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***Abstract*—Over the past decades, interest in Unmanned Aerial Vehicles (UAVs) has grown exponentially. The development of a new generation of UAVs implies satisfying two fundamental requirements: the availability of a fully integrated and high-performance sensors network and a human-machine interface tool. To this end, the paper analyses the potential advantages of the combined use of an embedded optical fiber-based sensors network in the structure of the UAV and the visualization of these data through Augmented Reality (AR). A specific test campaign has been organized to study and verify this interaction properly. In particular, a specific software has been developed to interactively allow the user to reproduce the UAV and the onboard sensors in an AR environment. Moreover, a flight testing activity was conducted to verify both the capability of optical sensors to generate data and the capability of the viewer software to show them. Despite the preliminary nature of this work, the results fully demonstrated the great potential of this approach, allowing to hypothesize its application in future complex UAV-based mission design.**



***Index Terms*—aerospace, augmented reality, data visualization, databases, device-to-device communication, graphical user interfaces, Internet, middleware, optical fiber sensors, wireless communication**


## I. Introduction

Over the past decades, interest in Unmanned Aerial Vehicles (UAVs) has grown exponentially. Their cost-effectiveness and versatility have led to a wide range of applications, from traditional Search and Rescue missions to more recent uses in supporting the development of smart cities and other emerging fields [1], [2]. Additionally, swarm intelligence is a key area of interest, which involves the coordinated management of UAV fleets [3]. However, their increasingly widespread use requires achieving adequate levels of system safety and reliability, as well as a high level of situational awareness for operators [4]. As a result, UAV development must incorporate innovative solutions for monitoring the performance of key onboard systems and supporting predictive maintenance through appropriate prognostics and diagnostics algorithms. Two fundamental elements are required to meet these objectives [5]. On the one hand, it is essential to equip UAVs with a distributed and minimally invasive sensing system capable of delivering high performance even in harsh environments [6] (e.g., immunity to electromagnetic interference, compatibility with electronic equipment, chemical passivity, and a wide operational temperature range), while also enabling control algorithms to extract complex information. On the other hand, it is also necessary to develop a human-machine interaction methodology to enhance situational awareness both during operation and throughout the maintenance process [7], [8].

This paper presents a first approach to meeting these requirements. Leveraging the experience gained by researchers at the Politecnico di Torino, this study aims to conduct an initial feasibility assessment on the near real-time monitoring of specific UAV parameters through integrated fiber optic sensing technology and the visualization of generated data via Augmented Reality (AR). In particular, the state of an in-flight UAV was evaluated using a previously presented software called PhotoNext FBG AR Viewer. Following these tests, it was decided to release it alongside this article in an open-source version for unrestricted use.

## II. Flying Test Bench

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 [9], [10]. Since the software supplied with this interrogator does not allow sensors data transmission over the Internet, the authors recently proposed a new software pipeline to satisfy this need. It can read data from FBG sensors placed on the UAV composite and transmit it to a *Cloud Database*, which transmits it back to one or more UAV data viewers in near real-time. Such a system, depicted in Figure 1, is divided into two main parts:

- The physical part, which is composed of the acquisition and telemetry system and sensors attached to the half-wing of a UAV called *Anubi*.
- The software part, which takes care of receiving, transmitting, storing, and displaying sensors data.

### A. Physical Part

As previously anticipated, the flying test bench is physically constituted by a UAV called *Anubi*, which the Politecnico di Torino's ICARUS student team realized in 2017. Three lines of FBG optical fibers have been placed on one half-wing of the UAV, for a total of 12 sensors. Beyond the above-mentioned *SmartScan* Interrogator, *Anubi* is also equipped with:

- A 9V Lithium-Ion Polymer (LiPo) dedicated battery, used to power the interrogator.
- An Internet-enabled *Raspberry Pi™ 3 Model B+* board through the use of an *Alcatel™ IK40V 4G Internet Link Key*, having a maximum transmission speed of 150 $Mbps$. It is connected to the SmartScan interrogator via the Ethernet port and runs a software which will be discussed later, called *Middleware*, capable of receiving and transmitting sensors data to subsequent system blocks.
- An USB power bank, used to power the *Raspberry Pi*.

