ClimaWin: An Intelligent Window for Optimal Ventilation and Minimum Thermal Loss

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***Abstract*—In this paper the ClimaWin concept is introduced. The ClimaWin project's main goals are to improve both indoor air quality and the energy efficiency of new and refurbished buildings, through the use of novel green smart windows. Generally, in order to improve windows' energy efficiency better insulation materials are used in windows frames and glasses. However, this approach leads to a severe deterioration of indoor air quality (IAQ) especially in buildings that are not equipped with heating, ventilation and air conditioning (HVAQ) systems.**

The Climawin windows do not require wires neither for power nor for communications. The window is powered through a battery (for blind operation) and a solar panel, which makes it an ideal solution for retrofitting. In order to achieve the energy efficiency requirements, the Climawin system hardware, the microcontroller software architecture and the radio communication strategy were designed for low power consumption. Furthermore, all the information about the system status can be monitored and actuated using intuitive graphical applications developed for PCs and Android OS smartphones. A remote database keeps all the relevant information about the system, making it easy to detect any anomaly or even to adjust the control algorithm parameters from a remote location. A full-set of web services are also provided in order to simplify the communication with home automation systems.

***Index Terms*—Intelligent window, STM300, ENOCEAN, energy harvesting, energy efficiency, low-power, indoor air quality (IAQ).**

I. Introduction

Nowadays there is a growing social concern about energy efficiency. Whether motivated by the requirements imposed by governmental entities or simply by common sense, more and more people's habits, practices and decisions reflect this concern; the construction industry is no exception. There is a growing demand to find solutions capable of improving the buildings thermal insulation, in order to improve energy efficiency. However, there is a significant drawback with this approach because using better insulation materials and reducing air leakage, reduces the air renewal. So, if the building has no HVAC system installed, the IAQ is worsened leading to potential harmful consequences for human health.

A 2005 study [1] on the European windows market projected that in 2009 about 72 millions units would be traded, with an expected return of more than 16B€. More recently, in 2010, another study [2] pointed to over 125 million units, thereby increasing the expected monetary return. This clearly indicates the emergence of a new market niche that properly explored, can solve the previously explained problem.

The ClimaWin system was developed to meet this new demand. Based on intelligent windows equipped with completely novel technology, it uses radio communication, sensorial information and actuators to control ventilation, thus improving IAQ and optimizing the air flow. This system can either replace or coexist with the HVAC systems to significantly improve performance and reduce power consumption. The control algorithm relies on monitoring of comfort parameters, particularly humidity, temperature and carbon dioxide (CO_2) level from the occupied zone.

The system essentially comprises four components: the window controller, the zone controller, the router, and the remote control switches. As depicted in Fig. 1, the window controller is installed in each window and allows its respective control and monitoring. Due to energy harvesting mechanism implemented in the window controller, each sector has an associated zone controller responsible for storing the status of each window's sector. This device works like a repeater, and apart from communicating with the different windows, also sends all the information to the router. The router is responsible for storing all the information in local and remote databases, while allowing the monitoring and/or control of the window through a computer or an Android smartphone. The remote controls still allows acting on the blinds manually.

This paper presents an autonomous, efficient and low-power system, capable of controlling and optimizing air flow and IAQ, as well as simultaneously maximizing energy efficiency. The remaining of this paper is structured as follows: in section II the system architecture is presented and discussed; section III presents the developed hardware; in section IV the software is explained; section V shows experimental results; finally, section VI presents the conclusions.

II. System Architecture

It is crucial to the success of this system that no power or communication cables are needed, allowing retrofitting existing buildings without making significant changes to the building, and therefore, minimizing the installation costs and possible permit issues. Besides, the system components count should also be minimal, reducing the cost without compromising the scalability and flexibility of the system. As shown in Fig. 1, there are four main components: the window controller, the zone controller, the remote controls and the router.

