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Augmented Reality Visualization of Fiber Bragg Grating Sensor Data for Aerospace Application

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***Abstract*—Over the last decade, the use of Augmented Reality (AR) in engineering applications has grown exponentially. In the aerospace sector, this technology is attracting growing interest in several applications, ranging from monitoring, maintenance, and data visualization. This study falls into the latter type of applications and aims to present innovative software for visual monitoring systems using fiber Bragg grating (FBG) sensors via Microsoft HoloLens. Sensory data is presented to the user through a graph visualization. The software has been tested for temperature and strain measurements applied on a specific test bench, proving valuable for aerospace testing.**

***Keywords*—aerospace, augmented reality, data visualization, databases, device to device communication, graphical user interfaces, internet, middleware, optical fiber sensors, wireless communication**

I. Introduction

Visual information communication through Augmented Reality (AR) techniques has increased in recent years. Since 1992, when the term augmented reality was first defined, studies and applications in this field have increased hand in hand with the improvement of technology [1], [2]. Augmented reality can be described as an interaction between the real and virtual environments to enhance human sensory perception [3]. Unlike Virtual Reality (VR), AR allows users to maintain contact with the real environment while providing additional information. The rapid and significant success of this technology is due to two main factors: it provides simplified, intuitive, and immediate access to sometimes complex information, and it offers substantial support for technologically innovative challenges [4]. It is important to emphasize that this contribution is not solely a technical advantage but, perhaps more importantly, has psychological implications related to the user's familiarity with their surroundings [5]. Furthermore, augmented reality technology aligns well with the development of innovative sensor networks [6], [7] for data sensor fusion and systems monitoring in prognostics and diagnostics applications [8]. It provides an interactive view of the most significant data for the user, allowing the aggregation of information from different sensors on a specific interaction platform.

The development of innovative sensor networks and data visualization through AR are the focus of studies at the interdepartmental research center PhotoNext at the Politecnico di Torino, to which the authors are affiliated. In particular, due to their intriguing physical properties, great efforts are dedicated to optical fiber-based sensors, where their ability to read data in real-time is studied. This paper aims to propose a new software, called *PhotoNext FBG AR Viewer*, which uses AR to intuitively display the data coming from this type of sensor [9]. It is organized as follows. Section II presents the state of the art related to AR in the aerospace sector and the use of optic fibers for systems monitoring. Section III discusses how the *PhotoNext FBG AR Viewer* works and its features. Sections IV describe some software tests made in the laboratory. Finally, Section V draws some conclusions regarding the work done and some ideas for future work.

This work was carried out under the PhotoNext initiative at Politecnico di Torino (http://www.photonext.polito.it/).

II. Use of Augmented Reality and Optical Fiber Sensors in Aerospace Systems

In this chapter, two aspects are discussed:

- The analysis of the state of the art regarding AR in aerospace applications;
- The use of optical fiber-based sensors for lifecycle management of aerospace systems.

A. Augmented Reality and Aerospace Applications

In recent years, research activities in the field of augmented reality concerning aerospace applications have focused on two particularly relevant thematic areas [10]. The first concerns data visualization from remote platforms to create an environment where information from different sources can be integrated and presented effectively to users [11]. The second area of interest is operator training and support to maintenance activities [12], [13].

The first thematic area mainly focused on visualizing data from various sensors [14]. This activity represents a natural progression from traditional data visualization systems as it integrates the possibility of having a three-dimensional display space. Accessing telemetry from different interconnected platforms provides operators with a significant volume of data. In this context, the use of holographic displays plays a fundamental role. This technology allows the overlay of information from a specific sensor directly onto the sensor itself, thus reducing the workload required for data interpretation. This approach allows for maintaining the relevance of information, simplifying the analysis process, and facilitating the real-time understanding of critical data.

Regarding operator training, AR offers the opportunity to provide guidance capable of supporting and, in some cases, replace traditional documentation and manuals-based procedures [16], [17]. The ability to overlay notes and targeted artificial elements to capture the operator's attention creates greater familiarity with the real operating environment during the training phases [15]. This allows them to familiarize themselves with the procedure to be performed without exposing themself to potential associated risks and, as shown in Fig. 1, reduces the time required to complete the training [18]. In the subsequent stages after training, AR allows rapid and intuitive access to all the information needed to complete the operation, reducing the time and errors committed [15]. In addition to simple training, studies have also been conducted to assess the application of AR in supporting complex procedures for safety and product assurance increasing [19]. An example is represented by the *Augmented Toolkit for Lunar Astronauts and Scientists* (ATLAS) system, designed to provide a tool for astronauts during lunar missions of the Artemis program [2].

