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A fuzzy-logic IoT lighting and shading control system for smart buildings

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ABSTRACT

The paper introduces a working prototype of an IoT system which controls natural and artificial light balance in combination with a dynamic shading system. The proposed solution adopts a scalable approach to smart system integration in buildings based on sensing and actuating nodes (Arduino-driven) and on a main unit (Raspberry-driven). A control App is developed to allow user interaction by setting seasonal automatic modes or manual functionalities. The required illuminance threshold may be changed, while the shading system acts in accordance with seasonal profiles in line with bioclimatic design principles. The control system adopts a fuzzy logic solution which is able to ensure fast control without high computational effort. Preliminary tests of the developed prototype are reported showing its main functionalities and its ability to maintain the required illuminance even in high variance conditions by adjusting both shading and lighting in less than 100 s. Currently, the solution has reached TRL 3.

1. Introduction

1.1. General background

Smart technologies are changing the building sector by re-defining building energy behaviours and control approaches. Their ability to optimize energy consumption and guarantee comfort levels and user involvement via interfaces is a recognized essential factor as outlined in recent modifications to the EU directive EPBD recast on building energy performance – see [1,2]. In fact, the latest EPBD version [3] asks for advanced modalities to include smart sensors and actuators in energy modelling and in the labelling approach which describe energy building behaviour and its smartness index. The impact of ICT and IT on building design and operation is recognized and culturally discussed, suggesting an urgent need for re-engineering and re-designing current visions and technological paradigms – see for example [4–8]. Furthermore, the interest in training present and future generations of *digerate* engineers and architects has resulted in the activation of new university courses which focus on ICT-in-building-design and which are of interest to different profiles, from telecommunication engineers to designers. This educational effort is in line with recent innovative approaches towards intelligent buildings, including the efforts to make building technologies responsive and even proactive with respect to the surrounding environment. The development of these approaches in the building sector faces several challenges including: i) the adoption of IoT (Internet of Things) applications (e.g. [4,44]); ii) the integration of low-cost microcontrollers, e.g. Arduino, and computers, e.g. RasperryPi, into building control systems that increase their scalability and the adoption of intelligent control models (e.g. [28,44]). Finally, there is a need for iii) studies at prototype or real building operational levels, given that most control model research on the topic is based on advanced simulations and doesn't include the development of the hardware-software systems to run the checked models, as pointed out by several authors (e.g. [29,43,48,50]). The proposed paper aims at working on all these three aspects. As regards IoT solutions, a growing interest is evident. It is, for example, possible to mention the study of Jung et al. [9] in which wireless sensor technology is applied to building environmental monitoring supporting the development of IoT systems connecting node trough wireless applications. Focusing on Arduino and other simple solutions, a large differentiation in potential outputs is evident. Here below several examples of different prototype developments are reported. Remaining on the topic of wireless applications and on energy efficiency, Noye et al. [10] describe a prototype system to analyse post-occupancy measurements (thermal and ventilation purposes) which combines Arduino and commercial solutions in order to maintain comfort conditions while reducing energy needs in real building operations. As regards IAQ comfort issues, several prototypes have been implemented. For example, Chiesa et al. [11] introduce

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Nomenclature

EPBD	Energy Performance of Buildings Directive
ICT	Information and Communication Technologies
IoT	Internet of Things
MQTT	Message Queue Telemetry Transport
URL	Uniform Resource Locator
IDE	Integrated Development Environment
DC	Direct current
I2C	Inter-Integrated Circuit
MCU	Micro-Controller Unit
FL	Fuzzy logic
IAQ	Indoor Air Quality
TVOCs	Total Volatile Organic Compounds
RH%	Relative Humidity
ACK	Acknowledgment
JSON	JavaScript Object Notation
PWM	Pulse width modulation
MOSFET	metal–oxide–semiconductor field-effect transistor
NodeMCU	a low-cost open source IoT platform – node micro-controller unit
PID	Proportional integral differential
TRL	Technology Readiness Level

an innovative solution aimed at controlling fan-driven ventilation to ensure indoor air quality by acting on several indicators at the same time (TVOC, CO_2, RH%, Temperature). This system is controlled through a multi-purpose app interface which informs users thanks to a colour scale and allows building managers to define and monitor pollutant levels and thresholds. Another interesting prototype study in the building sector deals with the development of a smart exit signal system based on Arduino which adopts a serverless solution [12]. This study aims at resolving some of the difficulties connected with server-independent exit signals, such as signal transferability through obstacles. Finally, to highlight the great potential of applications under study, we should mention an interesting prototype development to clean façade windows with robots by adopting, among others, stepper motors and LIDAR distance sensors to support module movements [13]. From among the wide range of applications, this paper focuses on developing a smart lighting system which is connected to smart façade solutions. The developed prototype aims at connecting a natural-artificial-light-balancing approach with a smart shading system positioned on the building façade.

1.2. Lighting and shading system background

Lighting is a major energy consumer in buildings, representing about one-third of the electricity needs in commercial buildings and even more in office buildings [14,37]. Even if outdoor light levels generally go above and beyond the illuminance-required threshold for indoor activities during the most of the day, the exploitation of this potentiality to reduce electrical consumption of lighting systems has only partially been reached [15]. However, several approaches have been developed to boost potentiality by adopting control systems – see for example the works of Wang [16] and Sinopoli [17] –, even if the control of natural lighting levels entering indoor spaces has to be accurately balanced during the summer season to prevent the risk of overheating. There are geometrical and physical characteristics of transparent building surfaces defined during the building design phase which are fundamental to providing daylight in confined spaces. As highlighted in several studies concerning window-to-wall ratio – see for example [18,19] –, the increase in natural light will directly reduce lighting energy consumption and, if there is a correct balance between insulation and solar gains, heating demand, even though it may negatively affect cooling needs. Tzempelikos et al. [40] study the implication of exterior roller shadings – design and control issues – on space lighting and cooling energy needs and show a high potential reduction by using dynamic simulations. As noted in a recent parametric study, by connecting lighting, cooling and heating energy needs with envelope characteristics thanks to massive dynamic energy simulations [20], shading control solutions can increase the optimal window-to-wall ratio thus allowing for excellent winter performance combined with good summer performance if the proper controls are in place. As regards shading systems, fixed solutions (e.g. overhangs, side fins, fixed blinds, see the classifications in Grosso [21] and Bellia et al. [22]) are the ones that are most commonly used all over the world. Nevertheless, fixed shadings are designed basing on seasonal analyses which combine winter solar access and summer solar protection based on relevant days and hours (solstices) – see for example the approaches described by Olgyay and Olgyay [23], one of the first references on the topic, or the overview reported by Voss et al. [24] – and do not allow for operational control. Dynamic shading solutions allow for smart and dimmable control of incoming light and solar energy in relation to outdoor conditions, daylighting demands, and solar altitudes, while maximising occupant comfort, including glare protection, and energy savings [25]. Most movable shading systems are manually controlled though manual operation results in insufficient blind activation in the short-term thus reducing their effectiveness [38], especially to adapt to variations in solar radiation [49]. For this reason, automatic control solutions may be required [39]. A recent study of prediction models to define people's behaviour in lighting and shading control in single offices is presented by Ding et al. [51] underlining the differences among user behaviours. Similarly, Sadeghi et al. [52] demonstrate, by adopting a Bayesian modelling approach, that human attributes are an important factor in predicting human interaction and behaviour. On the other hand, as regards automatic control systems Al Touma and Ouahrani [41] state that shading controlled systems acting on blind angles may reduce lighting energy needs by 26.1%, by applying EnergyPlus simulations to test shading controls on validated office space models. The paper suggests that it would be important to control shading systems following an energy balance approach (cooling, heating and lighting). The same space model was also used to simulate in EnergyPlus the reduction in energy needs for different orientations when lighting is linearly dimmed and shading blinds are controlled to avoid discomfort glare by blocking direct solar beams entering the space [42]. Results show a good energy saving potential even for fully-glazed facades. From among the possible movable shading solutions, the development of dynamic façade systems is growing worldwide. Properly designed and smart controlled shading systems can, in fact, improve visual and thermal comfort as well as remarkably reduce electric lighting, cooling (solar gain prevention), and heating (solar gain maximisation) energy consumption, as illustrated by Lee et al. [26]. For example, Chi et al. [39] introduce a new automatic shading system based on 3-rotation directions, by analysing its performance using ArchiWIZARD and EnergyPlus, but without including hardware solutions. Kunwar et al. [43] adopt a closed-loop to dim lighting and control a roll blind system by testing control strategies based on work plane illuminance and vertical illuminance sensors in full-scale experimental rooms. The effect on energy needs is also analysed showing a high saving potential when minimal and maximal illuminance thresholds (1830 lx) are adopted following a UDI (useful daylight illuminance) approach. An upgrade of the work including venetian blinds and solar angle profiles to reduce second reflections has recently been reported by Kunwar et al. [48]. Shen and Tzempelikos [46] have also studied the positive impact of introducing a maximal illuminance threshold (2000 lx) to control visual comfort.

The importance of maintaining low illuminance values which are not sensibly higher than assumed comfort thresholds is also underlined in Sadeghi et al. [53], who look at human interaction with respect to different control solutions. Their work also underlines the importance of adopting interfaces which connect control systems and users. These two issues are considered in the current paper. A recent study by Elzeyadi [27] helps to classify existing dynamic shading typologies, by defining 6 classes based on the adopted technologies. Similarly, a review study on dynamic shading systems including evaluation strategies and platforms was recently reported by Al-Masrani and Al-Obaidi [28] in consideration of both a design geometric-based analysis and a performance-driven approach. Real and prototype cases are discussed, including roller shades, louvres, venetian blinds, vertical fins, folding panels, kinetic cladding, 3D origami shades, and grid-based systems (e.g. honeybee structures). This study deals with the technological and architectural issues related to dynamic facades. The authors underline that additional studies on this topic are needed including the development of evaluation methods that are based on climatic data and controls in order to satisfy comfort requirements. Finally, the urgent need to develop additional control systems which adopt low cost hardware, such as Arduino microcontrollers is focused on. Similarly, the recent review of current and future trends in lighting control systems by Wagiman et al. [44] underlines the need to develop studies which include mobile-device integration – user communication and interaction on thresholds, for web-interfaces see also [53] –, IoT solutions, cloud computing and the adoption of solutions which can be run on single-board computers (e.g. Raspberry Pi and similar). Additionally, as regards control systems, the authors classify lighting controls in three main technological categories: conventional controller (e.g. PI, PID) – e.g. [16,48] –, intelligent controllers (optimisation-based), and hybrid controllers. Intelligent controllers include learning-based methods (e.g. fuzzy systems [55–57], neural network, regression) and model-based control (MBC) methods – e.g. [45,46,54]. Future trends are underlined especially in the development and hybridization of intelligent controllers, a topic that is also underlined by other authors, e.g. [50]. The study of Motamed et al. [55] adopts a new vision sensor (High Dynamic Range) and indirectly tests the usage of a Fuzzy Logic (FL) approach using survey results. FL is defined as a decisional filter action which is tested in an advanced case that behaves 32% better in electricity demand terms than a reference control test room. The authors also test the high dynamic range sensor and FL in a long term validation study [56] showing good potentiality, even if they stress that the FL open-loop control may require tuning processes when installed in a new space. Motamed et al. [57] recently reported a further study which combines open/closed loops in FL and demonstrates very good potential in FL-driven intelligent control systems. Nevertheless, they point out that additional work, e.g. considering seasonal behaviours, is needed on FL applications. The review paper by Jain and Garg [50] also underlines the need to integrate real-time information, and develop scalable working prototypes and quick responsive algorithms. They also state that one of the major challenges in current lighting and shading control studies is the gap between advanced-simulation-based research and applications. Additionally, an analysis of the impact that prototyping has on the development of dynamic smart building envelopes is reported by Kim and Kim [29]. The mentioned study demonstrates the importance to develop prototypes in order to fully test ideas behind sole simulation approaches. Prototypes are identified as an essential phase in novel system design development, allowing to analyse technological validity since low TRL (technology readiness level) levels. The adoption of scale prototypal models has also been demonstrated to act as a good representation of real rooms for lighting and shading control strategies by Yun et al. [47], while the importance of testing the real-world applicability of shading and lighting control systems has also been underlined recently by Kunwar et al. [48].

1.3. Paper's objectives

This paper mainly focuses on the development and the prototype implementation of a lighting IoT control system which controls shadings and artificial lighting sources, in order to guarantee comfort conditions, reduce artificial lighting energy needs, and act on solar heat gains by maximising them in winter mode and minimizing them in summer mode to prevent overheating. More specifically, five implementation goals have been defined:

i. Develop a shading system to measure and control internal daylight intensity for visual comfort control by adopting a fuzzy logic approach to ensure fast response and low computational power;
ii. Design and build a LED lighting system which can be operated by three control modes: manual and automatic mode for the winter season and automatic mode for the summer season in line with a seasonal approach to lighting/sun control;
iii. Integrate the shading and lighting system into a functional prototype to check and solver hardware and software connection issues;
iv. Adopt and test the possibility to use Arduino and single-board computers (RaspberryPi) to drive an IoT lighting/shading control system;
v. Develop a mobile application to allow users to control both lighting and shading systems by defining seasonal modes (automatic summer/winter modes), changing illuminance threshold, and/or setting manually led intensity (PWM) and shading positioning (manual mode).

In addition, the IoT proposed solution has been defined in order to be scalable, replicable, and potentially adaptable to different specific technologies (e.g. the types of lamps used) and spaces. As mentioned in the previous sections about the state-of-the-art, these objectives are directly connected with current open issues in lighting control system development. Unlike other studies reported in Section 1.2, the proposed paper includes the development of a prototype hardware sensor/actuator system, which is part of the proposed methodology that includes IoT aspects. The Technology Readiness Level (TRL) indicator [36] is adopted to describe the maturity level of the developed technology on a 1 to 9 scale, where the lowest level represents basic principles of a certain technology and the highest level is for technologies that have reached commercialization. In the present work, objectives will be pursued to reach a TRL level of 3, which corresponds to “Analytical and experimental critical function and/or characteristic proof-of-concept”. For this reason, current testing results refer to the already mentioned TRL level.