The window controller's job is to control/command the actuators installed in the window (blind position, valve and

Fig. 1: System Architecture: overview

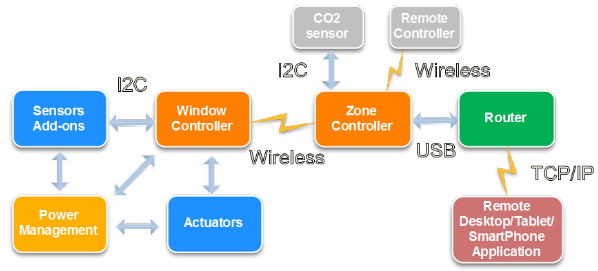

Fig. 2: System Architecture: block diagram

air flow) based on sensors information. This actuation may take place either by the windows control algorithm decision or as a response to a remote control command emitted by a device present on the system network. As such, and taking into account that the radio frequency (RF) receiving circuit consumption can range from some milliwatts to several thousands, a compromise must be considered: with the receiving circuit always enabled, the batteries will drain very quickly requiring larger solar panels and batteries; on the other hand, if the receiving circuit is off during large periods, the associated risk of losing RF packages poses an unacceptable scenario. To solve this issue, the window controller will be allowed to sleep (very low power consumption) for short periods of time; at the same time, a mailbox system will act as a middleware layer between the window controller and the system network, hence the need for a zone controller device.

So, the zone controller's role will be to hold any data dispatched by other system devices, while the window controller is sleeping, and forward it to the window controller as soon as it awakes. A single zone controller can manage the mailbox of several windows; it remains, nonetheless, an optional device required only when data needs to be forwarded to the window controller, such as, the CO_2 value, remote control commands or information from a backbone connected to a home or building automation system. Since the zone controller's RF receiving circuit must be always enabled, this device can work as a signal repeater, thus enforcing the signal strength of the surrounding network nodes. Each zone controller can have an optional CO_2 sensor; it is the customer's choice to either get the CO_2 values from a 3rd party sensor or from the zone controller itself. The quality of this measurement is limited by the position where it can be placed (since the zone controller must be line powered) especially in retrofitting installations.

The remote controls are meant to control the window itself, somewhat similar to an air conditioner or even a TV remote control.

Another optional but appealing element for the system is the router. Commercial routers, apart from being well established, massively used and reliable devices, are an excellent choice to serve as a gateway connecting the ClimaWin system to the building's network and latter to the internet, if need be. This way, the router will provide a service from which 3rd party applications, designed for Windows or Android, can retrieve information about any sensor part of the ClimaWin system network and also command any actuator.

Fig. 2 depicts how the basic building blocks of the system interact among themselves. The window controller is physically placed inside the window and it is able to read the temperature, humidity and light sensors (interior and exterior). Since there are no cables coming out from the window, a single zone controller can manage a room with more than one window; in this case the CO_2 value that is retrieved from this zone controller, can then be forwarded to the window controller as needed by the control algorithm. Finally, a commercial router (with a free standard USB port), can serve as a bridge between the ClimaWin system and any remote hi-tech device, like a tablet or a smartphone.

III. ClimaWin: Hardware

All hardware that implements the system, with the exception of the router, was designed, developed and assessed in-house, by the ClimaWin development team. In other words, both window and zone controller, as well as the sensors and actuator board add-ons, were developed ex-nihilo. The router, in turn, is a commercial of the shelf product (COTS) to speed up the development process.

A. *Window Controller*

As explained in the previous section, the window controller board is responsible for the window's control and monitoring. Therefore, it is made up of sensorial, actuation, computation and communication components.

So, this board is equipped with a system-on-chip (SoC) STM300 from ENOCEAN [3], the unit responsible for all computation and radio communication (operating at 868MHz) with zone controller. For the sensors, some connectors are provided to link add-ons, explicitly inside and outside humidity and temperature sensors, magnetic rotary encoder (to determine valves' position), and light sensor. In all of them some power management mechanisms are implemented, in order to power the sensors only when it is necessary to

