figure 1.** On the top FBG principle of sensing system. At the bottom photos of the optical interrogator and fiber optic chain.

the strain and/or temperature of the FBG grating and thus varies with them. To make an FBG in a pristine fibre, the periodic modulation of the refractive index is achieved by various techniques. One common technique is to use an ultraviolet (UV) laser that locally alters the physical properties of the core, slightly modifying its refractive index, thus creating a refraction modulation pattern inside the core. The Bragg condition, which provides the back-propagating wavelength's peak $\lambda_B$, is defined by the equation $\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda$ where $n_{\text{eff}}$ is the effective refractive index of the fiber core and $\Lambda$ is the grating pitch. Typical values are $n_{\text{eff}} \sim 1.5$ and $\Lambda$ values ranging from 505 nm to 535 nm.

## 3 Proposed installation for the "Po" river

Permanent monitoring and consequent timely detection of the evolution of debris accumulation, enables more efficient dredging planning and exceptional interventions, minimizing potential drawbacks for the navigability. The end users are barge operators, logistic service providers, waterway managers, and calamity abatement operators. The availability of permanent monitoring will also generate data that will be contributing to the assessment and fine tuning of digital twins and forecasting models of the waterways.

The pads have to be installed at sections that are critical to that issue as per the water depth and the related safe navigation (figure 2). FBG technology is adopted as it allows the development of weighing pads which have a fully passive optical working principle, with a very simple mechanical construction and no moving parts, with no need of electrical power at the measuring point. Use of a pattern of pads, possibly cabled with pass-through fibre optical backbone is previewed to monitor the full riverbed section or area of interest. Use of FBG sensors for weighing application has been investigate and demonstrated in past works and for various applications [6–8], but no submerged applications have been reported to our best knowledge.

Within the CRISTAL project, first it is planned to study the feasibility of the weighing pad solution in a laboratory test bench. The weighing pads operate according to the bending plate principle, thus



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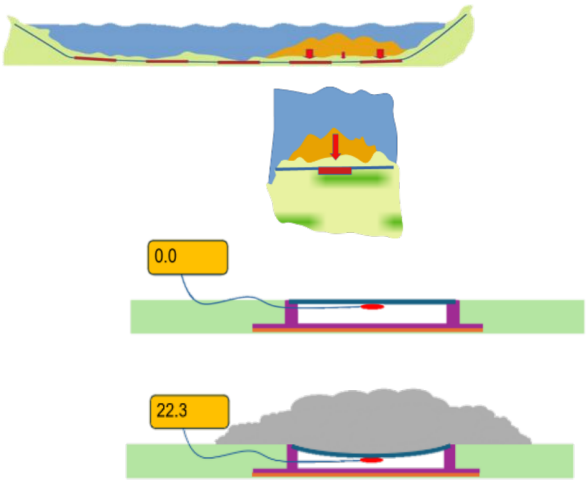



**Figure 2.** Weighing pads in the riverbed. On the top: sectional view of the river. Bottom drawings: debris accumulation can be detected by a weighing pad. This is made with fiber optic sensors that send signals in real time.

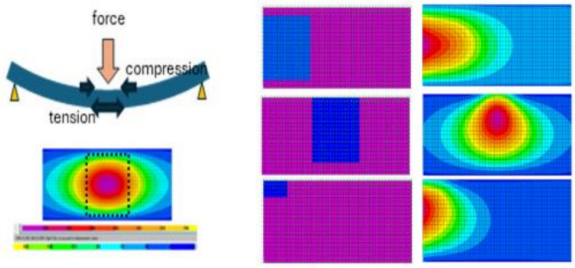



**Figure 3.** Principle of a weighing pads to measure a column of debris.

avoiding the use of moving parts with consequent benefit for the system's durability. Here it is that FBG sensors by measuring the plate deformation, due to the weight of the debris, allow to estimate the height of the debris column accumulated on the pad (figure 2 and 3).

## 4 Dry testbench

An elastic plate of finite width is subject to strain of opposite sign on the two opposite surfaces. The value of the strain is related to the acting force. Its mapping over the surfaces depends on: i) the constrains (simple support); ii) the acting force (direction, distribution, etc.); iii) the material of the plate. The first version of the pad has simple design: a rectangular plate in simple support along two opposite sides. The support was provided by two rails with triangular section fixed on a rectangular basement, in order to minimize the mechanical constraint of a frame. Aluminium was used as material of the basement and plate, brass for the rails (figure 4). The plate was instrumented with three FBGs.

The figure 5 shows the result of a preliminary test of the weighing pad. The scale was tested and calibrated on a testbench in dry condition by using multiple reference masses made of blocks 1600 g heavy each. The blocks were loaded and unloaded one by one, slowly, waiting for the scale settlement. The 3 FBG sensors show different response ($\Delta\lambda$) to the mass variation, as expected since they are positioned at different positions on the plate.



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**Figure 4.** Scheme of the first weighing pad and its photo. Some weights placed on it during first test.