The paper is organised into a methodological section (Section 2), which describes methodologies and prototype development, while results of the testing phase are reported and discussed in Section 3. A conclusion and future work section is to be found in Section 4. Section 2 (Proposed methodology) is divided into 2 sub-sections which deal with system framework and control logic (Section 2.1), and prototype development (Section 2.2). In particular, Section 2.1, System framework and control logic, defines the whole system framework (main process unit in Section 2.1.1; sensing/actuating subsystem nodes in Section 2.1.2) and its logic including control system definition (Section 2.1.3), and how the compatibility of the different subsystems before their integration is ensured. In this section, the newly developed control logic is described for both shading and lighting systems in order to cut energy needs by reducing solar heat gains during summer and maximising them during winter as well as strategically using daylight to reduce the need for artificial lighting. Section 2.2, describes the methodologies which are adopted to develop each part of the prototype. In particular, Section 2.2.1 focuses on the shading system and describes the developed blind structure which is used to control the amount of light entering the considered space – i.e. the box prototype – and which is controlled by a stepper-motor system. In this section the implemented

control scheme to test the system before its integration with the lighting system is also defined. In Section 2.2.2 the lighting system is defined. Both the artificial lighting sources – i.e. LED system – and the illuminance sensor system (luxmeters) are described together with the adopted control scheme. Furthermore, Section 2.2.3, Mobile Application, describes the design and implementation of a mobile application that allows users to operate the overall system by providing different control modes and thresholds. Finally, Section 2.2.4, Integration and Testing, is devoted to describing the developed prototype box, together with the integration process of all systems, including early testing of all parts and their integrated performances.

2. Proposed methodology

This Section details the implementation process followed for all subsystems in line with the structure presented in Section 1.3. The adopted model and the definition of its subsystems are represented in the schematic diagram in Fig. 1, which takes into account their functionalities, components, and tools. In addition, the block diagram shows subsystem inter-correlation including the definition of information that is interchanged between the subsystems. The prototype is defined to work in three ways. Via the Mobile App the user chooses the automatic summer mode, the automatic winter mode or a manual mode.

The whole method was tested thanks to the development of a prototype box. The prototype was implemented with a dynamic blind shading system together with a light system composed of LEDs. Both shading and lighting systems were controlled based on the measurements of internal and external light sensors according to different control modes. The adopted prototype box, in line with the mentioned TRL level, is a model in scale of a building space allowing to test technical functionalities. Nevertheless, it cannot allow to check users' experiences such as in a real environment. In order to make the system scalable, it was decided to separate and execute the sensing, processing, and actuating tasks using three different micro controllers. Thanks to this choice, it was possible to localise sensing and actuator microcontrollers (based on Arduino) respectively close to sensors and motors, which are elements that need wired connections. In contrast the processing module (based on RaspberryPi) can be placed in a different and safe location as it communicates with microcontrollers through a wireless connection, in line with real-building scale applications. Fig. 2 shows the internal and external components of the proposed solution, given that the RaspberryPi is in charge of the processing task and the two Arduinos are in charge of the sensing and actuation procedures (see also the diagram in Fig. 1). System framework and control logic methodologies are described in Section 2.1, while the methodology adopted to develop the prototype systems is reported in Section 2.2.

2.1. System framework and control logic

As illustrated in the block diagram in Fig. 1, the developed system is made up of three main sub-systems: i) the main processing unit (Section 2.1.1); ii) a sensing subsystem, and iii) an actuator subsystem (both sensing and actuating frameworks are defined in Section 2.1.2). Section 2.1.3 defines the adopted fuzzy control logic, which is implemented in the main process unit from which output control information is transmitted to actuators via the developed microcontroller subsystem. Each sub-system requires a processing device to manage all planned functions of the subsystem itself. In particular, the sensing subsystem – see also the left block in Fig. 1 – was implemented using a NodeMCU ESP8266 microcontroller – see Fig. 3 (a) – since it is compatible with Arduino and includes a Wi-Fi module, the actuator subsystem – see also right block in Fig. 1 – was implemented using an Arduino Uno R3 microcontroller board – see Fig. 3 (b) –, and the main processing unit – central block in Fig. 1 – was composed of a Raspberry Pi 3 B+ board – see Fig. 3 (c).

2.1.1. Main process unit

The main process receives and collects information from sensors, processes data, takes decisions, and sends consequent commands to the actuator subsystem. Due to the high number of tasks that have to be managed by this subsystem, a Raspberry Pi board was chosen because of its high processing capabilities in comparison to microcontroller units. In fact, the Raspberry Pi is a very small and cheap computer, which has only one circuit board and, for this reason, it is also known as a "single-board" computer. There are several types of Raspberry Pi models: for this prototype development, the Raspberry Pi 3 model B+, which has a processor speed of 1.4 GHz, 1GB of RAM, an embedded Wi-Fi, an Ethernet port and Bluetooth was chosen. Python 2.7 was chosen as a programming language to develop all the functionalities of the main process unit. The implemented software was divided into the

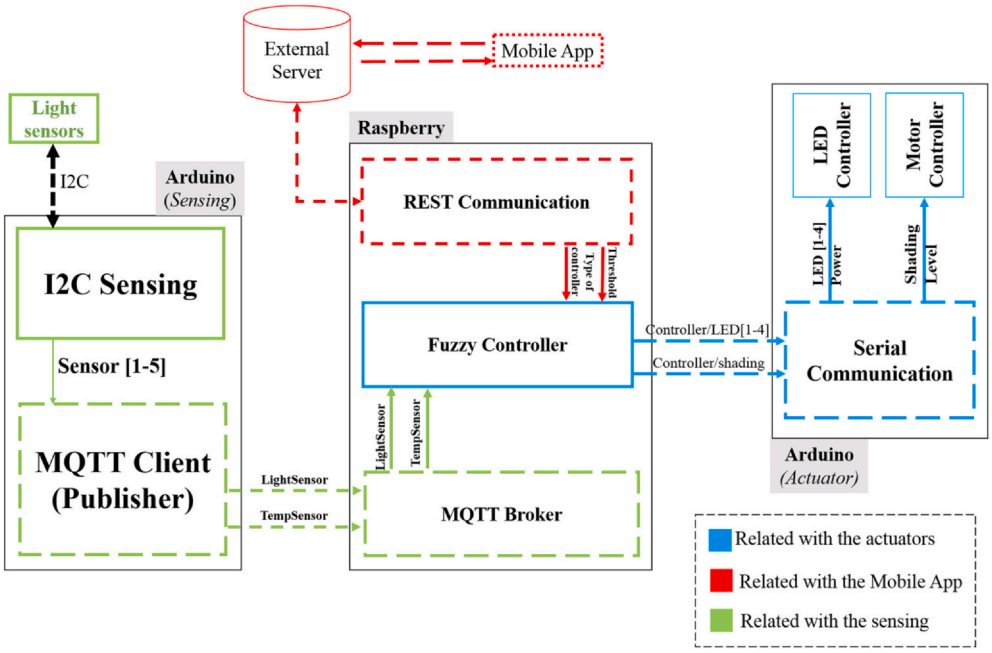

Fig. 1. Schematic block diagram of the system.

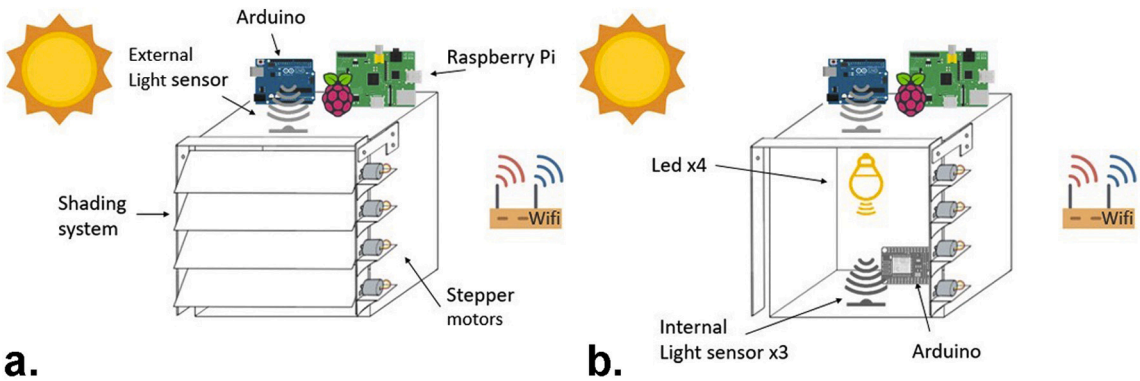

Fig. 2. Schematic depiction of the (a) external and (b) internal components of the IoT proposed solution.

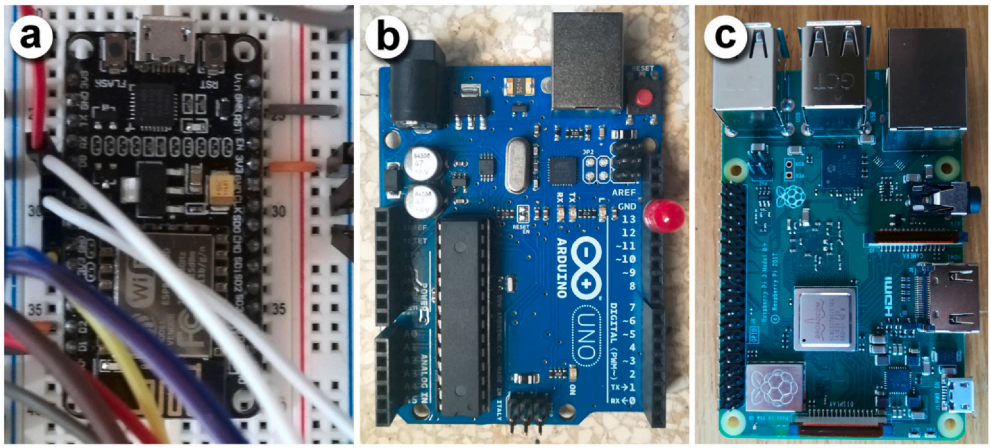

Fig. 3. The chosen control system devices: (a) NodeMCU ESP8266 with Wi-Fi module, (b) Arduino UNO R3, (c) Raspberry Pi 3 B+.

following four procedures:

1. MQTT communication protocol with the sensing Arduino sub-system;
2. Serial communication protocol with the actuator Arduino sub-system;
3. Implementation of Fuzzy controller;
4. Communication to the mobile App through an external server.

The first procedure defines the interaction with the first Arduino – sensing (left block of Fig. 1) – and is based on the MQTT (Message Queue Telemetry Transport) protocol. The sensing sub-system collects all data from indoor and outdoor light sensors and sends them to the main processing unit through MQTT. The sensing Arduino node acts as MQTT client publisher while the Raspberry Pi node acts as MQTT client subscriber, while the chosen broker is a public broker (HiveMQ). A comprehensive description of MQTT logic and methods is reported by Hillar [58] and by Lampkin et al. [59].

The second procedure defines the adopted serial communication protocol which allows for the exchange of information between the Raspberry Pi node and the actuator Arduino sub-system. These two devices are connected using a USB cable. The developed serial communication diagram is reported in Fig. 4 and is based on a feedback process between the two devices. Firstly, the Raspberry Pi is responsible for sending a type that represents the system mode received by the App – see the description of procedure 4. As mentioned before and detailed below, the system is implemented to work in i) an automatic summer mode, ii) in an automatic winter mode, and iii) in a manual mode. All these three modes may have an effect on the two-actuator systems: the lighting system composed of LEDs, and the shading system, composed of blinds activated by motors. In particular, for this first step and according to the user mode chosen, the RaspberryPi checks the reply of both lighting and shading systems (i.e. in manual mode, corresponding to single type “M”, and in automatic winter modes, single type “A”) or one of the two actuating systems (in the automatic summer mode, single type “L” for LEDs or “B” for blinds). After this first handshaking step, the Raspberry unit waits for an ACK (acknowledgement) signal from the Arduino-actuating unit. Thirdly, after receiving the ACK, the respective payload is sent to the actuator by the main process unit. The payload type depends on the system modality message defined before. If the mode is set to summer and refers to an “L”, then the payload of LEDs is sent, while if the mode refers to a “B”, then the payload of motors is sent. On the other hand, when the manual mode “M” or the automatic winter mode “A” are set, the two payloads (“L”, LEDs, and “M”, motors) are sent in the following order: first the stepper motor payload and then the LED payload. The Stepper Motor payload is composed of 18 bytes (integer digits) ranging from 0 to 17. This 18-byte code is organised in such a way as to transmit the information required. In particular, digits 0 to 7 represent the four current angle degrees of each motor (2 digits for each number) while the range from digit 8 to digit 15 represents the four new degree angles of each motor. Furthermore, digit 16 indicates which motor will be activated, or if all motors will be activated together. Finally, the last digit, 17, represents the sign of the angle. The LED payload is composed of a dynamic array. The length of the payload (field length in integer digits) changes with respect to the length of the LED intensity value. The first digit represents the mode of the value – i.e. 1 and 2 for automatic summer, 3 for manual and 4 for automatic winter mode. The second digit represents the LED selector – i.e. 0,1,2,3 (single Led selection) and 4 for all. The next part of the message has a variable length (1,2 or 3 digits)