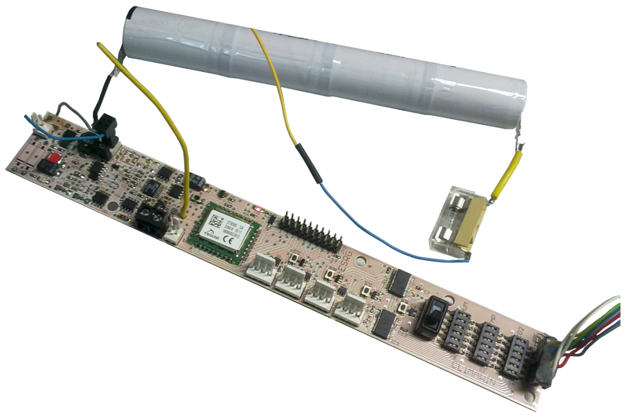

Fig. 3: Window Controller board

Fig. 4: Zone Controller board

measure the required comfort parameter. For the actuation, a connector is also provided to link a power board that controls blinds and valve motors. The window controller is powered through a 4-cell battery VHT Cs from Saft [4], and also has a storage system based on solar panels. Three solar panels are used (connected in series), with 1W and 6V nominal power and voltage, respectively. A battery USB charging system, based on LTC4011 chip from Linear Technology [5], was designed to solve emergencies like lower solar radiation during long periods (e.g. Nordic countries) or solar panel damages. Finally, some buttons are provided to configure the system, and also hardware to program the SoC. Fig. 3 presents the window controller board.

B. Zone Controller

In order to minimize power consumption, the window controllers spend much time in sleep mode, thus it was necessary to develop an intermediary hardware responsible to hold the window controllers information.

The developed circuit is equipped with an STM300 SoC, and incorporates a COZIR Ambient CO_2 sensor [6], with power management hardware to enable the power supply only when it is necessary to register the CO_2 level. As interfaces, zone controller provides: (i) USB interface for PC or router communication, and (ii) serial interface for router communication. There is also a display that identifies the house's sector, and hardware to reprogram firmware. To ensure system integrity, the zone controller must forward to the router all actions associated with each window and so it must be permanently powered. Fig. 4 presents the zone controller board.

C. Router

Since it was necessary to port an in-house application to the router, its model was chosen based on compatibility criteria and support level from the OpenWRT [7]. As such, from the lengthy list of possibilities, the final decision fell onto the WRN3500L from NETGEAR [8]. This device comes with the following: 480MHz of CPU speed; 8MB Flash; 64MB RAM; USB host support. When compared with its competitors, for instance, the Linksys WAG160N and the Asus N600, the selected model presents itself with better hardware at a lower cost.

IV. CLIMAWIN: SOFTWARE

The development of both the window and zone controllers software was greatly simplified by using the ENOCEAN SoC, which is provided with a stable and complete application programming interface (API) library that implements the proprietary ENOCEAN wireless standard.

A. Window Controller

The main software algorithm for this device is very straightforward with difficulties arising only due to hardware limitations inherent to the windows mechanism. It has seven main tasks: (i) read the local sensors data; (ii) request CO_2 from zone controller; (iii) apply control algorithm; (iv) actuate based on the control; (v) low power sleep for 100ms; (vi) verify if actuation is complete (i.e. if the valve and blinds is in the requested position); (vii) low power sleep for 2s.

After the microcontroller wakes up, from the low power sleep, and starts the first job, it is necessary to wake up the respective local sensor since they are shutdown from power to conserve energy. As such, this operation must be dealt with care taking appropriate turn-on delays before starting to communicate with the modules. Albeit being a tedious software effort it heavily contributes to the board's life expectancy. The implemented control algorithm is based on specific thresholds of some physical quantities. For example, if the CO_2 level is higher than 1500ppm, the window controller should actuate the valve to renew the air in the room. The software must also be prepared to deal with the various types of motors that can be plugged to the window. Other feature of this device is the learning protocol that is explained in the zone controller section.

B. Zone Controller

The zone controller device manages the communications traffic of a window controller due to the low power strategy that is crucial to the feasibility of the system. Since it would be overkill having one zone controller for each window, the zone controller's software makes it possible to associate a number