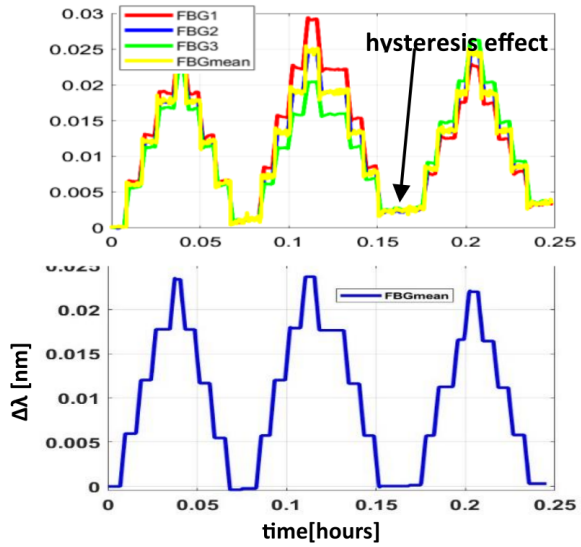



**Figure 5.** Load and unload tasks in dry operational condition by 1,6 Kg blocks. In the bottom the data processed to reduce the relaxing effect of the resin/fibre interface.

For this type of test, no temperature variation was considered because, during this short measurement acquisition period (15 minutes), it was approximately constant and therefore any effect was reliably considered as marginal. In fact, it shall be considered that FBG sensors are intrinsically sensitive to both temperature and strain, and thus temperature compensation techniques (well know and routinely used in engineered applications) shall be adopted if necessary. The graph shows a hysteresis behaviour depending on the relaxion effects of the plate and the resin/fibre interface, glued with epoxy resins.

Applying a data processing algorithm based on running average on a 5 s time lap [9], the effect of the hysteresis can be reduced as figure 6 shows.

The reported results suggest a different choice of the coating of the FBG sensors. FBGs with acrylate coating were used, getting an excessive relaxation effect, although within elastic and repeatable behaviour. The use of FBG with polyimide coating can cancel this effect by improving the optimization of the data processing algorithm to cope with the relaxation effect of the metal material; in fact, by engineering the pad for a real application, the effect of resin and fiber coating has been revised to minimize the relaxation effect (see section 6).



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## 5 Tank tests

For the tank test with submerged bending plate, the FBG sensors were protected by waterproofing coating. The prototype was laid on the bottom of the tank and then submerged by pouring water in the tank. Later, the test was performed with coarse sand that was progressively dropped on the prototype. The FBGs raw data, reported in the upper plot of figure 6, show a slow progressive variation due to temperature variation of the water. The first rapid increase (before time 50 h) is due to the mechanical assembly and to the tap water which at the beginning was much colder in respect to the room temperature, so that the signal increase comes from both temperature variation of the environment and additional filling of the tank with water. In this first prototype, not provided of an FBG sensor for temperature compensation, in order to reduce the temperature effect a differentiation algorithm was adopted, by subtracting threshold on the difference between successive averaged samples of data, the result shown in the top plot of figure 6, its intermediate frame shows only the variations (spikes) due to the sand and tap water pouring action while the temperature effect was filtered out. The bottom frame was obtained as an 'incremental' by adding the amplitude of the registered variations, in such a way as to have a signal in which only the variation in wavelength depended on the variation in weight on the scale plate. The bottom plot is the zoom at the moment of interest, during the step-by-step weight loading action.

Clearly an improved pad shall include additional sensors not mechanically glued to the plate and which will serve to compensate for the variations in the wavelength of the other strain sensors. The purpose of this first prototype was in fact to verify that the entire weighing system for the debris accumulated in the riverbed was functional.

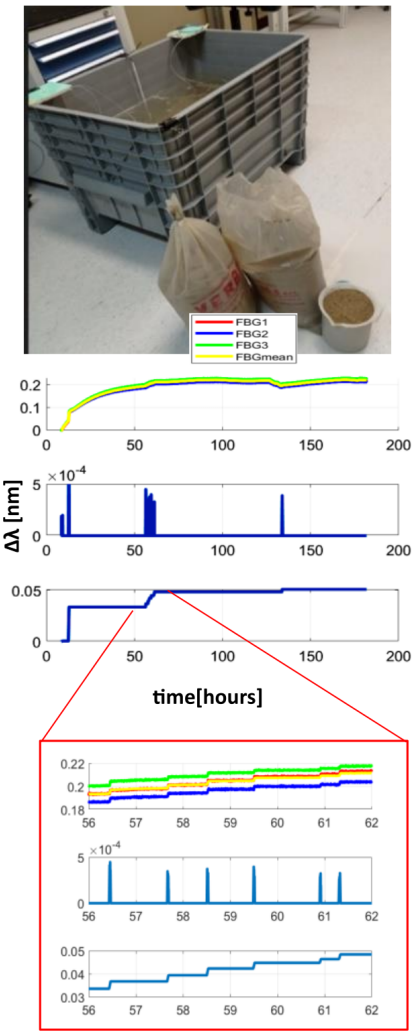



**Figure 6.** Picture of the tank used for the test. On the bottom the FBGs wavelength raw data and processed data by the algorithm to reduce the temperature dependency.

