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Sensors and control solutions for Smart-IoT façade modules

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***Abstract*—Measuring the operating conditions of buildings' components is generally applied to technical systems for improving the energy and environmental management, especially exploiting the IoT functions. However, the measuring and connectivity capabilities are not largely applied to the building envelope. This paper presents the development of a sensing and control system integrated into prefabricated envelope elements, with the functionalities typical of an IoT system. In fact, the Smart-IoT façade is based on the idea of transforming the buildings' façade into a IoT device, capable of communicating with external actors: building owner/manager, building management systems or local controller. Given the importance of the façade as interface between indoor and outdoor environments, the possibility of having real-time data on the envelope operating conditions, is significant to improve the building operation, in terms of comfort and energy efficiency, enabling the adaptive or intelligent façade concept. To this aim, the RenoZEB project is developing a plug&play façade module for building renovation, with embedded sensors and actuators. The module with the sensing architecture is completely assembled off-site, reducing the amount of work to be done on-site. Once installed and configured, the module sends data to a IoT platform, that makes them available for third parties. Different configurations of sensors/actuators can be developed. Among them, this paper presents a solution to optimize the control of windows' shadings. Thus, the façade sensing system has been integrated with an advanced controller that aims at optimizing the shadings position to provide the maximum comfort but allowing the right amount of solar radiation to pass through the windows.**

***Index Terms*—Sensors, IoT, Intelligent façade, Shading Control**

I. INTRODUCTION

This paper presents the design and development of the Smart-IoT façade module, capable of measuring the operating conditions of the building envelope to allow functionalities typical of a smart and adaptive façade, suitable for buildings' renovation. Smart façades already exist in the market, but they are suitable for new buildings or as building automation components to be installed on-site after the renovation [13]. The innovation of the proposed approach is that the façade module becomes itself an ICT component that is completely assembled off-site, ready for plug&play installation and configuration for internet connection to start sending data to the cloud. The data can then be available for different purposes: local optimal control of the building systems, calibration for energy analysis, maintenance or optimization of the monitoring system [1]. It is widely known that increasing the measurements capabilities and data availability in buildings could bring to improved indoor environmental conditions and energy efficiency [2]–[5]. Within the RenoZEB project [6], the module has been designed, and sensors configured to measure the outdoor solar radiation and illuminance to allow the implementation of an advanced shadings controller. The adoption of adaptive façades is important because as said in [7] "Adaptive building envelopes can provide improvements in the building energy efficiency and economics, through their capability to change their behaviour in real time according to indoor-outdoor parameters, by means of materials, components and systems. Therefore, adaptive façades can make a significant and viable contribution to meeting the EU's 2020 targets.". The building façade is the main interface between indoor and outdoor environments, where the scope is to guarantee the optimal comfort for the occupants but maximizing the energy efficiency. The capability of managing the amount of solar radiation and external air inlet has a significant impact on the final building energy consumption. For example, the use of active automatic on/off shadings and lighting control can result in 77% reduction in electricity demand for lighting and 16% reduction in annual cooling demand [8]. The study performed by Wen at al. in [9] showed that the implementation of sensors and actuators network for active shadings control provides an energy savings up to 57% in lighting electricity and 28% reduction in cooling demand. Similar results were achieved also in [10], where the performance between active and passive façades were compared. Although the proven evidence of benefits from the adoption of active façades, the recent analysis performed by the COST Action TU1403 "Adaptive Façades Network" [11] revealed a very low adoption of such technology in the construction sector. Several barriers were identified to justify such reality and to provide guidelines for future researches that should solve the actual challenges. First of all, there is a problem of trust and acceptance. Occupants tend to prefer manual control, considering automatic moveable shadings as a source of discomfort [12]. In addition, the complexity of adaptive façade solutions and smart sensing and control technologies is another barrier that deters a wide adoption of controllable façades. In fact, each solution requires a strong effort for the fine-tuning due to local conditions and characteristics that vary in function of the location, end-use, construction typology and social/cultural rules. One of the main issues revealed in [13], [14] is that the classical way to monitor adaptive facades is based on ad-hoc measuring approaches that are not integrated within the façade. In fact, sensors are introduced in the façade after the construction, even when a building management system is used. This is more evident when considering existing buildings, because of the difficult installation and connection with the system (power supply and data transmission). Thus, it can be concluded that there is a disjunction between the façade and the rest of the building. One conjunction point can be created thanks to the large diffusion of IoT technologies in buildings, enabling advanced functionalities and easy communication between different components of a smart building [15]–[17]. The IoT paradigm is based on the idea that things can be connected and exchange data. Thus, the main prerequisite is that an IoT device has to include an interface enabling the connection to a local or wide network. This is largely applied to several buildings components as thermostats, appliances, split conditioners and many others. The data acquired from the connected devices are then used for the optimal management of the building by centralized control systems (BMS) or by autonomous interaction with the occupants through mobile devices. Thus, the adoption of the IoT approach could spur the adoption of adaptive façades. To answer the research question resulting from the literature analysis, RenoZEB develops the concept of the Smart-IoT façade module, derived from the experience presented in [18]. The proposed technology aims at transforming the façade module into an IoT device, connected to transmit the data measured from embedded sensors. The module is designed to integrate natively the required device and ready for a plug&play installation for existing buildings.