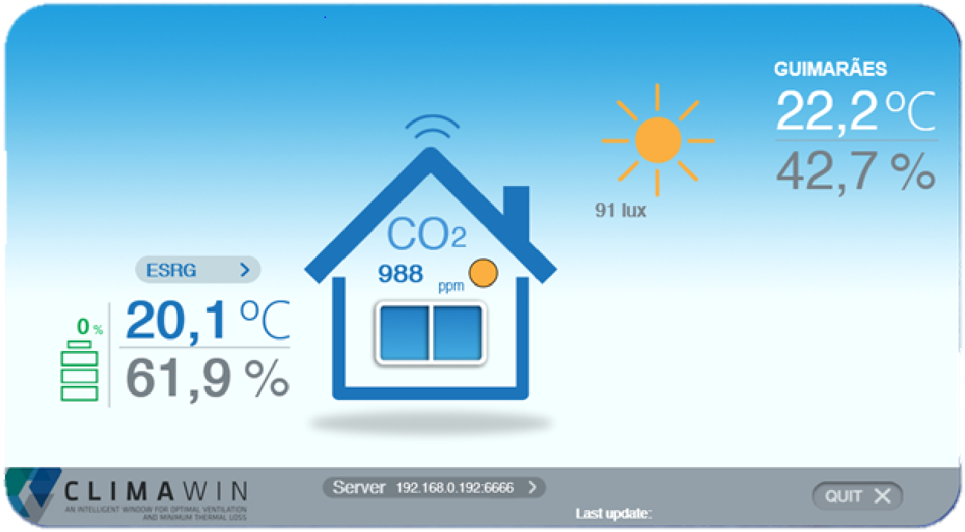

Fig. 5: PC GUI

of windows to its mailbox system. However, since this is a wireless management, a concerning problem arises; how is the zone controller supposed to find out which windows will it manage? This is clearly an issue that should be dealt with at the system installation/maintenance because the specific windows that are installed in each building are unforeseeable at production time, thus creating the need for a sophisticated learning methodology. As such, either at installation or maintenance time, the zone controller device is able to enter a learning state, at which time, one or more windows can issue a learn request. Upon each successful acknowledge from the zone controller, a virtual link is then established between the window and the zone controller, becoming the last responsible for that window communications traffic. The same process is used to link a remote controller to the specific window it must control. Despite all this, the system must also be prepared to deal with a removal or even a relocation of the window. As such, the learning protocol permits the window to secede its zone becoming readily available to join another one.

To manage the communications traffic of the several windows a zone controller can manage a mailbox system implemented based on the API available to the EO3000I chip. The zone controller intercepts, in real-time, all RF signals and matches the data against the list of learned windows and remote controls; if there is a positive match (the respective devices are present of the learn list) the zone controller manages a mailbox so that the messages and exchanged when the window controller device is turned on. The memory management subsystem stores this data table in flash memory area so that it is not lost even in case of a power failure, which would otherwise result in the seceding of all devices and thus requiring another learn action.

C. Router

Since the zone controller feeds every recognized radio telegram to the USB port, the router must take measures to interpret that information so it can be provided to any hi-tech device that wishes to read its information. A daemon is then listening at the USB port, being capable to parse and recognize the ENOCEAN standard protocol, thus detecting when a learn action is successfully completed. This allows a partial replication of the zone controller's device mailbox table; the entailed purpose of this lies elsewhere, being that it is only essential to filter out the data relevant to identify the windows and each window's sensors and actuators state, as well as the CO_2 level for that zone. Since the hi-tech devices are supposed to play a dynamic part, the router must also listen to requests concerning the state of the window actuators, for instance, the blind position. All traffic is recorded to a small local database being periodically uploaded to a remote bigger database, because routers typically have low memory resources. Despite the previous reason, this opens other doors, like the possibility of merging data from all buildings to perform global analyses and viewing usage patterns through an enriched web page, which can also be used, for instance, to control multiple windows at the same time.

D. GUI: PC and Android Smartphone

To monitor and control the ClimaWin system, two remote applications were developed, one for a Windows PC and another for Android OS smartphones. Since the look and feel of both applications is very important, they were designed separately allowing each to mold itself better to the target architecture it is meant for. In order to work, they must either connect directly to the router or even from anywhere in the world in case the router is also connected to the internet. The main functionalities are basically the same, which are to monitor each window individually and change any of its parameters, as well as to read the CO_2 value for the zone it is inserted. Fig. 5 presents a screenshot taken from ClimaWin PC application.