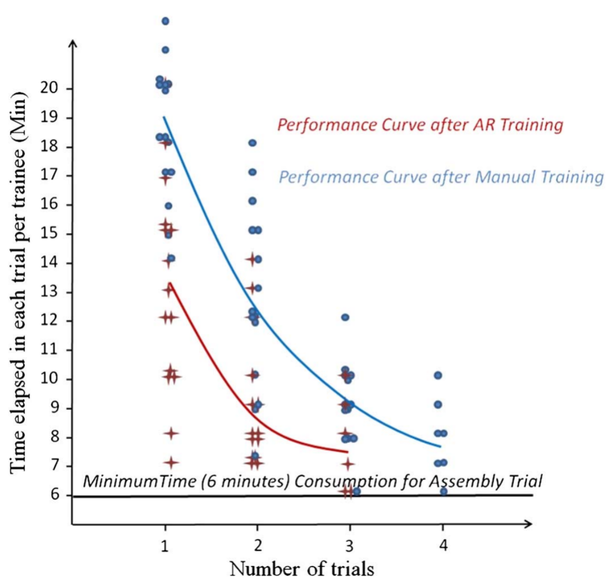

Fig. 1. Operator performance comparison after Manual and AR training [15].

B. Fiber Optic Sensors Network for Systems Monitoring

In recent decades, optical fiber technology has become widely established for various engineering applications, extending far beyond the realm of telecommunications [20]. It leverages the ability to embed sensors within optical fibers sensitive to various physical parameters, such as temperature, strain, vibration, pressure, and more [21]. Furthermore, fiber optic sensors maximize the advantages offered by the physical properties of the fibers themselves. Among the most notable advantages are immunity to electromagnetic interference, minimal invasiveness, chemical inertness, and a wide operating temperature range [22]. In summary, optical fiber sensing technology can deliver high performance even in harsh environments, a key requisite for aerospace vehicle systems [23]. Among the sensors available in the market, those based on Bragg gratings represent the best compromise in terms of cost and performance. They are created through a laser photo inscription process that periodically alters the refractive index within the core of the optical fiber. The core is the innermost layer of a typical optical fiber structure through which optical signals propagate. This re-modulation, referred to as a Bragg grating, possesses the unique property of reflecting a specific

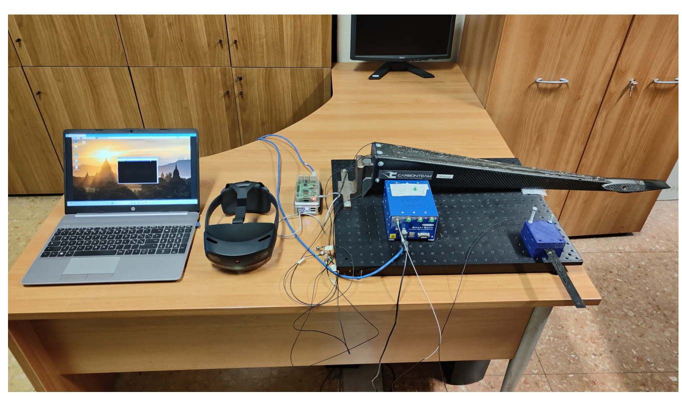

Fig. 2. A snapshot of the settings used for strain measurement tests.

frequency within the electromagnetic spectrum that traverses the fiber according to the following equation:

$$\lambda_B = 2 * n_eff * \Lambda \tag{1}$$

where λ_B is the Bragg frequency (the sensor output), n_{eff} is the altered refractive index of the core, and Λ is the grating pitch. The proportionality between the optical response and the grating pitch allows for the correlation of the Bragg frequency to physical parameters acting on it. The following equation represents the most simple way to describe it:

$$\Delta\lambda/\lambda_B = K_\varepsilon \Delta\varepsilon + K_T \Delta T \tag{2}$$

where $\Delta\lambda = \lambda_i - \lambda_0$ is the wavelength variation of the measure λ_i from the value at rest λ_0, K_ε is the coefficient of proportionality of the strain, $\Delta\varepsilon = \varepsilon_i - \varepsilon_0$ is the strain variation of the measure ε_i from the value at rest ε_0, K_T is the coefficient of proportionality of the temperature, and $\Delta T = T_i - T_0$ is the thermal variation of the measure T_i from the value at rest T_0.