II. Concept of the Smart-IoT façade and sensing functionalities

The Smart-façade is based on the concept of façade elements with embedded sensors and actuators, converting the building envelope into an intelligent component, interoperable with building management systems and other third-party systems (Fig.1). The core of the system is the DAQ (Data Acquisition) system, that allows the acquisition of sensors signals, the data storage and transmission through the network. The designed solution, with sensors selected for the project scope and results from initial testing activities are presented.

A. Design of the data acquisition and transmission system

The DAQ has been designed to fulfil the requirements of signal acquisition and connectivity typical of an IoT system. The module has been developed starting from the commercial solution named "Gevino Opto", an industrial and certified (CE) version of the Arduino Zero board. In collaboration with the manufacturer, a customized version of the board has been developed to satisfy the requirements for the Smart-IoT façade, as shown in Fig.1.

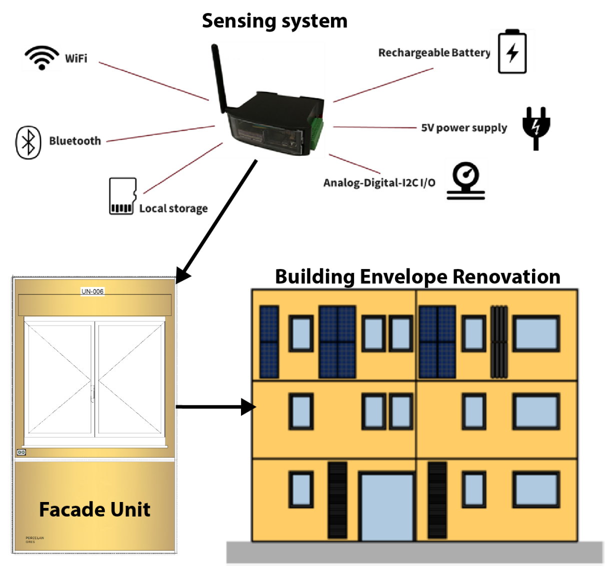

Fig. 1. Smart-IoT facade concept.

The board provides three main channels for communication with external devices:

- WiFi: the ESP8266 wireless module is integrated in the board supporting 802.11 b/g/n protocol;
- Bluetooth: the HC-06 Bluetooth module is integrated in the board for a direct connection with other devices (e.g. smartphone, BMS etc.) to send measured data or to provide an interface for local configuration of the Smart-IoT façade;
- Serial with USB: the micro-USB port is available for serial communication with BMS, e.g. using a USB-RS232/485.

The WiFi communication protocol has been included in the first prototype, but other approaches could be applied, such as LPWANs. The power supply can be configured according to the project requirements and available power sources. The IoT paradigm aims at maximizing the possibility of making a device as much as possible stand-alone. For this reason, the DAQ system integrates a battery that, together with the wireless connections, makes the system potentially capable of autonomous operation. A PV panel can be connected to the system to provide the input voltage. Given the discontinuous availability of the sun and consequently of the PV power generation, the battery allows the continuous operation even during periods when no sun is available.