### B. Software Part

The software part can be further divided into three parts, which will be briefly described in the following lines. Their development was facilitated using a software called *Emulator*, which can emulate the SmartScan interrogator operation [11].

*1) PhotoNext Middleware:* The *PhotoNext Middleware* is the application in charge of receiving peak data from the interrogator and transmitting it to the *Cloud Database* using an Internet connection. It is usually installed and run on a *Raspberry Pi™ 3 Model B+* connected with the interrogator through the Ethernet port and internet-enabled through the use of a *4G Internet Link Key*. It was created using Linux System Calls and the C and C++ languages to maximize execution performance.

*2) Cloud Database:* The data sent by the *Middleware* application is received by a *MongoDB®* database, which stores them. Using the Change Stream technology, it can also forward this data to all listening *3D Viewers*.

*3) PhotoNext FBG Data Analyzer:* Sensory data can be visualized using a Personal Computer (PC) using this application [10]. This application has been tested in both the laboratory and the field and is irrelevant to this article; it is only mentioned here for the reader's information.

*4) PhotoNext FBG AR Viewer:* Sensory data can be visualized in AR using this application [12]–[14]. It will be discussed in more detail in the next section.

## III. PhotoNext FBG AR Viewer

As previously anticipated, this paper wants to focus on the flight tests made on *PhotoNext FBG AR Viewer* [9]. This particular viewer version allows the pilot or co-pilot of a UAV on the ground to fly it safely and view its data via a wearable AR device. For safety reasons, they cannot take their eyes off the UAV they are flying for any reason. As a wearable AR device, the choice fell on the *Microsoft HoloLens 2* [15], which is currently one of the most advanced AR visors on the market. The choice of the *Unity* game engine [16], was almost natural given the availability of the *Mixed Reality Toolkit* (MRTK), a project managed by Microsoft that offers a set of features and components that help accelerate the development of cross-platform Mixed Reality (MR) applications [17]. The language

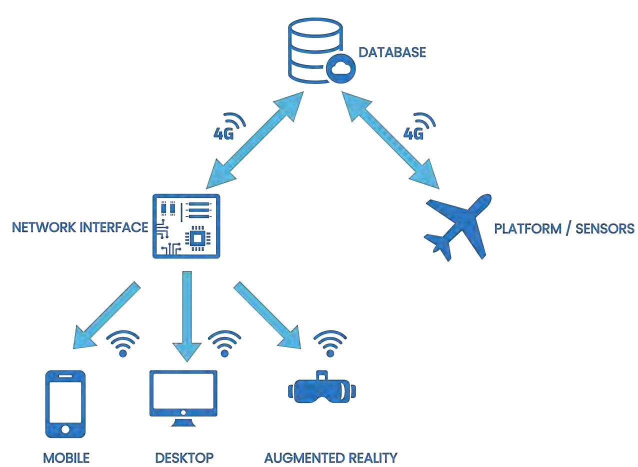


Fig. 1. The architecture of the complete system.


Fig. 2. A picture showing the Selection phase of the *PhotoNext FBG AR Viewer* software. The "Import Model" located at the top of the window allows the import of a new model, while the "New" button allows the creation of a new sensors configuration. Any other buttons created right or below it are relative to any previously created sensors configurations.

Fig. 3. A picture showing the Configuration phase of the *PhotoNext FBG AR Viewer* software. The "Save" and "Start" buttons located on the top of the window allow the current sensors configuration to be saved and the Monitoring phase to start. The central part of the windows allows to view the detected sensors to change their respective type and position them on the chosen model.

commonly used to develop applications with Unity is C# (pronounced C-sharp), an object-oriented scripting language.

### *A. Program Flow*

The typical flow of use of the program can be divided into three main phases: Selection, Configuration, and Monitoring. They will be detailed in the following sections.

*1) Selection Phase:* The Selection phase, reported in Figure 2, starts when the software is launched. It allows users to create a new sensors configuration, load a previously created one, and select the 3D model used to display flight information. Three-dimensional (3D) models having a .obj format present in the folder UserFolders\LocalAppData\PhotoNext 3D Viewer\LocalState\Models are loaded automatically when the program is started and shown among the available models. A 3D model of Anubi, created using the 3D creation suite Blender, is present in the software as a default model [18].