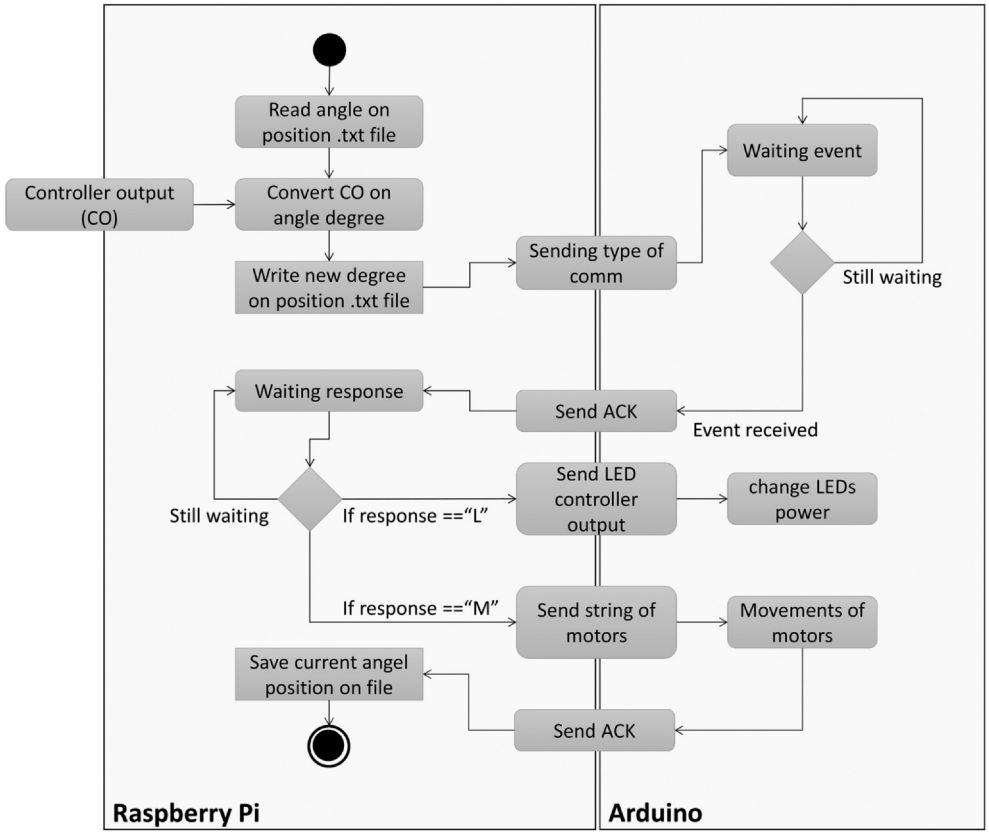

Fig. 4. Block diagram of the serial communication between the main process unit and the actuator sub-system.

representing the value of led intensity. Finally, the last digit modifies the array according to the previous information – i.e. if the intensity LED value has only one digit, then the total payload is composed of 4 digits, otherwise it is composed of 5 or 6. After sending the payload(s), the main unit waits for an ACK before storing the new motor positioning (chosen motors do not provide direct feedbacks on their position).

The third software procedure is devoted to the implementation of the fuzzy controller. Two fuzzy controllers were created with a dual system: one for blinds (stepper motors) and one for LEDs. The blind-controller function receives the indoor illuminance, the outdoor illuminance and the assumed threshold as parameters, and returns a positive or negative value. The idea behind this controller is to indicate to the system how necessary it is to open/close the blinds. Finally, the result of the blind controller modification is added to the current angle position. The LED controller function is similar to the blind-controller one as it has the same input parameters, i.e. indoor and outdoor illuminance values and threshold. However, in the LED controller, the

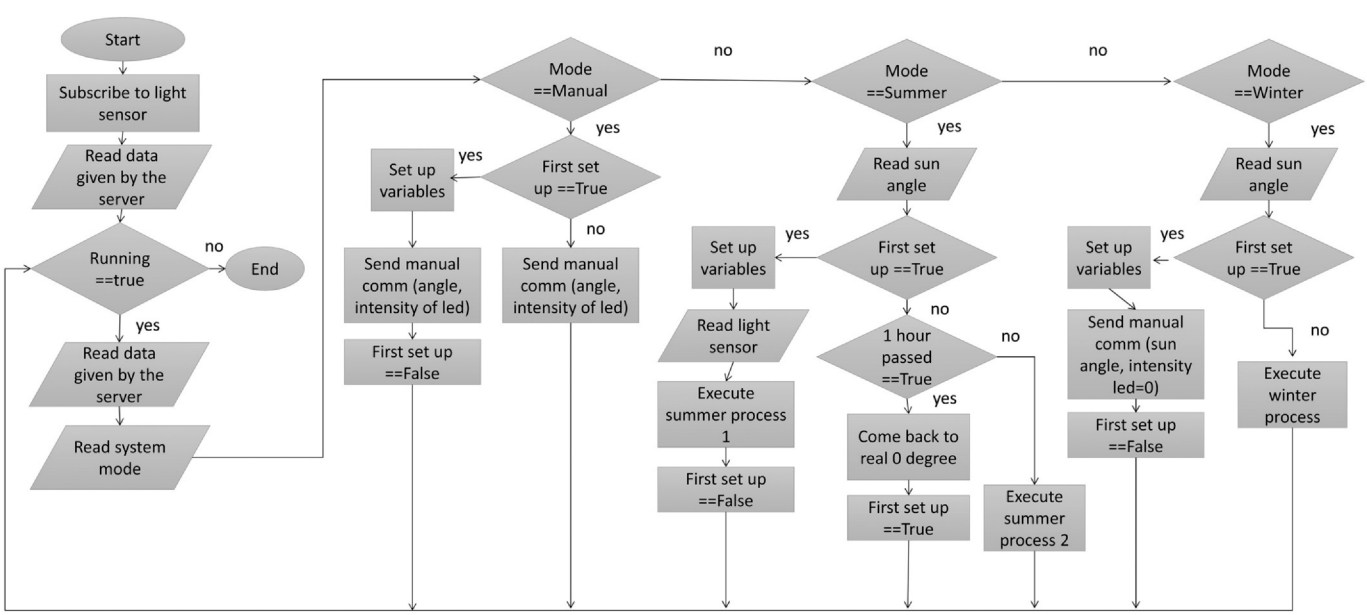

Fig. 5. Block diagram implemented for the main process unit.

output produced defines how much the system needs to increase/decrease the LED power.

The fourth procedure focuses on the communication between the main-process-unit and the mobile App through an external server. This enables the RaspberryPi to interact with the server that hosts the mobile app by adopting existing python-based tools which are able to read an URL that contains a JSON format message. In this way, it is possible to get the information sent by the mobile app and process it in the Raspberry Pi node. The message is based on user information regarding system modes – automatic defining seasonal mode winter/summer, including the illuminance threshold, and manual mode, including the required light power of LEDs and the angle degree of blinds – see the description in Section 2.2.3.

Fig. 5 shows the implemented block diagram used to control the main process unit, which runs on the Raspberry Pi. The algorithm defined for the Raspberry Pi is based on a 2-step running cycle. The first step checks connections with sensing node(s) and server information while the second runs the control system. Initially, the connection of the main process unit to the sensing Arduino node is established (left column, second block in Fig. 5). In this procedure, the Raspberry Pi acts as a client by subscribing to the MQTT broker using the topic "light-sensors" to get data collected from indoor and outdoor light sensors. After getting sensor data, the algorithm proceeds by reading the external server (which is connected to the mobile app) in order to store commands that are in a JSON format. These commands refer to the mode of the system (automatic summer, automatic winter, or manual) (see Fig. 5 – third block in the left column). When the retrieved mode is automatic summer or automatic winter the set illuminance threshold is read while in manual mode, both the angle degree and the power of LED selected by the user are read. Finally, the system enters the main running cycle (2nd step), which is set to "true" until the user decides to turn off the system. When the running cycle starts, sensors and mode data are read again to check which system mode was selected by the user. According to the retrieved mode, specific sub-routines are run: Manual Mode, Automatic Summer Mode, and Automatic Winter Mode.

In Manual Mode the user wants to define a specific angle degree for blinds and a specific intensity for LEDs. The first time the algorithm passes through this set in a running cycle, the global variables related to the manual communication function are set up and communication activated. On the other hand, during additional activations of the Manual mode in the same running cycle, the algorithm simply executes the serial communication – called "Manual comm" – and sends the angle to the actuators and the light intensity stored in the server to the Leds.

In the Automatic Summer Mode, the system reacts automatically based on the given illuminance threshold and summer bioclimatic principles to reduce overheating risks – see for example [30–32]. This mode depends, in fact, on apparent solar position (sun elevation angle) to prevent solar gains. Hence, the automatic summer sub-routine first reads the sun elevation angle calculated on the basis of the given location positioning and timing, i.e. hour of the day and day of the year, using a python script, and then, the automatic controller mode is started. When this mode is activated for the first time in a running cycle, global variables related to this type are set up and the "Summer-position-1" block is executed – see the related flowchart reported in Fig. 6 (a). The code for this specific procedure checks if all the four motors are sending data (decision block in Fig. 6(a)). When the answer is positive, all blinds are positioned perpendicularly to the sun elevation angle, thus defining a new zero reference for motor movement. This first block only controls the shading system. When shading is in the set position zero, the "Summer-Position-2" block is executed – see the specific flowchart illustrated in Fig. 6 (b). During this second phase of the automatic summer mode, the system starts to use the fuzzy controller. Firstly, the block checks if the algorithm needs to work with the "blind" or with the "LED" procedures. The system follows a waterfall logic. When indoor sensors read insufficient illuminance levels, the system starts with the blind controller procedure to open shadings, and furthermore, when blinds are totally open, activate the LED controller procedure. The opposite is the case when the indoor illuminance level exceeds the threshold. In this case, the system firstly reduces the LED intensity to zero and then activates the shading closing process. Finally, the automatic summer mode resets after a given period of time, which for prototype development is set to 1 h, by recalling the original zero references for blinds and reading again the updated sun elevation angle. A shorter time may be set to increase solar control precision.

In Automatic Winter Mode the system activates a bioclimatic winter approach by maximising solar gains. This mode sets blind directions parallel to sunrays, following sun elevation angles and removing the further illuminance blind controller to maximise direct solar gains – potentially upper UDI (Useful Daylight Illuminance) [60] illuminance thresholds can be added to automatic shading control, maximising solar gains while preventing glaring. Sun elevation is calculated in real-time, as in the automatic summer mode, using geo-astronomic expressions – see for example [33,34]. In this mode, Fuzzy control only acts on the LED controller for lighting setting. Nevertheless, during those hours when the sun azimuth angles is behind the prototype, the angle selected

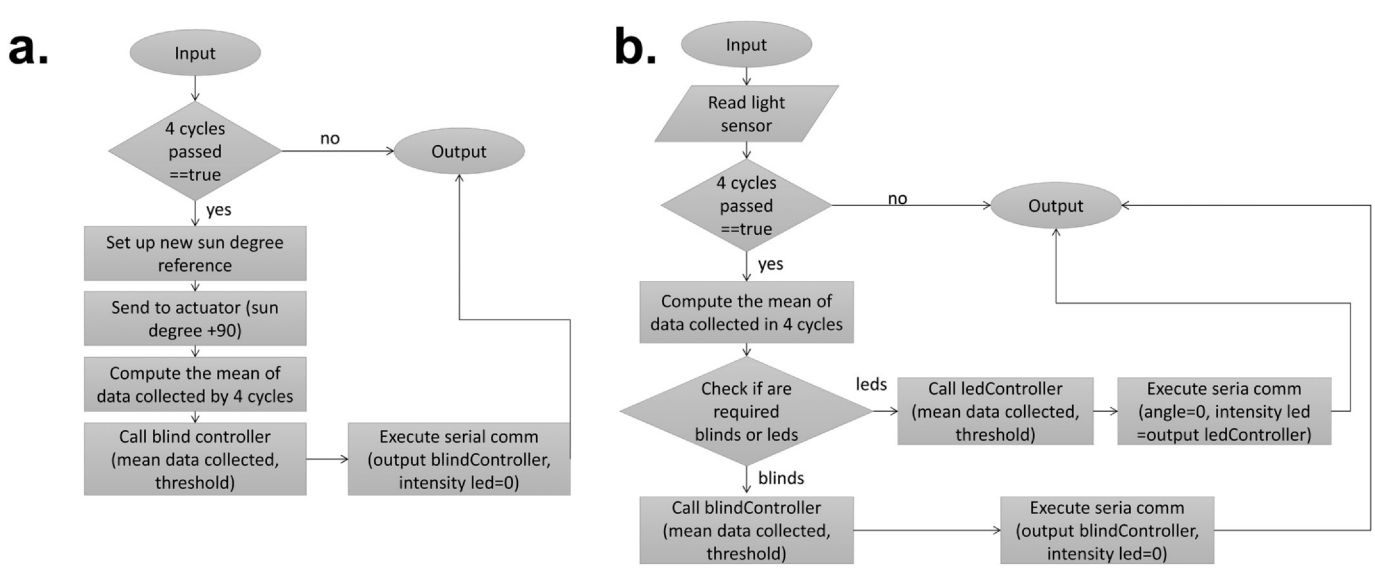

Fig. 6. Flowcharts of the summer blocks: (a) Summer position 1; (b) Summer position 2.

for motors is set to 0° degrees, in order to have the blinds opened perpendicularly to the glass.

2.1.2. Arduino-based nodes (sensing/actuating frameworks)

As mentioned above, the two subsystems which are devoted to sensing and actuating are based on microcontroller Arduino boards. For this project, two different Arduinos were used. An Arduino UNO R3 controls the actuator sub-system, while the Arduino-compatible Node MCU ESP8266 – which includes a Wi-Fi module – is used for the sensing sub-system. The first Arduino gives commands to the LEDs through PWM to turn them on/off and dim their power. Furthermore, it also controls stepper motors by defining blind movements. On the other hand, the ESP8266 sensing node collects data from the installed light sensors and transmits them via Wi-Fi using the MQTT protocol. The sensing sub-system adopts a simple flow-chart and implements given code parts to control the considered sensors – see Section 2.2.2 –, while the block diagram of the actuating sub-system is detailed here below. Fig. 7 illustrates the algorithm implemented for the actuator subsystem. This subsystem basically moves stepper motors and controls LEDs. In order to activate the system and further guarantee the required movement (motors) and/or power (LEDs), the implemented algorithm waits for a message from the main process unit to consequently activate the desired function(s) – see single type message described in Section 2.1.1 and further description.