## 6 Weighing pad for the pool test

A weighing pad has been built as a first semi-engineered prototype. The pad has the aspect of a large metallic waterproof sealed box instrumented with fiber optic sensors. Both the side and the bottom surfaces of the pad are massive and have structural functions only, whereas the upper surface (referred to as the weighing surface) has controlled elastic properties and performs the weighting function according to the 'bending plate' operation principle. FBG sensors stay inside the pad and are thus protected from water by the watertight seal of the scale. The figure 7 shows a drawing and a picture of the pad, also the proposed layout of the sensors and their cabling is shown, too. This weighing pad will be placed inside a large pool where the tests will be carried out to simulate real operating conditions.



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The 10 sensors of the weighing pad have been grouped into 2 chains and the data are recorded separately, furthermore it is equipped with 2 internal temperature sensors mounted on the pad frame. Figure 8 shows a preliminary test where the effect of the temperature on the measurement is clear. The temperature variation $\Delta T \sim 5°C$, visible in the blue trace of the plot, has a significant impact on the measurement and must therefore be compensated. The green trace represents the average data from the four internal sensors, (positioned as shown in figure 7), the red trace corresponds to the four external ones. At time 1.6 day (about 38.4 h) a weight of 25 kg of river sand is placed on the plate, all sensors detected this. As expected, the internal sensors undergo a greater deformation than the external ones, because the latter are closer to the static constraint of the pad frame.

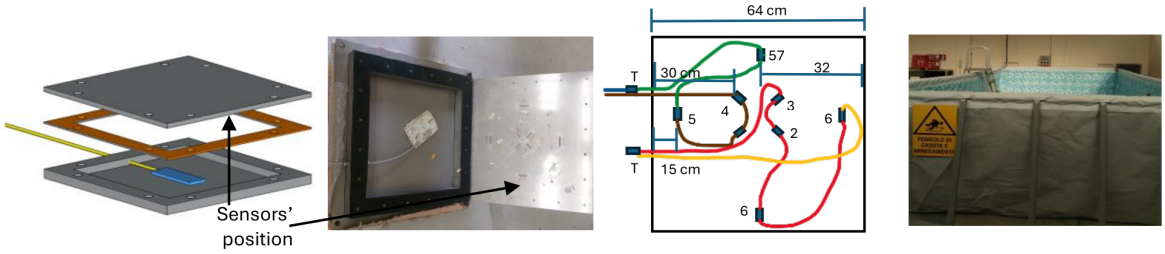



**Figure 7.** On the left the weighing pad drawing, the second picture shows the new built weighing pad. The third picture represents the scheme of the sensors position on the plate. On the right, a photo of the pool is shown.

Using the FGB temperature data, the signal is "recalibrated" to obtain the weight data "purified" by the temperature. In the figure 8, the black trace represents all these signals by taking the average of the data from all the sensors.

It's possible to conclude that the preliminary data of the weighing pad, once carefully calibrated, can be used as a reliable measure of weight in underwater conditions. The next step will be to model the weight of a column of debris and correlate it with its height. In this way it will be possible to enable real-time detection of debris accumulation on the riverbed and allowing for the identification of potential obstacles to navigation.

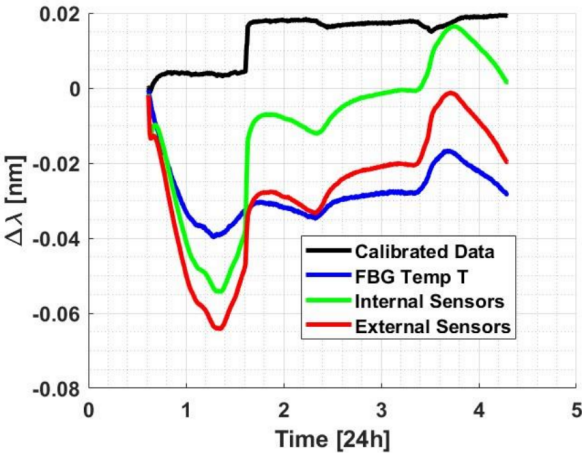



**Figure 8.** Data of weighing pad for the pool test.

## 7 Conclusion

The intended device of the weighing pad instrumented with FBGs, for measuring the height of debris to be laid on the riverbed, was described. Its design and prototype realization are under development in the ENEA FOS (Fiber Optic Sensor) laboratory. The use of a pattern of the weighing pads is intended for the permanent monitoring of the accumulation of sand/debris along sections of waterways, thus providing early warning of critical decrease of water depth and related safe navigation. The submerged installation heavily calls for passive solutions, as the FBG technology is, to lower failure events and required maintenance.



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The experimental test of a weighing pad based on the bending plate principle has been here reported, the results obtained first with known weights and in dry conditions, and subsequently with sand in a submerged condition. The setup of the weighing pad resulting from the first promising tests are detailed. The engineering choices included in the second prototype pad is under test in a large swimming pool to approach true operating conditions.

The next steps include further pool tests, a large location that allows varying amounts of sediment accumulations, as well as different sand densities. If these tests are successful, the final test of the weighing pad prototype can be performed in an outdoor location, such as a small river with realistic conditions.

## Acknowledgments

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