*2) Configuration Phase:* The Configuration phase, depicted in Figure 3, is started when it is wanted to create a new sensors configuration. As the name implies, it allows to place the sensors in the previously selected 3D model and to change their measured magnitude between temperature and strain, which are the ones of interest for the study application. This procedure is necessary for the heat-map visualization to work. User gesture allows the model to be freely manipulated and resized to position the sensors in the best possible way. It is also possible to reposition those previously placed on the 3D model: moving one of the hands closer to one of them makes it enlarged for better manipulation. After placing the sensors in the desired location, the configuration can be saved to avoid repeating the procedure next time. Positioning of all detected sensors is not required to proceed to the next phase; those not positioned will be ignored.

*3) Monitoring Phase:* The Monitoring phase, reported in Figure 4, can be started at the end of both previous phases. As the name says, it aims to display the value of the sensors to the user in two different ways:

- A graph visualization, showing the temporal variation of the wavelength of each individual sensor with respect to its resting value.
- A heat-mapped visualization, showing the previously selected 3D model with the sensors placed on it. The area around each sensor changes color depending on the variation in wavelength intensity and sensor type. Orderly by wavelength intensity change, the colors displayed are green, yellow, and red for temperature sensors and light blue, dark blue, and dark purple for strain sensors.

These views are detailed in Figure 5. The buttons reported in the upper bar allow to:

- Choose whether the entire interface must occupy a fixed spatial position or follow the user's head movement.
- Show or hide the two views individually.
- Exit the software.

To improve the performance of the software, the received data is subsampled to reduce the calls to update the graph.

Fig. 4. A picture showing the Monitoring phase of the *PhotoNext FBG AR Viewer* software during the tests carried out. The buttons at the top of the window allow to hide or show both views, fix the window, and close the software.

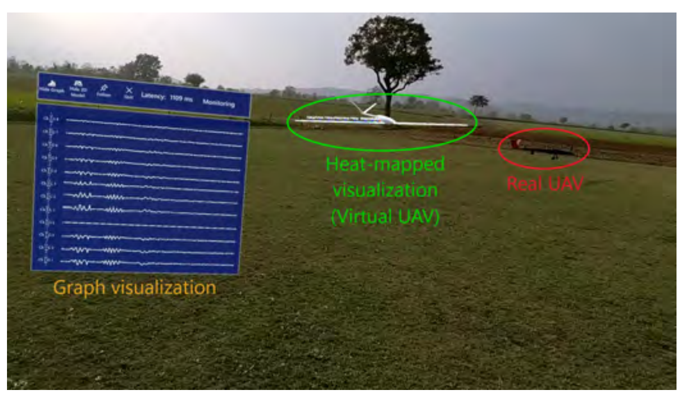


Fig. 5. A picture detailing the different visualizations offered by the *PhotoNext FBG AR Viewer* software.

Fig. 6. A picture of the setup used for the flight test.

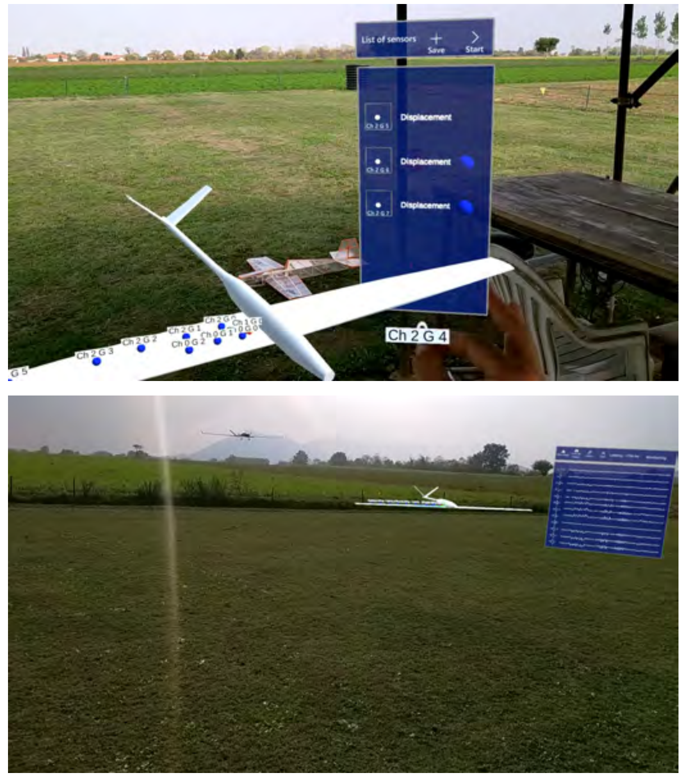


Fig. 7. A picture representing one of the moments of the configuration phase (top) and monitoring (bottom) of the *PhotoNext FBG AR Viewer* which took place during the flight test. It is possible to note that the strain sensors have been positioned along the right wing of the Anubi UAV to reproduce its attitude faithfully.