III. PhotoNext FBG AR Viewer

The authors of this paper have recently presented a flying test bench for FBG sensors, which is based on the use of *SmartScan* interrogator from *Smart Fibres* for reading their value [24]–[26]. It can read data from FBG sensors placed on the composite of a UAV named Anubi and transmit it to a *Cloud Database*, which transmits it back to one or more UAV data viewers in near real-time. As previously mentioned, this article wants to go further and present a new AR visualization software for the data read by FBG sensors. It was developed using the *Unity* game engine and the C# programming language for use via *Microsoft HoloLens 2*, which is currently one of the most advanced AR visors on the market. When started, the software checks the connection with *Cloud Database*: if unsuccessful, it provides information based on the error (connection failed, no new acquisitions), vice versa it recovers the sensory data relating to the acquisition in progress and display them to the user using a graph visualization, showing the temporal variation of the wavelength of each sensor with respect to its resting value. The interface buttons allow the user to lock it in a fixed spatial position or follow the movement of the user's head, hide or show the graph visualization, and exit the software. The received data is subsampled in such a way as to reduce the number of calls required to update the graph. This is a small compromise necessary to increase the speed of using the program.

IV. Laboratory Tests

A laboratory test campaign was carried out to validate the functionality of the *PhotoNext FBG AR Viewer* software. The settings of the tests performed are depicted in Figs 2 and 3.

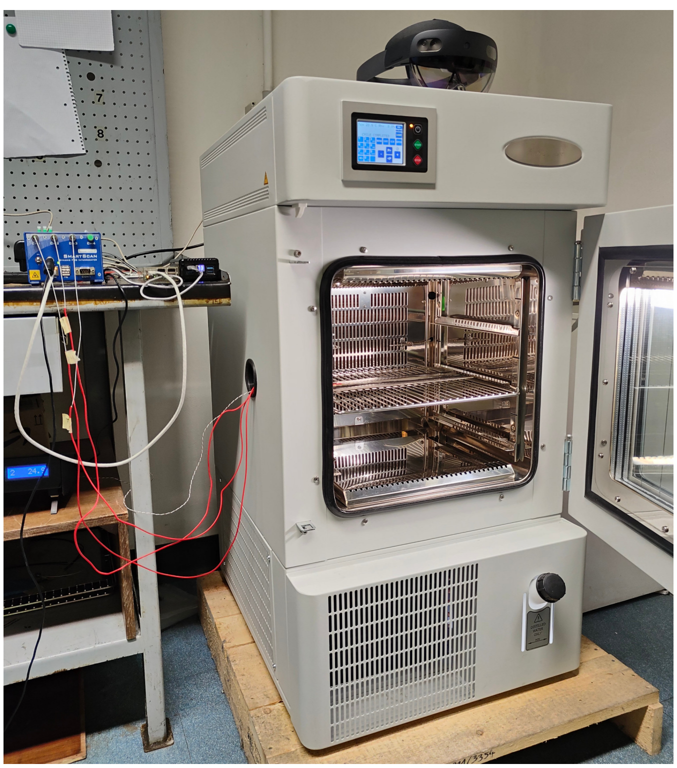

Fig. 3. A snapshot of the settings used for temperature measurement tests.