B. Sensors

The DAQ system has been designed to guarantee the maximum modularity. This means that most of the sensors generally used for buildings monitoring (e.g. temperature, humidity, solar radiation, CO2 etc.) can be configured and connected to the system. Measured data can then be made available interfacing the cloud platform. The monitoring configuration depends on the intended use of the Smart-IoT functions. In the case of RenoZEB project, an intelligent controller of buildings' shadings is under development and it will benefit of the Smart-IoT façade to get the data required for shadings actuation. The scope of the controller is to maximize visual comfort while optimizing the solar gain control. The data required for the control are thus related to the outdoor conditions: solar radiation and illuminance. For the first one, the Apogee Instruments SP110 pyranometers have been chosen. They consist of a cast acrylic diffuser (filter), photodiode, and signal processing circuitry mounted in an anodized aluminum housing, and a cable to connect the sensor to a measurement device. Sensors are potted solid with no internal air space and are designed for continuous total shortwave radiation measurement on a planar surface in outdoor environments. The sensor output is an analog voltage that is directly proportional to total shortwave radiation from the sun. The voltage signal from the sensor is directly proportional to radiation incident on a planar surface, where the radiation emanates from all angles of a hemisphere. The Apogee SE100SS has been selected for the illuminance measurement, which is based on photodiode. The construction characteristics are similar to the SP110, described previously, allowing the outdoor installation. Table I presents the sensors' detailed characteristics. Both the selected sensors are passive and this characteristic is fundamental to minimize the overall power consumption of the proposed solution, especially when operating in battery-mode.

TABLE I
METROLOGICAL CHARACTERISTICS OF THE SELECTED SENSORS

	SP110	**SE110SS**
Sensitivity	0.2 mV per Wm-2	0.001 mV per lx
Calibration factor	5 Wm-2 per mV	1000 lx per mV
Calibration uncertainty	±5%	±5%
Calibrated output range	0 to 400 mV	0 to 200 mV
Measurement range	0 to 2000 Wm-2	0 to 200 klx
Measurement repeatability	Less than 1%	Less than 0.5%
Non-linearity	Less than 1%	Less than 1%
Response time	Less than 1 ms	Less than 1 ms
Field of view	180°	180°
Spectral range	360 to 1120 nm	CIE 1931 luminous efficiency function

III. INTEGRATION WITH THE IOT PLATFORM

Any IoT device requires an interface with a platform that allows the data collection together with analytics capabilities. ThingSpeak is an IoT analytics platform service that allows to aggregate, visualize and analyze live data streams in the cloud. The firmware developed for the DAQ allows the connection to the ThingSpeak server to write measured data into the channel. The HTTP GET or POST methods can be used to send data to the platform. To do that, the device has to be connected to the ThingSpeak API starting a TCP connection to the server "api.thingspeak.com", port 80. Then, using the auto-generated Write API key of the channel that is stored in the channel control panel, the user can write data in the channel fields with the following GET command, where the 16 characters of the API key have been substituted by a series of X:

```
GET /update?api_key=XXXXXXXXXXXXXXXX&field1=13&field2=43
```

The above command will write the value 13 in the first field of the RenoZEB channel that has been dedicated to the solar radiation, and the value 43 in the second field of the channel, dedicated to the illuminance. ThingSpeak stores all the information in one central location in the cloud with easy access for online or offline analysis. Private data is protected with an API key that is managed by the account administrator. Once logged into the ThingSpeak account, the user can use the web to securely visualize and download the data stored in the cloud. Data can also be read programmatically in CSV or JSON formats using a REST API call and the appropriate API key. Other devices can also read data from a ThingSpeak channel by subscribing to an MQTT topic. Data can also be imported from third-party web services including climate data, public utility data from local utility providers.

IV. PROTOTYPE TESTING IN A REAL CASE STUDY

A complete prototype of the sensing system to be embedded into the RenoZEB façade module has been developed and tested. Fig.2 shows the prototype configuration.

Fig. 2. Configuration of the prototype tested in the laboratory of UNIVPM.