### *B. Connection*

Sensors data are retrieved directly from the MongoDB-based *Cloud Database*. The connection with it is checked every time the software is started. If this operation is unsuccessful, the software is closed, and instructions are provided for entering the requested data. In particular, the database IP, port, user name, and other data must be entered in the *config* file present in the folder UserFolders\LocalAppData\PhotoNext 3D Viewer\LocalState. Using a configuration file helps simplify the Graphical User Interface (GUI) of the software.

### *C. Release*

As anticipated in Section I, *PhotoNext FBG AR Viewer* is distributed in open source format [19]. It can, therefore, be used as is or modified at will to accomplish the desired task.

## IV. Flight Tests

Basic and advanced lab tests of the *PhotoNext FBG AR Viewer* were conducted in [12] and [13], respectively. Its robustness was further evaluated through four flight tests at the Tetti Neirotti airfield near Turin. Therefore, the software was connected to the physical system, previously introduced as the composition of the Anubi UAV and all components required for in-flight data gathering. The setup for the flight test is depicted in Figure 6. In practice, the flight test is quite complex. First, it is necessary to consider that the optical contribution detected by the instrumentation is not entirely due to mechanical strain, as it is also sensitive to temperature. As a first approximation, it is possible to consider the environmental temperature constant during the flight. That said, the deformation measured by the sensor can, therefore, be considered due to flight mechanics, with multiple loads aging on the wing simultaneously. The same approach used for laboratory tests was also applied for this case: the data shown to the user during experimentation were compared with those saved in the *Cloud Database* and graphed in post-processing. Considering the complex physical background, the simplest output that could be considered is the capability of FBGs to be sensitive to maneuvers, corresponding to a peak in the reflected wavelength values (as already tested in [9]). The output generated by the developed AR system allows to see the variations in the wavelength reflected by these sensors induced by flight maneuvers. In this regard, Figure 7 shows two of the moments relating to the configuration and monitoring phases of the *PhotoNext FBG AR Viewer*. The compressions and tractions that act on the right wing of the Anubis during the four different flights are also clearly visible in Figures 8 and 9, which show the post-processed data from two strain sensors, one located in the upper part and one in the lower part, respectively. Several sensors are on the wing, but for clarity, only two are shown in the plots. In particular, for all the graphs shown, it is possible to clearly distinguish, even without the use of special filters or control logic, the main flight phases. In fact, take-off and landing are clearly visible thanks to the sudden wavelength variation visible at the extremes of the interval. In this way, among other things, it is possible to distinguish the sensors positioned on the back from those installed on the belly of the airfoil. In fact, the former will experience compression (wavelength decrease) while the latter will experience traction (increase). During the flight, the variation of the load factor acting on the aircraft, induced by the different maneuvers and the related accelerations, leads to sudden tensile or compressive loads at the measurement points, as shown in Figures 8 and 9. Finally, it is also possible