When the system mode is set to 'Automatic Summer Mode', the Raspberry main process unit sends a call that defines which function(s) has(have) to be activated to the Arduino subsystem – i.e., in the case of lighting payload ("L") the Arduino calls the LED function, which is described in Fig. 8, otherwise in the case of the stepper motor payload ("B") the Arduino calls the shading function, see Fig. 9. However, when the system mode is set to Manual, i.e. the received typo message is "M", the Arduino subsystem calls the shading function first – Fig. 9 – and then the LED function – Fig. 8. Similarly, when the Automatic Winter mode is set – typo "A" –, the same flow described for Manual mode is applied. The Arduino subsystem calls firstly the shading (motor payload) function and secondly the lighting (LEDs payload) function.

The adopted subsystems' hardware for shading and lighting parts are described respectively in Sections 2.2.1 and 2.2.2 and the schematic hardware connection of the actuator sub-systems is illustrated in Fig. 10, while both LED and stepper-motor connections are described in the mentioned sections.

2.1.3. Fuzzy control logic

Fuzzy logic is a computer approach in which machines are driven to think more like our brains. Fuzzy logic defines 0 and 1 as extreme cases of truth but also includes various states of truth in between these extremes. A similar kind of process is used in neural networks, expert systems, and other artificial intelligence applications. In order to control and understand if the amount of indoor light is acceptable, the fuzzy logic approach is adopted here. If we consider the developed solution, fuzzy logic shows several advantages with respect to conventional control approaches because: i) the proposed system is not binary and controllers have to be defined in a set of ranges, which are dimmable for both LEDs and motors; ii) in fuzzy logic the system can work with any type of input; iii) the construction of fuzzy logic is quite simple and provides very efficient solutions to complex problems; and iv) the algorithm can be described with little data because it does not need too much memory or calculation power – when compared to other intelligent control approaches. For this reason, fuzzy logic control is adopted here to be tested on the developed IoT system based on a RaspberryPi main process unit. From the architectural point of view, the Fuzzy Logic approach includes four parts.

- Fuzzyfication: this is used to convert crisp inputs – i.e. exact inputs measured by sensors – into fuzzy sets;
- Defuzzyfication: this is used to convert the obtained fuzzy sets into a crisp value by using an inference engine;
- Base Rule: this defines a set of rules – i.e. IF-THEN conditions – to establish the decision making system, using linguistic information;
- Inference Engine: this i) determines the matching of fuzzy inputs with respect to each rule and ii) decides which rules are the correct ones to be applied according to inputs.

Furthermore, membership functions are defined to establish how each point in the input space is mapped to the membership value space in the 0-to-1 range, thus transforming numerical data into linguistic

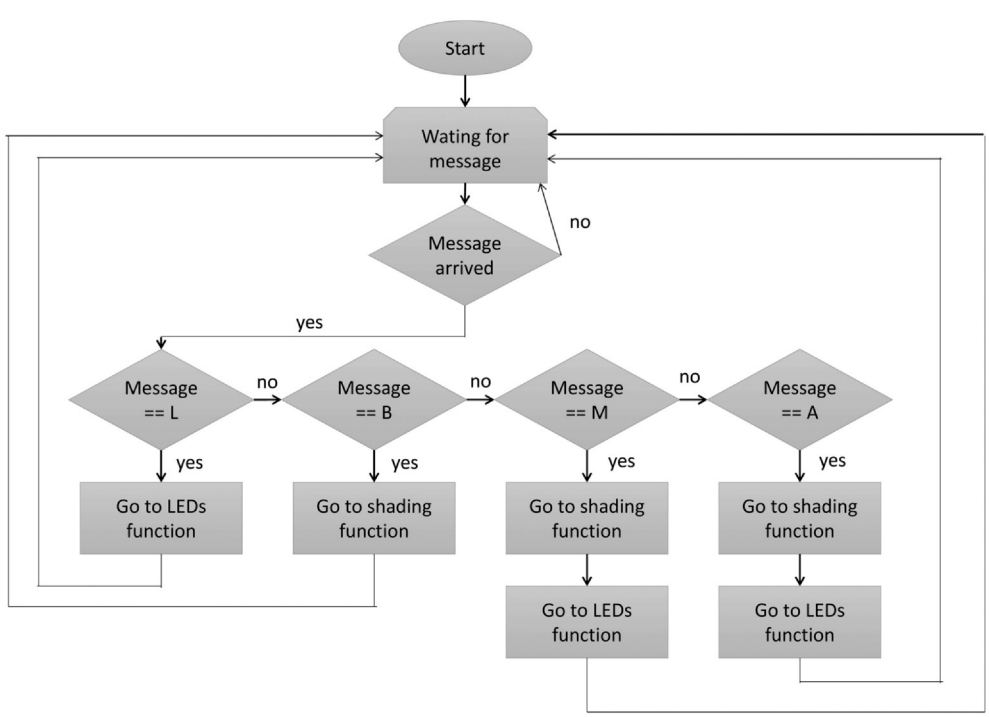

Fig. 7. The main block diagram implemented in the actuator subsystem.

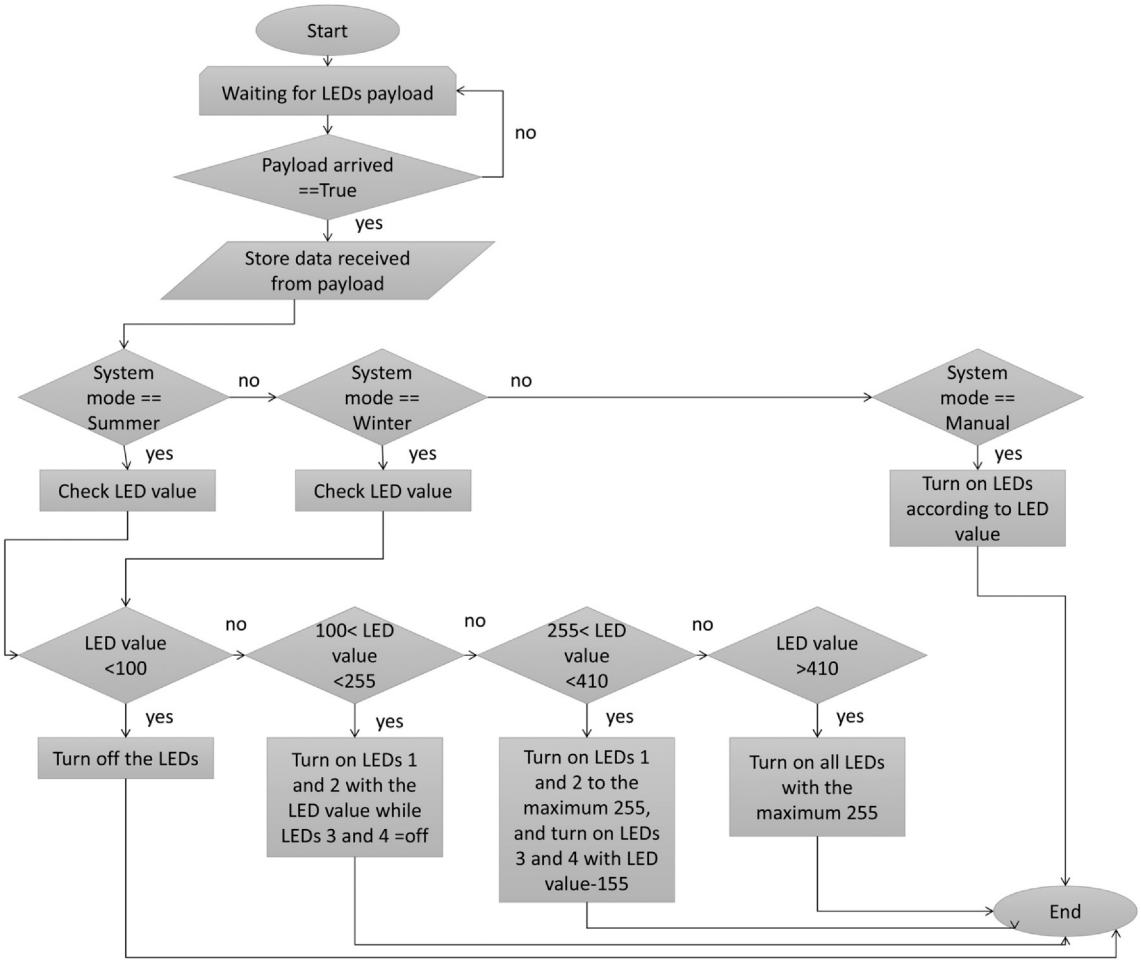

Fig. 8. The lighting (LEDs) function block of the actuator subsystem.

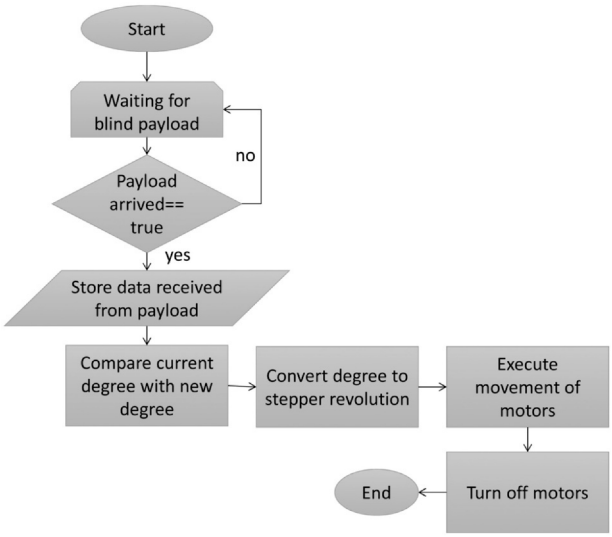

Fig. 9. The shading (motors) function block of the actuator subsystem.

data. In particular, a devoted membership function is created for each input/output value, i.e. indoor light, outdoor light, and outputs, for a total of 3 Membership Functions. The indoor and outdoor membership functions work for both LED and blind systems – see Fig. 11 – because the monitored input is the same (illuminance sensors [lx]), though one membership function for each subsystem is needed for outputs. Table 1 represents the indoor membership function which is divided into 5 categories, while, Table 2 shows the membership function of the outdoor light, which is divided into 3 categories.

In the output membership function for blinds, outputs are measured in angle degrees and the command given by the controller is to close or to open the blinds with differing intensity. The universal space ranges from −64 to 64 degrees. Table 3 represents the membership function for blind output. In the output membership function for LEDs, outputs are represented by the intensity of LED light. In this case, the universal space is fixed from (−80 to 80) lighting power. Table 4 represents the membership function for LED output.

The defined Fuzzy Controller Set of Rules are different for blinds and LEDs. 13 rules, based on an IF-THEN algorithm, have been defined for blinds, in order to cover all possible cases. The set of rules for blinds is reported in Table 5.

The set of rules defined for the control of LEDs follows a similar logic, but, in this case, instead of referring to an “open/close” process, the output will refer to an “increase/decrease” process which controls the LED power. Rules are reported in Table 6, while Fig. 12 shows the behaviour of both controllers in a sample case in which the indoor measured illuminance (250 lx) is below the desired threshold (300 lx), and the outdoor illuminance (1000 lx) is sufficient to guarantee indoor comfort conditions. It is observed that, in this specific sample, on the one hand the blind controller opens the blinds by 13 degrees (13.3) – see Fig. 12 (a) – and, on the other hand, the LED controller increases the LED power by a factor of 25 – see Fig. 12 (b).

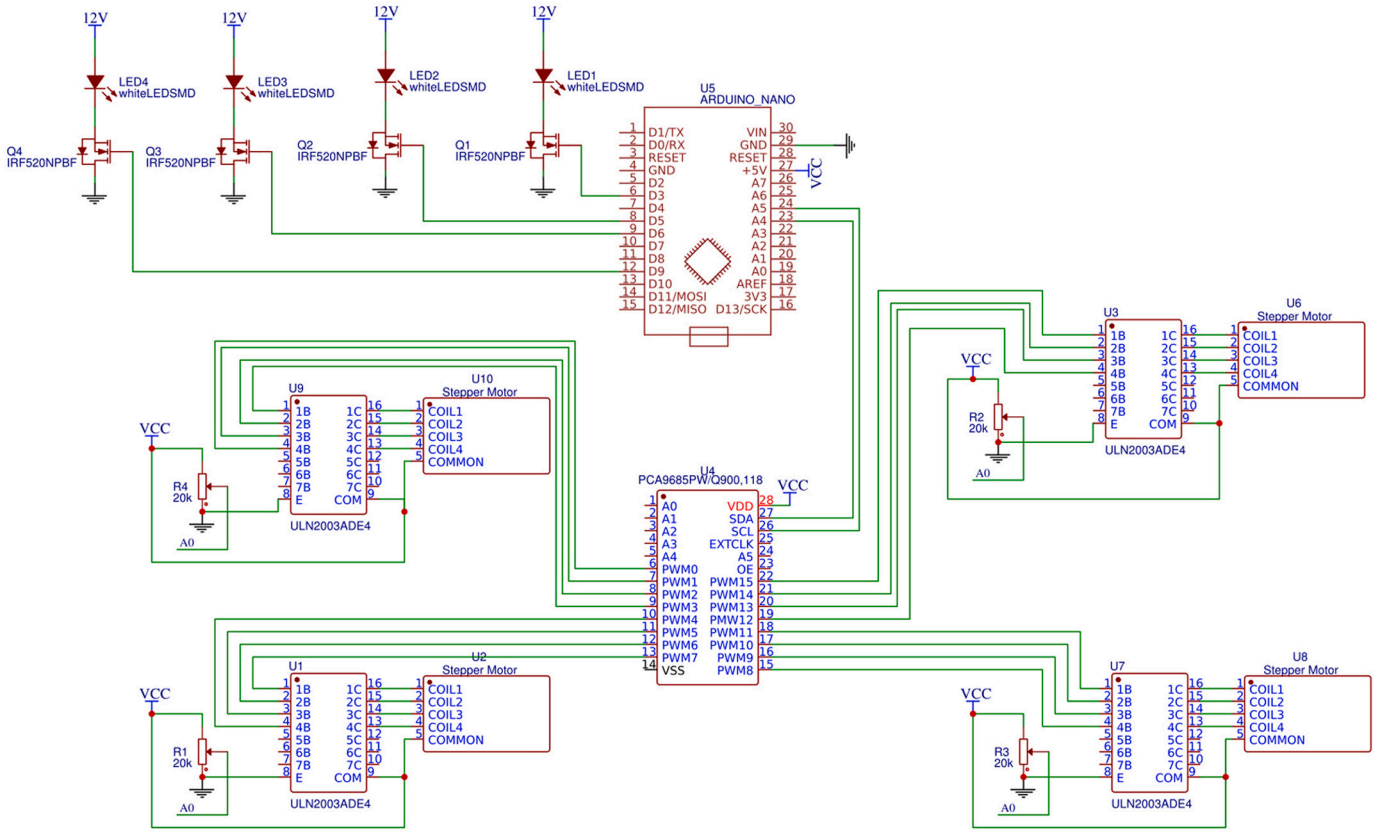

Fig. 10. Schematic of the actuator subsystem node.