The calibration with reference sensors in the laboratory environment was the first step of the testing. This turned out to provide an uncertainty of ±31 Wm^{-2} and ±68 lx, for solar radiation and illuminance sensor respectively. After the calibration, the prototype was tested in real conditions at Università Politecnica delle Marche, building settled in Ancona, Italy (Latitude: 43°35′15" N; longitude: 13°31′ 01" E; altitude: 140 m). Several testing sessions were done, applying sensors to different façades of the building. Fig.3 shows the data measured in October 2018, during a cloudy day, with sensors installed on the outdoor side. Measurements were performed on the east façade in the morning and west façade in the afternoon; data were acquired and sent to the IoT platform with a sampling time of one minute.

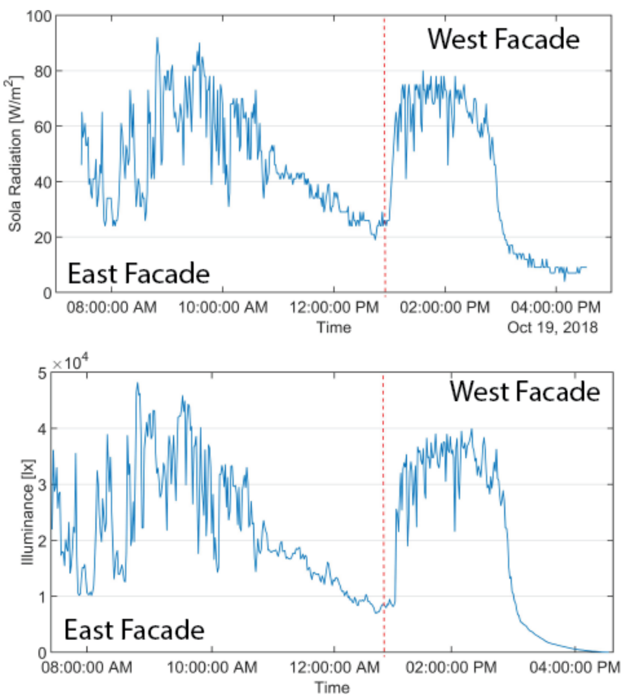

Fig. 3. Solar radiation and Illuminance measured on outdoor East and West façades.

The results from the prototype testing suggest that the system is working properly, according to the specification required by the project.

V. Application to Shading Control

The new sensors are applied to control the shading device of the Smart-IoT façade. Bueno et al. [19] proposed a workflow to develop control strategies for shading devices. The proposed workflow is based on the analysis of the façade from the point of view of its functions (daylight provision, glare protection, solar heat gain management, etc.) and on the application of state-of-art thermal and daylighting simulations of one room.

This workflow was used to develop control strategies for two of the case studies of the RenoZeb project, a residential and an office room in the region of Bilbao (Spain). In both cases, when the room is unoccupied, the algorithm is in energy efficiency mode. It compares the measured indoor temperature with a temperature Poinsett in order to decide whether to activate the shades during day blocking solar heat gains or to deactivate them during night enhancing heat transfer through the window. When the room is occupied, the algorithm prioritizes user comfort. A minimum daylighting level must be reached before the shade is closed. Once the daylight condition is fulfilled, the algorithm checks the indoor air temperature for both the office and the residential rooms. Additionally, the algorithm for the office also checks the maximum vertical illuminance to prevent glare.

The control algorithm developed by Bueno et al. takes the average horizontal illuminance and the maximum vertical illuminance as controlling variables. Indoor illuminance is, however, difficult to measure. Ceiling illuminance sensors depend on the reflection properties of the surfaces of the room and, therefore, provide different values for different uses of the room. Horizontal sensors interfere with the use of the room and can be disturbing. On the other hand, irradiance or illuminance on the façade is available through the sensors embedded in the façade module.

The approach followed in the RenoZEB project is to correlate indoor illuminance with measured irradiance on the façade. These two variables correlate well for a given scenario (room and window geometry, building orientation, location, etc.). As a result, a new correlation has to be generated for each new case study. For the residential and office case studies, a set of simulation with the Fener tool [20] are carried out to correlate the indoor illuminance (controlling variable) with the incident solar radiation on the façade (measured variable).