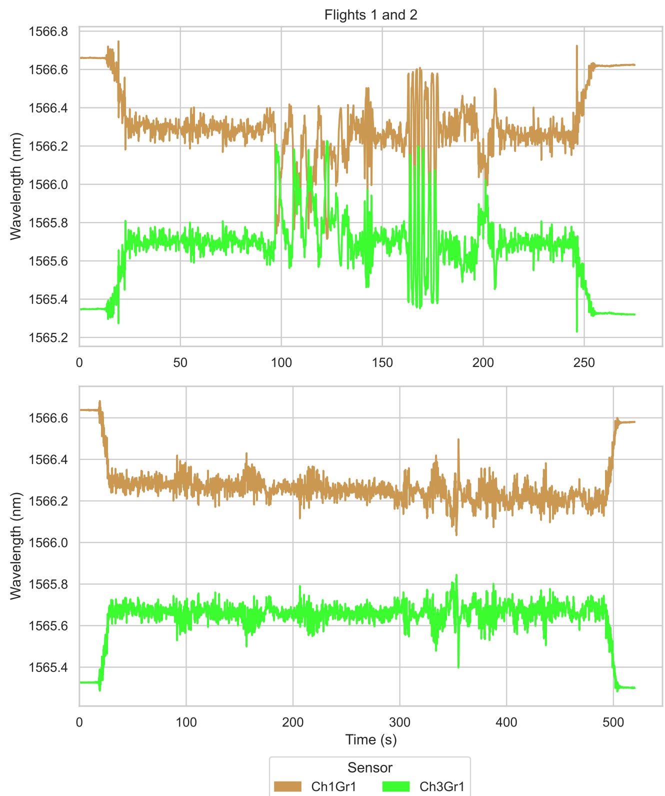


Fig. 8. First and second flight data acquired by two strain sensors, respectively positioned on the upper and lower right wing of Anubi.

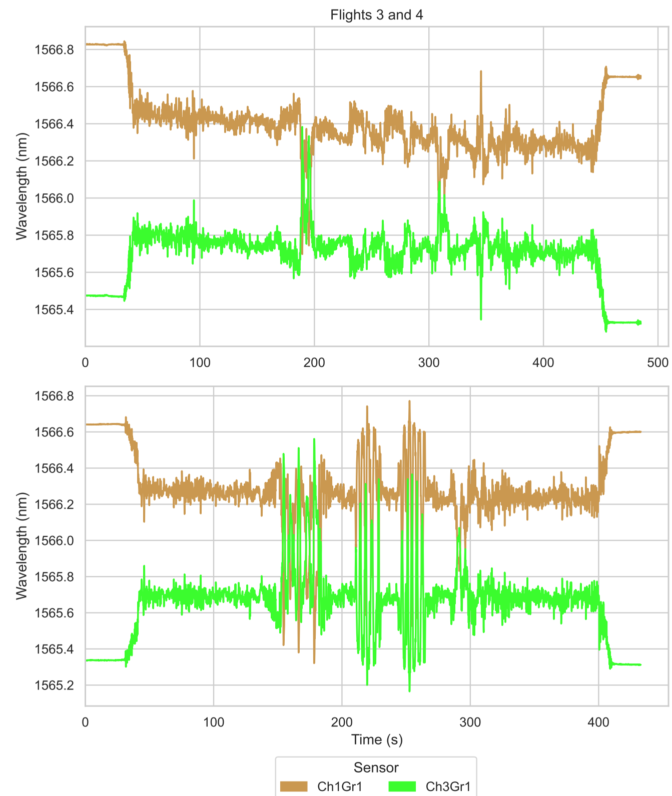


Fig. 9. Third and fourth flight data acquired by two strain sensors, respectively positioned on the upper and lower right wing of Anubi.

to observe a slighter drift in some measures due to thermal variations on the wing.
The ability to visualize sensor data in AR, therefore, becomes a fundamental aspect of UAV performance monitoring. In the near future, in fact, it will no longer be possible to graph in AR the raw trend of sensor data, but directly the information derived from them. Due to the presence of many sensors to monitor on a narrow screen, it cannot be easy to understand in detail the data measured by each sensor. However, the possibility of clearly visualizing the peaks relating to the most stressful maneuvers for the UAV is fundamental to providing crucial information to the pilots.

## V. Conclusions

This paper presented the field tests of innovative software for monitoring FBG data using AR, called *PhotoNext FBG AR Viewer*. It was developed with the aim of increasing the level of situational awareness in monitoring aerospace systems based on fiber optic sensors. This achievement can be considered achieved: at first, data coming from sensors were visualized on the software, and, more in particular, the overall AR interface provided by *PhotoNext FBG AR Viewer* was successfully tested. Furthermore, data from FBG sensors appear useful for more complex algorithms for evaluating flight mechanics' performances. The software has been published in an open-access format. In this way, the entire AR transmission and visualization pipeline is now freely usable by researchers working on the same topics.
In the future, the authors of this paper intend to improve the visualization in case it is wanted to display numerous sensory data, add the possibility of displaying data coming not only from optical sensors but also other typologies, and more.

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