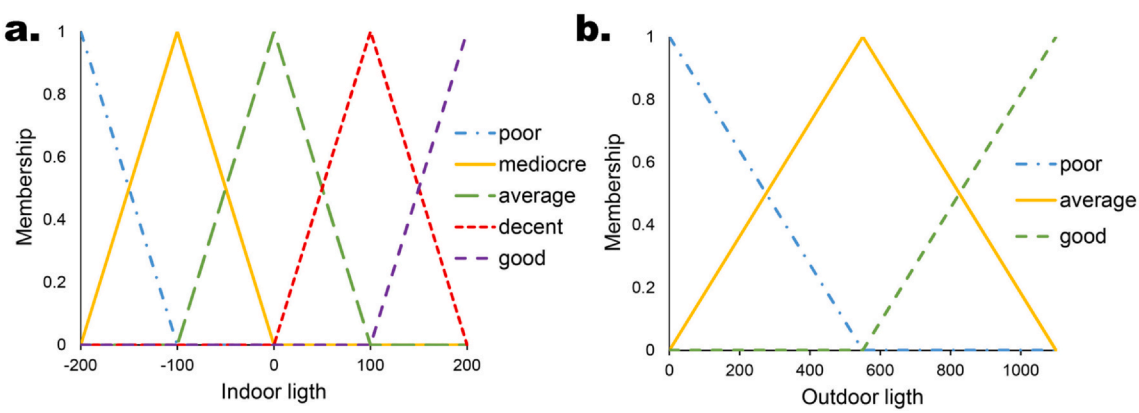

Fig. 11. Fuzzy logic. (a) Membership function for indoor light input; (b) Membership function for outdoor light input.

Table 1
Indoor light membership functions.

Categories	
Poor	−200: −200: −100 [lux]
Mediocre	−200: −100:0 [lux]
Average	−100:0:100 [lux]
Decent	0:100:200 [lux]
Good	100:200:200 [lux]

Table 2
Outdoor light membership functions.

Categories	
Poor	0:0:550 [lux]
Average	0:550:1100 [lux]
Good	550:550:1100 [lux]

2.2. Prototype development

Section 2.2 describes the hardware development, focusing on shading system and lighting system. Furthermore, in this section the development of the user App is also described. Finally, the built prototype is detailed.

2.2.1. Shading system development

The implemented shading system was conceived to control the amount of sunlight entering a considered space by acting – opening or closing – on a set of horizontal blinds. In addition, the system is also adapted for vertical blinds solutions, such as the ones that may be adapted for east and west oriented facades. This system is composed of: i) a set of horizontal blinds, ii) a set of stepper motors (one per blind)

Table 3
Output membership functions: blinds.

Categories		
Fully close	fc	−64: −64: −20 [degrees]
Close	c	−40: −20: −0 [degrees]
No movement	nm	−10: −0:10 [degrees]
Open	o	0:20:40 [degrees]
Fully open	fo	20:64:64 [degrees]

Table 4
Outputs membership functions: LEDs.

Categories		
Very dark	vd	−80: −80: −40
Dark	d	−60: −40: −0
Normal	n	−10: −0:10
Bright	b	0:40:60
Very bright	vb	40:80:80

Table 5
Set of rules: blinds.

	Indoor light	Outdoor light	Output
Rule 1	IF poor	AND poor	THEN fo
Rule 2	IF poor	AND average	THEN fo
Rule 3	IF poor	AND good	THEN o
Rule 4	IF mediocre	AND poor	THEN fo
Rule 5	IF mediocre	AND average	THEN o
Rule 6	IF mediocre	AND good	THEN o
Rule 7	IF average		THEN nm
Rule 8	IF decent	AND poor	THEN nm
Rule 9	IF decent	AND average	THEN c
Rule 10	IF decent	AND good	THEN fc
Rule 11	IF good	AND poor	THEN c
Rule 12	IF good	AND average	THEN fc
Rule 13	IF good	AND good	THEN fc

Table 6
Set of rules: LEDs.

	Indoor light	Outdoor light	Output
Rule 1	IF poor	AND poor	THEN vb
Rule 2	IF poor	AND average	THEN vb
Rule 3	IF poor	AND good	THEN b
Rule 4	IF mediocre	AND poor	THEN vb
Rule 5	IF mediocre	AND average	THEN b
Rule 6	IF mediocre	AND good	THEN b
Rule 7	IF average		THEN n
Rule 8	IF decent	AND poor	THEN n
Rule 9	IF decent	AND average	THEN d
Rule 10	IF decent	AND good	THEN vd
Rule 11	IF good	AND poor	THEN d
Rule 12	IF good	AND average	THEN vd
Rule 13	IF good	AND good	THEN vd

that are in charge of rotating the blinds, and iii) motor controllers, which are implemented using an Arduino-like microcontroller – see Section 2.1. The chosen stepper motors for prototype development are DC motors in which each time a winding is energized the shaft moves a specific distance which is called a step. By energizing each phase in sequence, the shaft starts rotating one-step at a time. Because of this ability these devices are commonly used in positioning mechanisms. Specifically, the use of the prototype four stepper motors of type 28BYJ-48 (5 V) has been proposed– one for each blind –, instead of using only one motor to move all installed blinds. This choice allows us to control each blind independently – see also the scheme of the actuator subsystem in Section 2.1.2. Fig. 13(a) shows the wiring and internal scheme of a motor 28BYJ-48. The motor is composed of four internal coils – at the end of each coil is a + 5 V wire – together with a set of gears, which enable the shaft to rotate by 0.08789° in half-step mode or 0.17578° in entire-step mode, when coils are energized with 5 V in the correct sequence. The power supply is given to the coils that are grounded at the opposite end, while those coils with both ends on +5 V are not energized. Driver boards ULN2003A are used to drive these DC motors – see Fig. 13 (b). Each Stepper motor is fed by the 5 V Arduino power supply. As mentioned above, each stepper motor has 4 coils, which means that 16 available free digital pins are needed on the Arduino to control all coils. However, the Arduino UNO doesn't have this capacity because it only has 14 digital pins. For this reason, two shift registers have been implemented. This approach allows us to control 8 digital outputs using only 3 digital pins. By connecting the two shift registers in a cascade mode, it is possible to control all 16 coils of the stepper motors with only 3 digital pins – see the schematic view illustrated in Fig. 10.

2.2.2. Lighting system development

The proposed indoor lighting system is composed mainly of two subsystems: a network of luminosity sensors and a set of LEDs plus a wireless communication node. Luminosity sensors are responsible for collecting the indoor and outdoor illuminance levels [lx] – see also the description of the sensing node in Section 2.1 –, while the LEDs provide artificial lighting when natural light is not sufficient to reach the desired illuminance threshold – see the description of the actuating node in Section 2.1. The required light sensors are electronic devices with the ability to measure the luminous flux per unit area. For prototype development, TSL2591 Luminosity Sensor Breakout is chosen, because it has a light sensor module that measures illuminance up to 88,000 lx, with a minimum sensitivity of 188 μLux. This sensor module is chosen because of its accuracy, its high dynamic range, and the usage of digital communication protocols to send the collected measurements to the board. Inside the room-box prototype, 3-light sensors are installed in strategic positions – following the median line from the window to the opposite façade. Furthermore, another sensor is installed on the top of the box to measure natural (external) light illuminance. These sensors are connected through I2C protocol with the communication node that is directly connected to a local area network (LAN). The communication node is a NodeMCU which is responsible for collecting all measurements and publishing them into a broker via MQTT protocol – see the description of the sensing unit in Section 2.1.2. Moreover, the main process unit – see Section 2.1.1 – takes these measurements to calculate the opening angle of the blinds and the power intensity of the LEDs. From the lighting point of view, a LED system is defined – see the description of the actuating unit in Section 2.1.2. A light-emitting diode (LED) is a semiconductor electronic device that emits light when an electric current passes through it. The intensity of the light can be controlled by the current that passes through the LED. Usually, to control this current, the PWM (Pulse width modulation) technique is used. In order to provide enough indoor artificial lighting, it was decided to use four high-power LEDs – like the one shown in Fig. 14(a) – equally distributed inside the room-box prototype. However, since these specific LEDs require 1 W of power, MOSFET modules – see Fig. 14 (b) – are adopted to control the light intensity through PWM using a Micro-Controller Unit (MCU), like an Arduino.

The power supply required by the 4 High power LEDs is assured by using an external power source, which is able to provide 2A – each LED operates at 350 mA – and 3 V. LEDs are placed in parallel lines in order to work with the 3 V source. The inputs of the LED driver units (MOSFET modules) are connected to 4 PWM digital pins of the Arduino actuator node. Hence, it is possible to regulate the LED outputs by using PWM signals – see the schematic view configuration in Fig. 10. LEDs may be controlled individually but for this prototype they are divided into 2 parallel lines, one of which collects the 2 LEDs near the window and the other, the 2 on the back of the box. This choice allows us to control the 2 lines, by maximising firstly the light on the line farthest

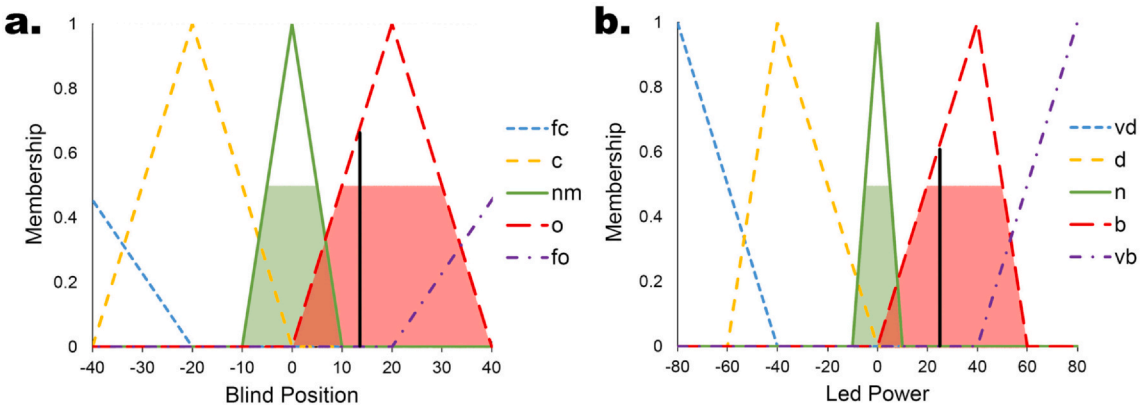

Fig. 12. Output membership graphs and simulations for a sample case. Indoor Light starting at 250 lx, threshold set to 300 lx, and measured outdoor Light = 1000 lx. (a) Fuzzy logic output for shading controller; (b) Fuzzy logic output for LEDs controller.

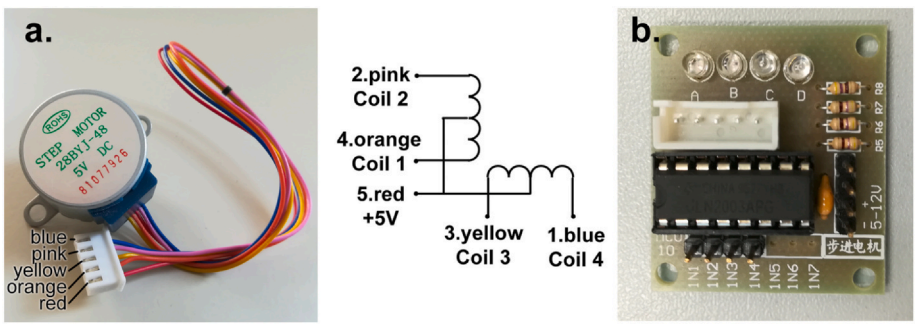

Fig. 13. The 28BYJ-48 Stepper Motor: (a) wiring and internal scheme; (b) the used driver board.