Figure 4 shows the relationship between average horizontal illuminance with the solar radiation on the façade for the office case study. The graph shows two different sets of data points, which correspond to the time-steps in which the shades are closed or opened, according to the control algorithm. That means that the algorithm has two different irradiance set-points for the same illuminance set-point depending on whether the shades are closed or open. Two different functions for opened and closed shades are generated based on the correlation of average work-plane illuminance and the solar irradiation.

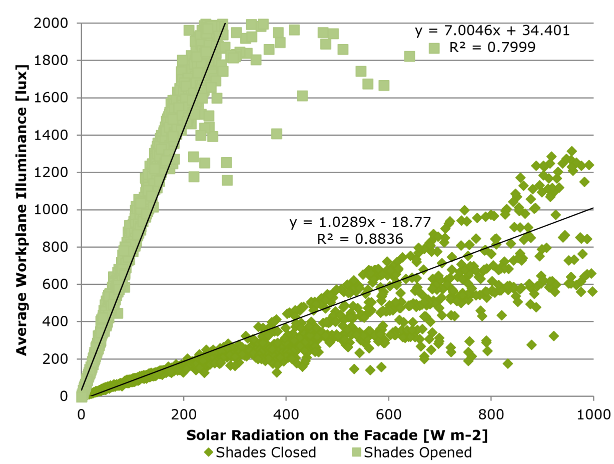

Fig. 4. Relationship between the average horizontal illuminance and the irradiance on the façade for the office case study in Bilbao. Data points represent time-steps of the simulations.

When the shades are closed, the correlation is given by (1):

$$i = 1.0289I - 18.77 \quad (1)$$

When the shades are opened, the correlation is given by (2):

$$i = 7.0046I - 34.301 \quad (2)$$

Where I is the solar radiation on the façade [W/m^2] and i is the average work-plane illuminance [lx]. The same approach is applied for the vertical illuminance in the office room and for the horizontal illuminance in the residential case study, obtaining different correlations between these controlling variables and the measured irradiance on the façade.

In principle, the new control algorithm can be designed with the irradiance set-points that corresponds to the illuminance set-points for the closed position of the shades or the one for the open position. However, some of the resulting irradiance set-points are too high or too low for control decisions. The resulting control algorithms for the office and residential cases are described in Table II. To evaluate the impact of the proposed retrofit solution as compared to existing baseline scenario, dynamic simulations have been run with the Fener tool considering an office and a residential building. In the baseline scenario, the roller blinds are activated according control algorithms described above. For the office case, by taking into account only the occupied hours, the results indicate that the application of the exterior roller blind would provide an important reduction of cooling energy demand (63%). For the residential case, the results indicate that the application of the exterior roller blind would result in a reduction of both heating energy demand (13%) and lighting energy demand (58%). The application of the IoT solution allows the façade controller to be remotely run. In the RenoZEB project, the controller will be run at one of the servers of Fraunhofer ISE. This has the advantage that the controller can be continuously maintained and updated by the developer without having to travel to the installation site. The controller will be run every 5 minutes. For every cycle, the controller reads monitoring data from the IoT server by using JavaScript Object Notation (JSON) file formats. The controller then runs the control algorithm to determine the state of the shading device that fulfils the given conditions. If the new state is different from the current one, the resulting state is sent back to the IoT server and to the actuators.

VI. Integration of the monitoring system into the façade module

The integration of the measurement solution fits with the characteristics of the RenoZEB envelope system to create the concept as presented in 5. With the purpose to create a Smart-IoT façade within the RenoZEB envelope solution, it was fundamental to identify the most valuable solution for the integration in line with the ongoing activities of the RenoZEB system design. The final goal is to develop a plug&play, multifunctional and prefabricated solution that could maximize the operation off-site and reduce the operation on-site and with this purpose, the RenoZEB envelope system has been designed as an unitized system, composed by many unit typologies, each one including different components and the Smart-IoT façade module is one of the possible configurations. The designed solution is a unit with a window, installed in a monoblock with a roller blind and related actuator. The sensors are installed inside an external electrical box that could guarantee a high level of water tightness; for this reason, an electrical box with IP64 has been used. The box guarantees the removal of the external lid to be inspected. The lid has two slots for the sensors that guarantees the functionality together with the protection from mechanical impacts, during the envelope manufacturing, transport and installation. The outdoor box is connected to the inside of the building through and electrical conduit Ø 27 mm where the sensors' cables pass through and with the capacity to be adapted because of its ability to be bent. This electrical conduit installed inside the unit can guarantee the removal of eventual damaged sensors as well as the introduction of new cables for new sensors in case of further sensors embedding. The electrical conduit arrives to an internal electrical box with a DIN rail to host the transformer and the DAQ. Most of the operation are done off-site, during the manufacturing process, and the on-site activity consists only in plugging the unit and complete the required wiring.