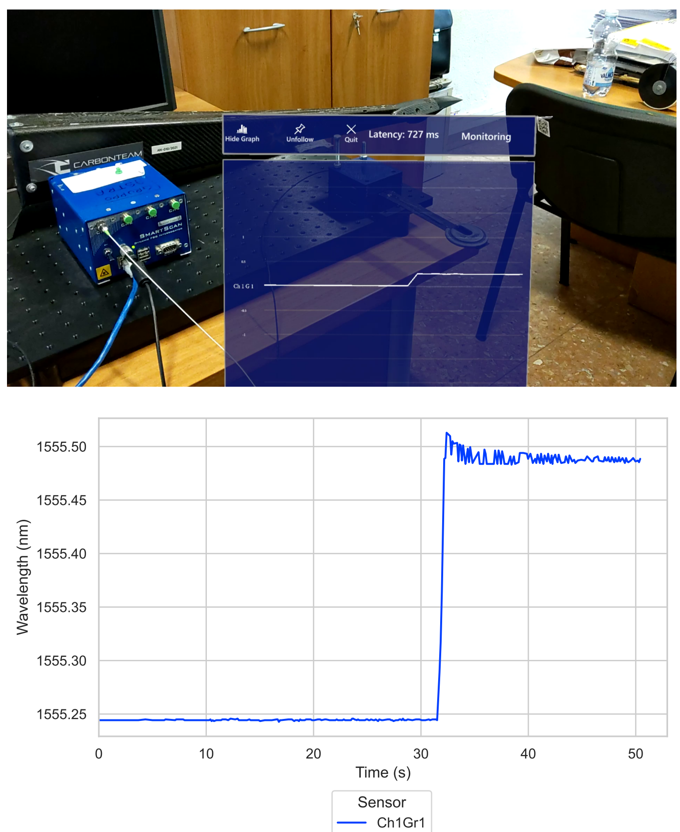

Fig. 4. A snapshot of the first strain measurement test (top) and the respective results saved in the *Cloud Database* (bottom).

The various tests carried out are reported below in an orderly manner.

A. Strain Measurement

The first measurement test measured the strain undergone by the instrumented carbon fiber sample. A transverse optical fiber is glued to it, and a single FBG sensor is at the end. Taking into account (2) and considering the environmental temperature constant during data acquisition, the reflected wavelength is directly proportional to the applied strain:

$$\Delta\lambda/\lambda_B = K_\varepsilon \Delta\varepsilon \tag{3}$$

Fig. 4 shows a snapshot of the testing phase viewed through *Microsoft HoloLens 2* and the sensors data saved in the *Cloud Database*, which have been graphed and compared to what was shown by the *PhotoNext FBG AR Viewer* to evaluate its visualization capability. In particular, the trend of λ_i is considered over time. Thanks to (3), the value of reflected wavelength is directly comparable to load-induced strain on the structure. In this way, the graph visualization offered by the software allows the user to immediately understand what is happening to the considered sensor. Due to the subsampling, it is possible to notice that the displayed data are not the same as the saved data. However, the general trend of the experiment is entirely understandable and constitutes an acceptable compromise.

Differently from the first measurement test, the strain experienced by the carbon fiber instrumented tail of the Anubi UAV was measured in the second one. Two optical fibers were glued on the upper surface, and the other two were glued on the lower surface, forming a total of four optical fibers. Each one has four FBG sensors distributed at various points across the tail. The same approach was also used in this test. An external load was applied to the tip of the tail, generating traction loads on two optical fibers and, contextually, compression loads on the opposite other ones. The general equation (3) is always true for monitoring data given by the software. Fig. 5 compares data shown by the software and those data saved in the *Cloud Database*. Only two sensors, one put into the tractioned fiber and the other dual, were considered for ease of viewing. It is immediate to understand how the software allows the user to understand the nature of load aging on the sensors by simply considering the wavelength trend displayed. In particular, it is easy to distinguish the symmetry of load induced by the geometry of the tail and the dual disposition of the sensor. Moreover, the single steps of the load are distinguishable in the time history offered by the *PhotoNext FBG AR Viewer*.

B. Temperature Measurement

The temperature measurement test analyzed the expansion and contraction experienced by a carbon fiber sample instru-