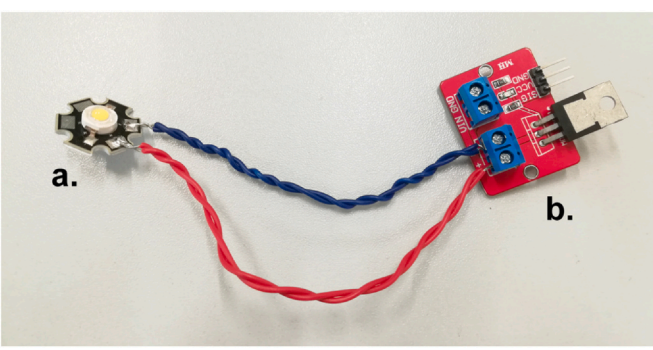

Fig. 14. (a) one of the adopted 1 W high power LED with white light; (b) one of the MOSFET driven modules used.

away from the window, thus acting on the zone in which natural light illuminance is lower, and then by also activating the second line if the desired level is not reached. The set illuminance threshold is guaranteed at an average level on the basis of all 3-internal sensor measurements.

2.2.3. Mobile application

A mobile application has been developed with the purpose of allowing users to control the lighting and shading systems. Two main control modes are defined. The first is a manual control mode, while the second is an automatic control mode. In both cases, the system enables specific user control actions – see Fig. 15. In line with several applications controlling IoT systems, the developed mobile app adopts a sign-up approach to manage user interaction and their correlated IoT solutions. This sign-in approach is chosen to increase system security and to enable each user to have control of his/her own system thus allowing for a scalable and multi-space control system. Fig. 15 (a) shows the login mobile interface which requires a user name and a password in order to have access to the control of the mobile application. As mentioned above, the system works both manually and automatically. In the automatic mode, the user cannot directly interact with LEDs and Motor functions. The system will automatically optimize the illuminance to a set-value specified during the installation in line with standard requirements. Nevertheless, via the mobile app users can specify the illuminance threshold to be maintained in the controlled space, allowing the system to provide the user with the required light level – see Fig. 15 (b). In manual mode, the user can control the intensity of LEDs, as well as the rotation angle of blinds, thus allowing for personalized configurations – see Fig. 15 (c). Automatic mode is further subdivided into winter and summer modes, as mentioned in previous sections, depending on seasonal bioclimatic conditions. However, the mobile application allows the user to change the automatic seasonal configuration, based on real time information, to satisfy user needs.

To guarantee a secure connection between the mobile application and the system, the “Rest” protocol which connects the app to the Raspberry Pi is used. This specific protocol allows the system to receive new information based on a request to the server and another server replies. To activate this information flow, a server and a domain for transferring the data to the “Raspberry Pi” was defined. It is also possible to use a local protocol to make a connection. To optimize the prototype development, both possibilities have been implemented. For instance, users can control and adjust the lighting/shading system remotely even when they are away from the controlled spaces and not connected to the local host. Fig. 16 shows this information flow based on a server used to transfer data to the Raspberry Pi, which provides a safe and reliable connection and reduces the risk of potential external attacks to the system. The link for the server developed for this prototype was: http://spenergy.ir/app/api/v1/system.php (last accessed Dec 2019).

In order to clarify interconnections between system parts, Fig. 17 reports a sequence diagram of the system. The reported diagram

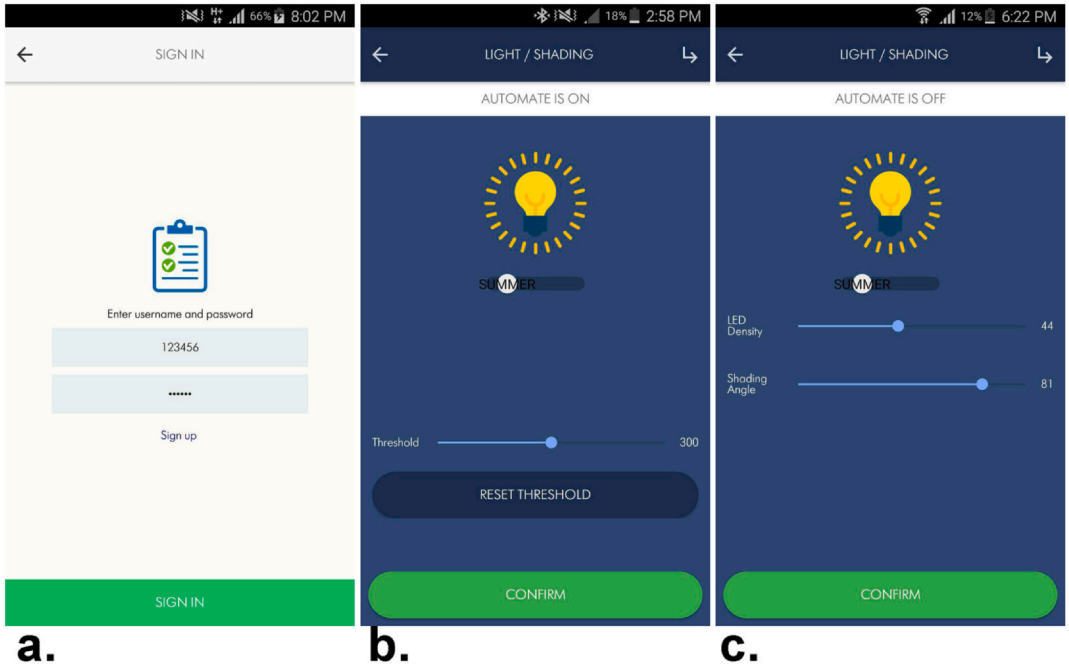

Fig. 15. The developed mobile application interface: (a) the sign-in procedure page; (b) the automatic control mode; (c) the manual control mode.

focusses in particular on the interactive part of the proposed control system and details the sequences arriving between users and the mobile application, while, for example, the fuzzy logic control part is less detailed being already discussed in the devoted Section 2.1.3.

2.2.4. Integration and testing prototype

The testing phase of the proposed IoT system is based on the development of a prototype. The simple prototype is a wooden room-box (50 × 50 × 50 cm. Internally). The frontal vertical face is a window with an external frame of 3.5 cm (net transparent surface of 46.5 × 46.5 cm, made out of 2 mm Plexiglas). Fig. 18 (a) shows the box prototype before system integration.

The developed prototype is shown in Fig. 18. Fig. 18 (b) illustrates the external components including the wooden shading system with installed stepper motors, the Raspberry main process unit, the Arduino actuating node, and the external light sensor on the top of the box. Fig. 18 (c) shows the internal components including the lighting system, the Arduino sensing node and internal light sensors. The prototype box is a scaled model to test technical functionalities of the proposed system. LED and shading systems are adapted consequently, even if chosen technologies may be scaled to different conditions, like the ones in a real environment. For example, the LED system may be adapted to higher power requirements by substituting MOSFETs, LEDs, and correlated power sources, without changing the system functionality. Furthermore, considering the mentioned TRL, electronic connections are at the prototyping level, i.e. using breadboards, while the development of devoted PCBs (printed circuit board) is expected in future development steps.

3. Results and discussion (TRL 3)

In order to observe how the implemented system behaves in different situations and test all the implemented control modes to reach TRL 3, three testing scenarios are defined to check the reaction of the room-box prototype: i) Heliodon testing, ii) Outdoor-condition testing, and iii) Indoor-condition testing. The first test is conducted using a sun simulator to check the general functionalities of the developed prototype. The second test aims at checking the system, when the prototype is positioned outdoors and reacts to environmental conditions. The third test is conducted in an internal space to check prototype reactions to different stimuli. Paper Section 3 focuses on describing each testing scenario and discussing the obtained results.

3.1. Heliodon testing

The Heliodon used is a physical sun emulator that allows us to adjust the angle between a testing surface and a light source that emulates the sun, producing almost parallel beams thanks to a special mirror system – see construction specifications reported by Manni [35]. This specific Heliodon facility allows us to work on a surface of more than 1.2 m in diameter. The testing area is fixed, while the sun simulator moves around it according to sun altitude and azimuths determined by given location coordinates, days of the year, and hours of the day. For the purpose of this paper, all tests are configured to be executed in Turin (Corso Massimo d'Azeglio No. 42, where the Heliodon Lastin-Lab is located) in consideration of both winter and summer conditions, assuming reference seasonal days – e.g. solstices. The equipment is enabled to test the reactions of the developed prototype when the outdoor light changes over time and to check response time.

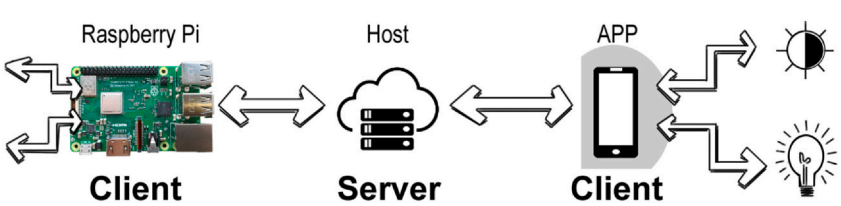

Fig. 16. Schematic representation of the developed back-end.

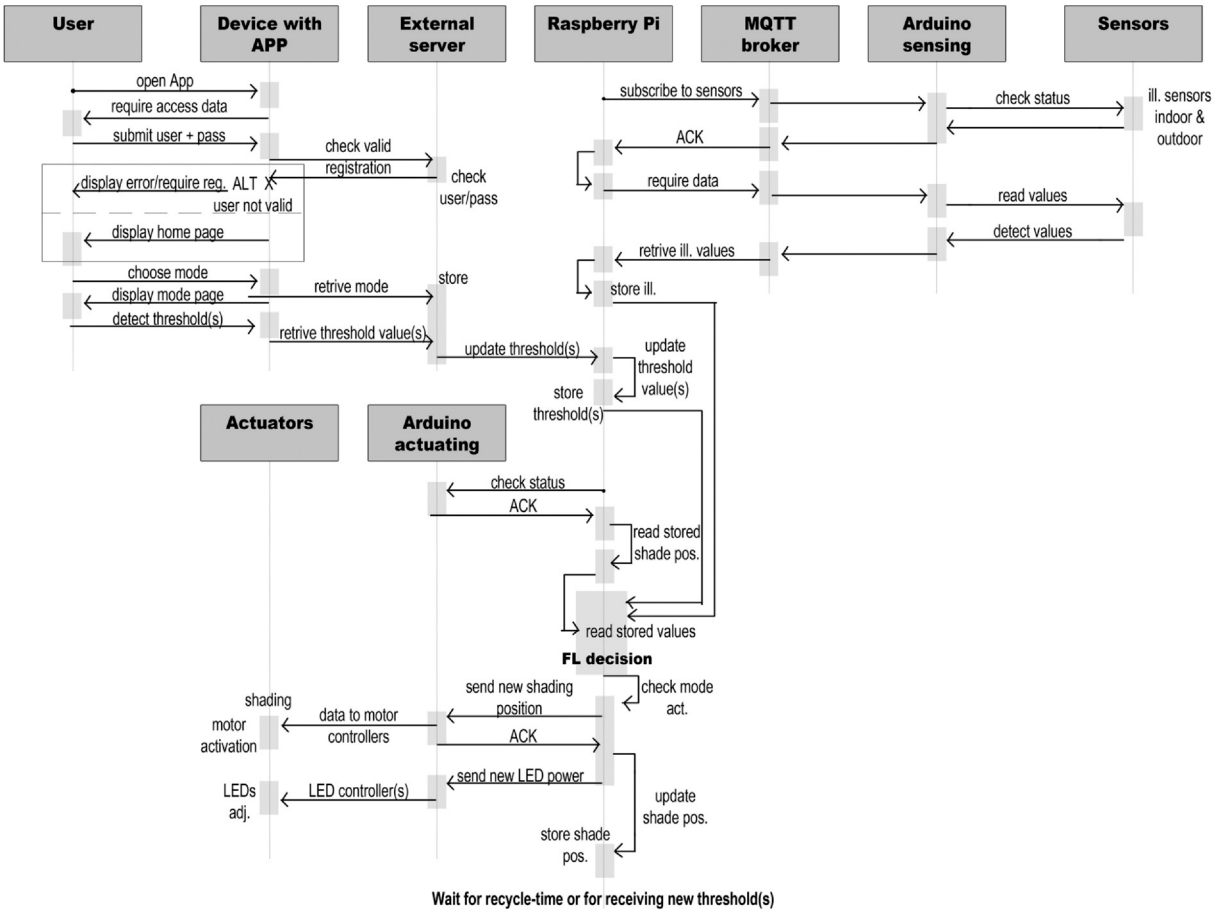

Fig. 17. A sequence diagram of the system focussing on the interactive aspects.

Furthermore, it is used to check if the solar altitude calculation included in the developed IoT system fits with solar positions at different times of the year, in order to correctly control the shading behaviour. The room-box prototype is positioned on the Heliodon simulation plane – see Fig. 19 –, while several conditions are simulated by running the prototype for different dates and hours and then the Heliodon facility is set. Fig. 19 clearly shows that the two independent systems – the Heliodon and the developed prototype – behave in the same way because in winter automatic mode the blind orientations are parallel to solar beams in all tested conditions. The alignment is based on the solar altitude and not on the solar azimuth given that the blinds rotate around their horizontal axes. Similar behaviours are noted for summer automatic mode since the 'summer mode' setting blind positions are perpendicular to the solar beams (90° from the winter mode).