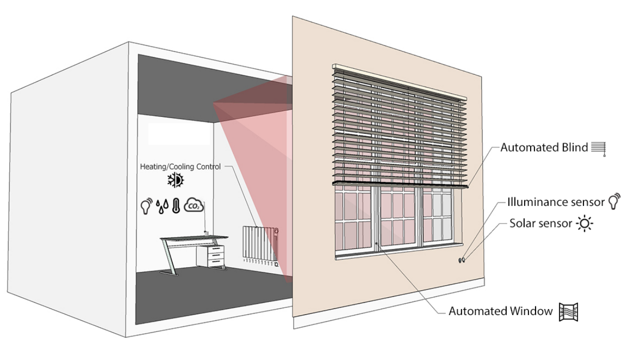

Fig. 5. Concept of the façade with embedded sensors and actuators.

VII. Conclusions

This paper described the preliminary ideas and developments of the Smart-IoT façade. The scope is to convert the façade module into an IoT device, capable of communicating with external actors (users or devices). The concept and the functionalities have been described, considering all the specifications required from the module. The DAQ system has been designed to acquire different types of sensors and to interface with external systems through wireless connections. The configuration proposed in this paper entails two types of passive sensors to measure solar radiation and illuminance, but other sensors can be used. The sensing solution has been interfaced with a IoT platform (ThingSpeak), making the data accessible by third-parts devices or users. Laboratory tests have been performed together with application similar to real-cases. Results showed the capability of the system to perform the required functions. To enable the deployment also a typical function of an adaptive façade, an advanced control strategy to optimize the shadings actuation has been developed. The controller is based on the Fener simulation environment and relationships to maximize occupants' comfort and energy efficiency have been derived for the location of Bilbao, where the complete prototype will be tested. Simulating a residential and an office environment, significant energy savings have been predicted for the cooling, heating and lighting energy consumptions. Finally, one of the façade units developed in RenoZEB has been re-designed to embed the DAQ and sen-

TABLE II
CONTROL ALGORITHMS OF THE FAÇADE SYSTEM WRITTEN IN PSEUDO-CODE.

Office	**Residential**
if occupation:	if occupation:
if irradiance on the facade $>$ 40 W/m^2:	if irradiance on the facade $>$ 192 W/m^2
if indoor air temperature $>$ 25°C or irradiance on the facade $>$ 388W/m^2:	if indoor air temperature $>$ 23°C:
CLOSE	CLOSE
else:	else:
OPEN	OPEN
else:	else:
OPEN	OPEN
else:	else:
if daytime:	if daytime:
if indoor air temperature $>$ 25°C:	if indoor air temperature $>$ 23°C:
CLOSE	CLOSE
else:	else:
OPEN	OPEN
else:	else:
if indoor air temperature $>$ 25°C:	if indoor air temperature $>$ 23°C:
OPEN	OPEN
else:	else:
CLOSE	CLOSE

sors. For the sensors and external enclosure has been included, facilitating the maintenance operations, connected with the inner side to allocate the electrical conduit. The DAQ has been located in the inner side, connected with the external box. Most of the operation to embed sensors, actuators and DAQ will be done during the manufacturing of the façade panel, reducing the on-site operations. Simple plug&play actions will be required to install the panel, and after a quick configuration to connect the module to the local WiFi network, the system starts to save data on the IoT platform. Starting from the design and testing results, the first complete prototype is going to be manufactured and installed in the Kubik laboratory building for detailed performance assessment and investigations about the reliability of the WiFi communication infrastructure. Further development will be done to include other communication infrastructure such as LPWAN to avoid potential interferences with the devices commonly used in residential buildings.

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