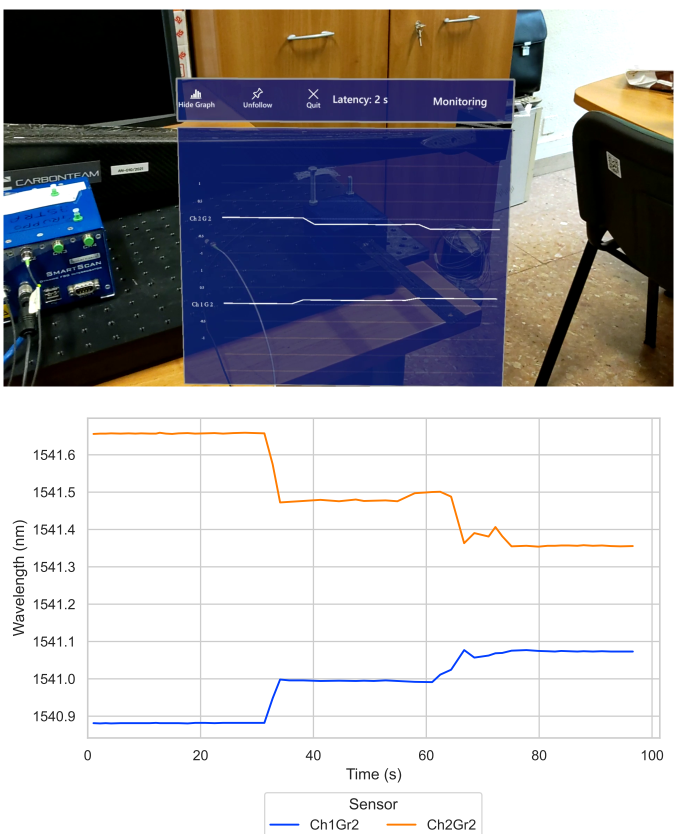

Fig. 5. A snapshot of the second strain measurement test (top) and the respective results saved in the *Cloud Database* (bottom).

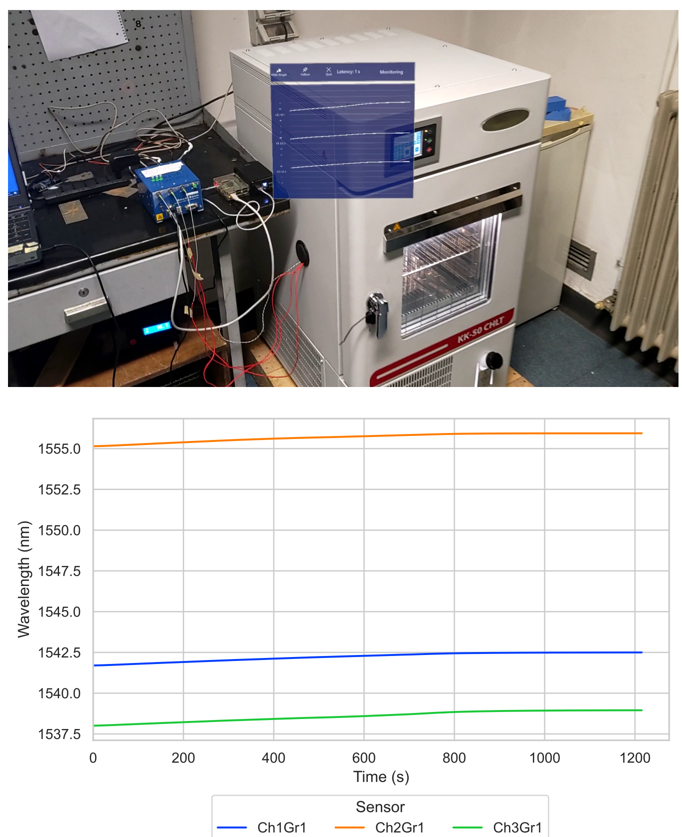

Fig. 6. A snapshot of the temperature measurement test (top) and the respective results saved in the *Cloud Database* (bottom).

mented with 3 FBGs. The carbon fiber sample was first placed in the *Beger KK-50 CHLT* climate chamber, which was set to reach an internal temperature of $100°C$ at the maximum speed starting from room temperature. This temperature was reached in less than 20 minutes. A similar approach to the strain test was also adopted for this test. Firstly, the wavelength and temperature correlation was defined as follows:

$$\Delta\lambda/\lambda_B = K_T \Delta T \tag{4}$$

This equation clearly shows a direct correlation between wavelength and temperature also in this case. Considering the trend in time of the reflected wavelength, it is possible to monitor the thermal variation undergone by the sensor. This is precisely what is done by the *PhotoNext FBG AR Viewer*, which shows intuitively the trend of the reflected wavelengths of the sensors. In the same way as what was performed during the previous test, in Fig. 6 the trend displayed by the software is compared to trends obtained by the post-processing analysis, in which data saved in the *Cloud Database* were graphed. Finally, it is possible to notice that the wavelength stops rising after reaching the set temperature, in coherence with the physical setup of the test.

V. Conclusions

This paper presented an innovative AR software for displaying FBG data called *PhotoNext FBG AR Viewer*. The software was developed with the *Unity* game engine and *MRTK* for explicit use with *Microsoft HoloLens 2*. Its performance and capability to correctly display sensor data were tested in laboratory tests, covering thermal and mechanical aspects. The results demonstrated the excellent matching between data visualized by the software and those saved in the *Cloud Database*. In the future, the authors of this paper intend to continue improving the application in all practical aspects.

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