In order to observe the behaviour of the other part (lighting) of the actuator sub-system, a further test is implemented by fixing a shading perpendicular to the façade and adapting LED powers. Fig. 20 (a) shows the behaviour of indoor and outdoor illuminances over time. It can be observed that the outdoor value changes over time from 1000 lx to almost 0 lx, and then grows again to 1000 lx. This behaviour is obtained by configuring the Heliodon in 2 steps: first moving from midday to 18.00 h (red left zone) and then from 18.00 h to midday again (green right zone). On the other hand, in parallel with outdoor light changes, the indoor illuminance is kept by the system at 300 lx, which corresponds to the set threshold. Fig. 20 (b) shows the changes over time in LED power (blue and orange solid lines) and the angles of the blinds (green dashed line) during the same test in Fig. 20 (a). In this figure, we can observe that the blinds are not controlled during this test and are fixed perpendicular to the façade (dashed line remains at zero degrees during the whole simulation period) but when the indoor light is lower than 300 lx, the system activates the LEDs. This figure shows that during the first part of the test, the first set of LEDs (those on the back of

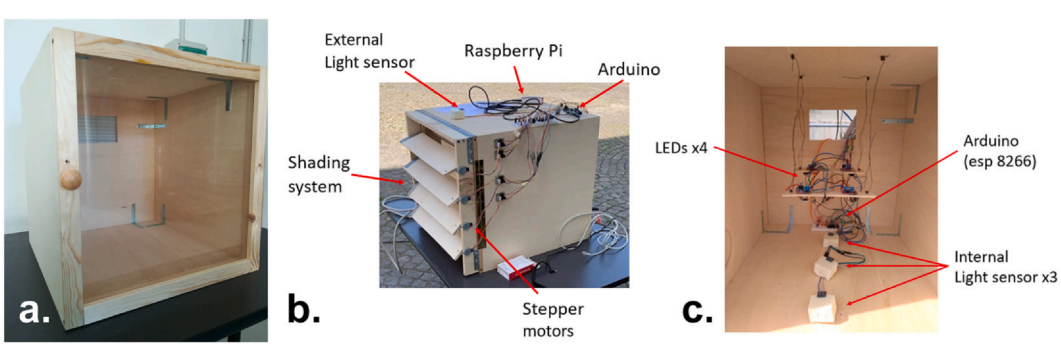

Fig. 18. (a) The prototype box before the installation of the shading system, and after hardware system integration showing (b) external and (c) internal views.

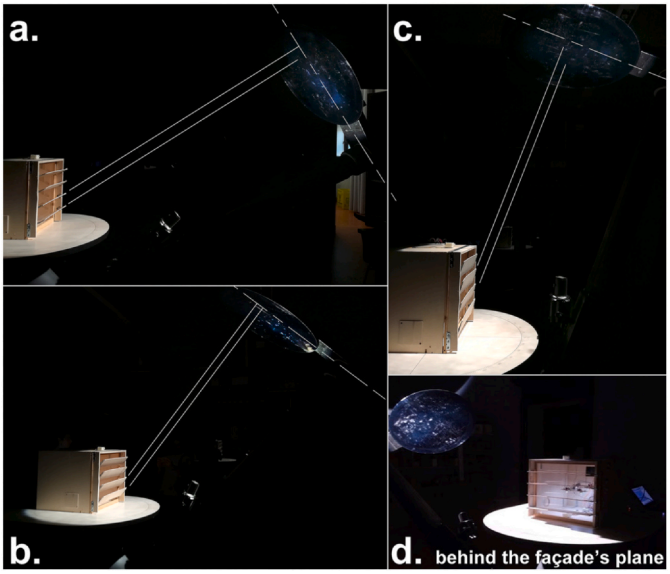

Fig. 19. Heliodon tests showing the alignment between the blinds, in winter automatic mode, and the sun when both the system and the Heliodon work in the same location, day of the year and hour of the day. In addition, case (d) shows the activation of the artificial lighting system to compensate natural illuminance levels. In case (d) blinds are horizontally positioned because the sun behind the façade.

the prototype box) are sufficient to keep the illuminance threshold. However, when the outdoor light goes below 1000 lx, the second set of LEDs has to be turned on with lower power to guarantee the average illuminance threshold. This behaviour shows the system's ability to control light power consumption thanks to the reaction to natural lighting variations over time.

3.2. Outdoor testing

The outdoor test was performed with the aim of observing how the system reacts in a real environment – see Fig. 21. These tests were executed on the 27th of June 2019. Being a sunny day, the outdoor illuminance was very high; for this reason, in order to facilitate the readability of the graphs, the outdoor light level is not shown in the graphs which report test results. In Fig. 22 the results of one of the executed tests are shown. Fig. 22 (b) illustrates how the angle of the blinds changes over time to keep the indoor light illuminance near the threshold value – see the graph in Fig. 22 (a). During this test, the system is set via the mobile app to summer automatic mode and the

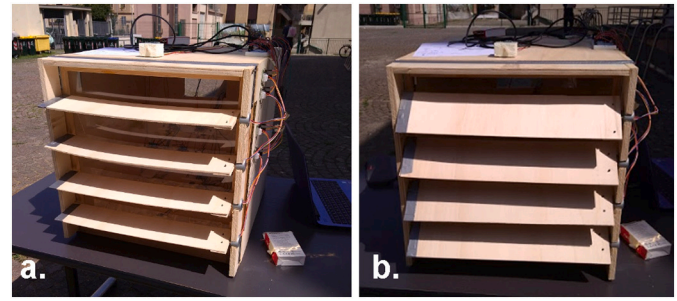

Fig. 21. Prototype positioning during the outdoor test; (a) blinds open completely during the initial configuration procedure; (b) blinds perpendicular to sunrays to reduce internal luminosity.

prototype reacts in such a way as to guarantee the required indoor illuminance level (fixed in this case to 600 lx), without activating lighting artificially. The system acts in order to ensure that only the required amount of sunlight enters by shading additional heat gains to reduce cooling loads. This indirect control helps to eliminate the risk of glare, even though additional tests on this specific point will be developed in future research. Variations in shading positioning are due to cloud movement. Results of a second test (II) are comparable to the discussed ones (test I) – see Fig. 22. In this second test the indoor illuminance level is also maintained at an almost stable level with respect to the mobile app threshold by automatically adapting the blind position. Since outdoor illuminance is drastically high, no artificial light is required.

In order to provide further quantitative analyses of the results, the margin of error of the controller was calculated based on indoor light measurements. As underlined in Fig. 22 and calculated for all given tests, the system reaches a steady state in less than 100 s on average. In order to characterize the error of the system for the two cases in Fig. 22, the system behaviour was divided into a transient state error phase (before 100 s) and a steady state error phase (after 100 s). In particular, the transient state error for test I, i.e. Fig. 22 (a) and (b), was calculated to be 13.83%, while its steady state average error was 1.81%. In test II, i.e. Fig. 22 (c) and (d), errors were respectively 11.98% for transient state and 1.57% for steady state. It is evident that the proposed solution is able in maintain the required illuminance threshold with a low error risk.

3.3. Indoor testing

In order to check the ability of the system to reach the desired threshold by controlling both shading and lighting subsystems, the prototype was tested on an indoor environment with a lower

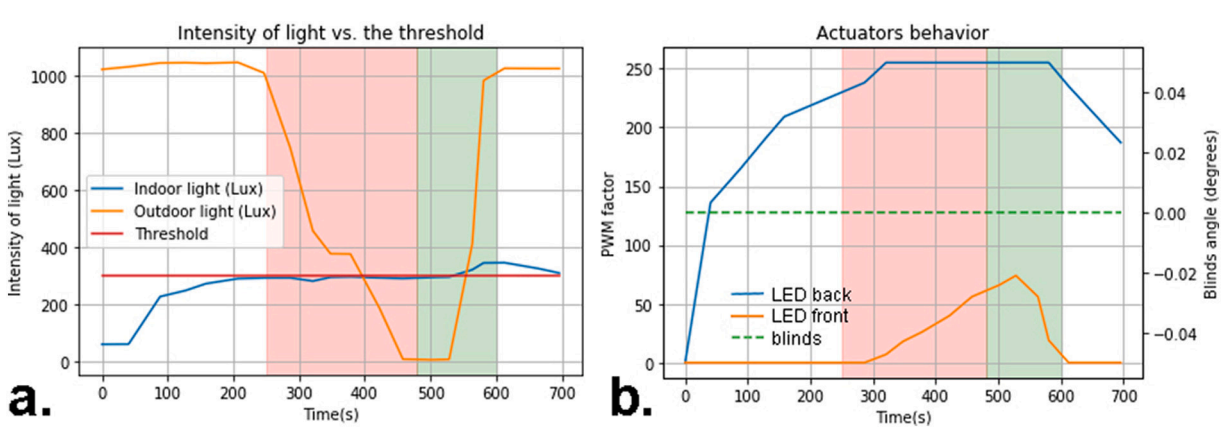

Fig. 20. (a) indoor and outdoor illuminance measured during the Heliodon test with fixed open blind position; (b) the LED PMW power factor which is able to maintain the indoor illuminance threshold over time (higher line refers to back LED line; lower line to window-nearer one).

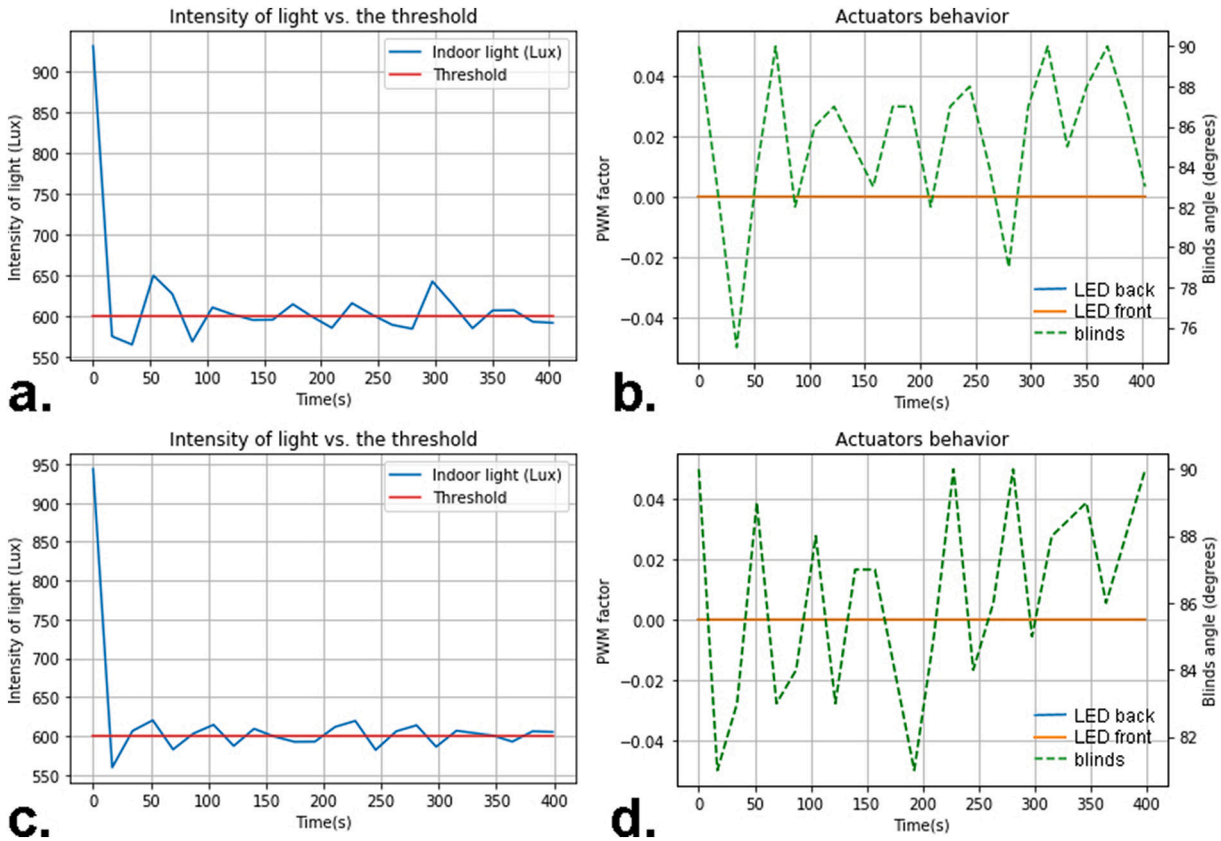

Fig. 22. Outdoor test I (above) and II (below). (a) illuminance monitored values in the indoor environment – outdoor levels are not shown as being sensibly higher than 10,000 lx; (b) blind angle variations over time. (c) same as (a), but for test II; (d) same as (b), but for test II.

environmental light illuminance. Fig. 23 (b) shows how the system actuators react to different threshold levels by changing the angle of the blinds (dotted green line) or by changing the power of the LEDs (continuous lines). Additionally, the advantage of having 2 independent sets of LEDs is observed (firstly by activating the line which is farther away from the window, and then the second line when higher artificial illuminance levels are needed). In this way, the indoor light distribution (average monitored values by the 3 sensors) can be controlled better and the energy consumption can be reduced. Furthermore, Fig. 23 (a) shows the sensibility of the system by demonstrating how fast the indoor illuminance reaches the desired threshold when the threshold value is changed. The system is able to reach the desired value in less than 100 s when the increase in the threshold level is of about 100 lx. However, looking at Fig. 23 (c), it can be noted that for larger changes (about 500 lx) the system may take more time. Additionally, in the case shown in Fig. 23 (c) the desired threshold of 600 lx was not reached because the combination of outdoor light plus artificial light was not enough to reach this illuminance (LED were dimensioned to assure about 350 lx on the monitored area). Fig. 24 shows the ability of the system to maintain indoor illuminance over time with a fixed threshold set at 300 lx, when the outdoor level is near 350 lx. It can be concluded that the system reaches the desired threshold, when the set illuminance can be delivered, in a reasonable time for a real building scenario.

The variation of the PWM factor that controls the LEDs – see Fig. 23 (b) and (d) – can be used to calculate the average power consumption of the artificial lighting system in consideration of the two tests presented in Fig. 23. In order to perform this calculation, the PWM is firstly converted into power by adopting Eqs. (1) and (2), and secondly the average power is calculated based on Eq. (3). P_o corresponds to the peak power of the LEDs, which according to their datasheet is set to 1 W.

$$P(t) = P_o \bullet (DC_{(\%)}) \tag{1}$$

$$DC_{(\%)} = PWM_{(factor)} \bullet \frac{1\,[W]}{255} \tag{2}$$

$$P_{(avg)} = \frac{1}{2T}\int_0^T P(t)dt \tag{3}$$

The first equation describes the relation between the duty cycle and the power. Eq. (2) defines the relation of the PWM factor (which is a number that varies from 0 to 255 for 8-bit PWM) to the duty cycle. Finally, Eq. (3) is the given expression to calculate the average power of a signal. Fig. 25 (a) and (b) shows how the power consumption of the LEDs varies in time. To calculate the average power consumption of the LEDs, Eq. (3) is applied using the trapezoids integration method. The average power consumption for a single LED was calculated for both tests reported in Fig. 23 in consideration of frontside and backside LED lines. In particular, the average power of a single frontside LED was 0.04 W and 0.09 W respectively for test I and II, while the average power of a single backside LED was 0.30 W (test I) and 0.26 W (test II). Based on these results, it is possible to calculate the average power consumption of all LEDs (there are 2 at the back and 2 in the front) in both tests, being respectively 0.70 W and 0.69 W. If we compare the results obtained with the system driven without any control (power consumption equal to 4 W, 1 W by each LED), it is evident that that the developed IoT solutions should be able to guarantee great advantages thanks to LED control. If the behaviour of the backside and frontside LEDs is compared, it is possible to check the effects of different control strategies. In particular, when frontside LEDs were controlled by the proposed approach, the power consumption (session II) was calculated to be 2.18 W if the backside LEDs were not controlled and 0.69 W, when both sides were controlled. On the other hand, when backside LEDs were controlled and frontside LEDs not controlled, power consumption was calculated to be 2.51 W. Of course, the great potential reduction in power consumption is due to the control of the illuminance threshold

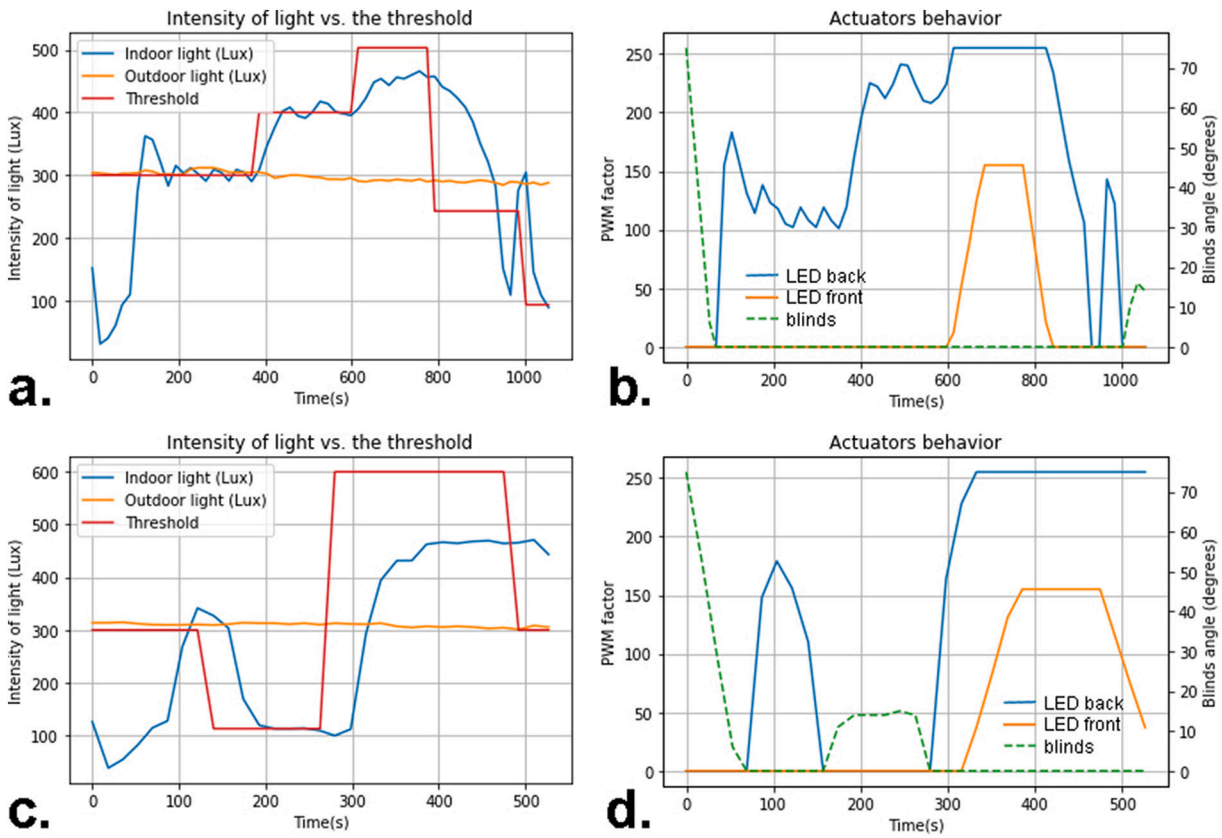

Fig. 23. Indoor tests: Test I, (a) changes in the illuminance monitored values in the indoor environment according to different defined thresholds; (b) blind angle and LED power variations over time to guarantee the required indoor threshold; Test II (c) illuminance levels monitored during wider threshold changes; (d) related LED powers and blind angles over time.

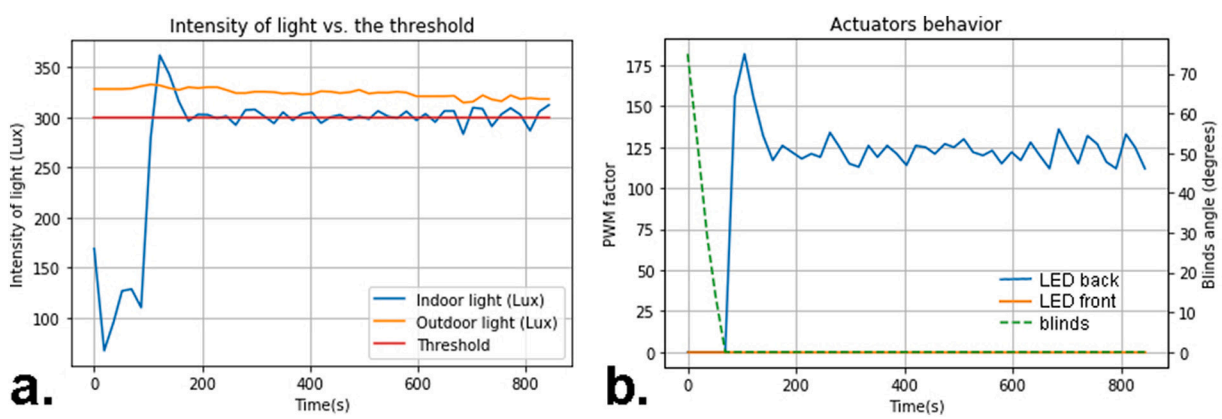

Fig. 24. Indoor test with fixed illuminance threshold: (a) illuminance monitored values; (b) blind angle and LED power variations over time to guarantee the required indoor threshold – blinds are operated in the first 100 s (opening) and then the system activates the LED procedure to reach and maintain the desired threshold.

acting on both artificial LED PWM and natural light maximisation to reach the given illuminance.

4. Conclusion, limitations, and future work

The paper presented a new low-cost IoT solution to control indoor illuminance levels by balancing daylight and artificial light. In addition, the system includes a shading control with seasonally defined modes. The required illuminance threshold can be set in line with standards, or modified by a users' mobile App thanks to which the automatically maintained threshold can be changed. Furthermore, a manual mode is defined and can be controlled via the same mobile App to enable people to set LED intensity and blind positions. Fuzzy logic was applied to control the whole system which resulted in fast response, prompt reaction to environmental changes, and low computational requirements. In line with underlined open challenges in literature, the whole system is based on simple microcontroller boards for sensing and actuator nodes and is driven by a RaspberryPi main unit. First testing results show that the developed prototype has good potentiality and could become a benchmark for low-cost commercial solutions for facilitated control of illuminance and shading systems in a space, while assuring system scalability. The paper describes the developed system framework and control logic together with a prototype implementation of the proposed IoT system reaching a TRL between 3 – “Analytical and experimental critical function and/or characteristic proof-of-concept” – and 4 – “Component validation in laboratory environment”. In fact, the

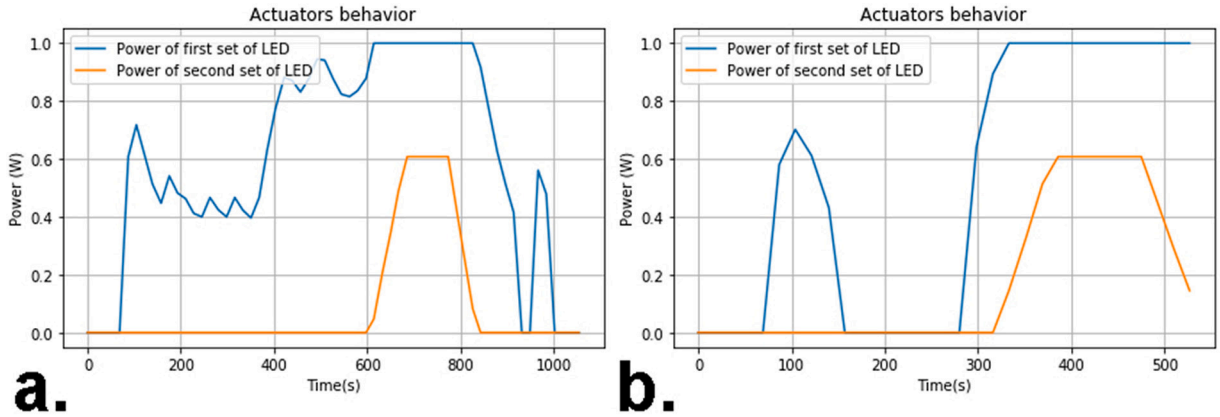

Fig. 25. Calculated power consumption of LEDs for (a) Test I reported in Fig. 23 (a), and (b) for Test II reported in Fig. 23 (c).

design idea and methodology is described in detail and implemented in a prototype that was tested for critical functionalities in specific conditions, in line with objectives. Nevertheless, advanced quantitative monitoring campaigns will be implemented in future works to test system functionalities over longer timespans and in comparison with other solutions. The following limitations need to be underlined. The chosen motors do not provide feedback of their current position. Hence, it is necessary to manually check that all blinds have the same starting position, because if this procedure is not well executed the error in the position cannot be automatically corrected over time. Nevertheless, this issue can be easily solved by adopting more robust motors that provide information about their current position, even if higher costs may be expected. In any case, even if in the proposed motor system works in an-open look control, changes in motor angle are recorded and saved in the RaspberryPi, while a feedback for the whole system is guaranteed by the upper level of the developed control, thanks to the closed-loop driven by illuminance sensor values. Thanks to this check, even if blinds are not aligned, the required threshold can be reached and maintained because the system self-adapts to conditions. During the development of the prototype, it was discovered that the adopted LEDs did not provide the correct amount of luminous flux – and consequent intensity [cd] to the task area – mentioned in the datasheet. Therefore, a small structure was implemented to reduce the distance between the LEDs and the light sensors to maintain the required illuminance – 300 lx – in the task area. If higher illuminance levels need to be guaranteed, such as the 500 lx threshold suggested in standards for several activities, higher power LEDs must be adopted. However, the system implementation would use the same hardware scheme that is described in this paper, thanks to its adaptability and scalability. Only MOSFET and LED power systems may be adapted, in line with the requirements of different LED sources. At present the prototype has been tested over a limited time period. The main functionalities of the proposed IoT system and control procedures have been checked, while longer test procedures are needed in future steps of the research to verify the functionality of the proposed approach in a whole seasonal/yearly operation which also includes a reduction in system activation when threshold is reached. Furthermore, a campaign which combines monitored results and (people sensation) surveys to gather user reaction would provide valuable feedback as regards the acceptability of the proposed control system and the interaction of users with the proposed mobile app. A connected limitation of this study refers to the need to analyse the passage form a prototype box to a real room environment to take care of users' real behaviours and sensations to compare the system technical functionality with user interactions. Furthermore, the prototype box was defined to work with one user at a time (the last user will define the required set of thresholds – like if there is a responsible people in the room or a shared tablet), while in future developments multi-user interactions will be tested to analyse how to balance parallel requests for different illuminance levels. Nevertheless, the system scalability allows already to define different LED actuating systems, being controllable by a specific user, by multiplying the number of sensing and actuating subsystems and correlating them with specific users in the App solution. Additional efforts are planned to provide a general room control of shading and average minimal illuminance values in combination with task-driven areas in which a specific user may manually change the local illuminance threshold. The following features are expected to be implemented in future research steps to improve the system. The first feature concerns the application of a full Internet of Thing parading which implements microservices and migrates the code to an object-oriented model. Furthermore, other sensor types are expected to be included to ensure a more complete comfort approach, including temperature sensors to substitute winter and summer modes, IAQ sensors to support window opening or fan activations, and additional light sensors and parallel LED lines to have a more precise control of zonal lighting in the space when required. Finally, a data analysis module can be implemented, based on the collected data, to improve system performance thanks to a learning approach, by hybridising fuzzy logic with other methods such as machine learning. Furthermore, the objective is to reach higher TRLs in the future thanks to additional funding in order to develop a full experimental validation of the implemented solution firstly in the box during over a long time span, as mentioned before, and also, in a real environment – e.g. an office room – to upgrade the solution until TRL 6.

Author contributions

Conceptualization, all; Data curation, DDV, AG, AHM, JCLR; Supervision and Funding acquisition, GC; Writing—original draft, all; Writing-reviewed version, GC.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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