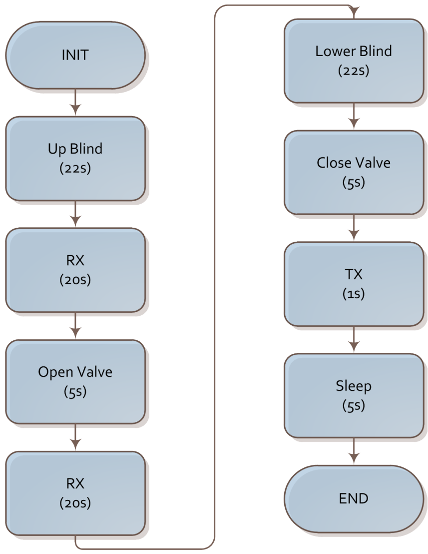

Fig. 6: Subsystems Comsumption Experimental Test: algorithm

V. Experimental Results

To assess the window's battery performance (window controller, sensors, and actuators), the power consumption of different subsystems was separately analysed. Fig. 6 presents a flowchart that describes the performed tests, while Table I presents the power consumption results. So, based on these results it is possible to predict the windows battery life. Hypothesizing three and five daily blind and valve actuations, respectively, Table I presents the results of this prediction. Assuming a safety coefficient (20%), which reflects battery self-discharge and temperature variation, it is expected that system can remain operational (without any charging) for 56 days (approximately two months).

Although the previous results present a battery life prediction of about 56 days, it should be considered only as a worst case scenario since no solar charging was considered. As already referenced in this paper, this system has a mechanism to store solar energy. As such, the window controller has built-in hardware to perform a constant charge for the battery, powered through the energy provided by solar panels. With this, battery lifetime increases relatively to the previous prediction. To understand how the solar radiation affects battery charging system, in other words, how much energy can the solar panels provide according to different radiation levels, it was necessary to develop a system capable of simulating solar radiation. This, in turn, makes it possible to simulate the estimated radiation in different cities from different European countries.

Based on a 10 years study performed by NASA [9], it was decided to realize experiences with two different levels of insolation: (i) $90W/m^2$ radiation, which resembles to an insolation below the lowest annual average radiation of all European countries; (ii) $30W/m^2$ radiation, which corresponds to winter average insolation in Nordic countries. The first experimental lasted more than 5 hours and reported an average current of

TABLE I: Battery Lifetime

Battery Lifetime	
Up Blind (A)	0,80400
# Daily Actuation	3
Consumption Time (s)	22
Daily Average Consumption (A-h)	0.01474
Lower Blind (A)	0,69500
# Daily Actuation	3
Consumption Time (s)	22
Daily Average Consumption (A-h)	0.01274
Open Valve (A)	0,12800
# Daily Actuation	5
Consumption Time (s)	5
Daily Average Consumption (A-h)	0.00089
Close Valve (A)	0,13200
# Daily Actuation	5
Consumption Time (s)	5
Daily Average Consumption (A-h)	0.00092
Consumption in TX (A)	0.01900
TX time (s) in 24 hour	100
TX Daily Average Consumption (A-h)	0.00053
Consumption in RX (A)	0.03300
RX time (s) in 24 hour	200
RX Daily Average Consumption (A-h)	0.00183
Consumption in Sleep (A)	0.00006
Sleep time (s) in 24 hour	85900
Sleep Daily Average Consumption (A-h)	0.00143
Total Daily Average Consumption (A-h)	0.03127
Ideal Life Time (Days)	64
Expected Life Time (Days)	56

TABLE II: Battery Lifetime including solar panels

Battery Lifetime including solar panels	
System Daily Average Consumption (A-h)	0,03127
$90W/m^2$ Daily Average Charge (A-h)	0,02200
Differential Daily Average Consumption (A-h)	0,00927
Expected Life Time (Days) - $90W/m^2$	190
$30W/m^2$ Daily Average Charge (A-h)	0,00720
Differential Daily Average Consumption (A-h)	0,02407
Expected Life Time (Days) - $30W/m^2$	73

22mA. In turn, the second test, which lasted for 4 hours, results on a average current of 7.2 mA. With these results we conclude that the expected battery life in the worst European scenario will last approximately 190 days. During winter it is capable of powering the system for almost 73 days. Table II summarizes the results obtained. However, considering the winter worst case scenario where the battery has to be charged after two and half months, it is expected that there is no need for a second charge throughout the year since in the remaining months the average level of insolation is greater than $90W/m^2$, reaching at least the $180W/m^2$ through summer. In short, based on the performed tests and the obtained results, it is expected that the system will work perfectly with only one USB annual charging, held at the end of the winter. Therefore, in addition to the solar panels charging mechanism, the system also has an USB charger for critical situations.

All measurements were performed using Precision Power Meter LMG95 of ZES ZIMMER Electronic Systems [10], and corroborated using the digital multimeter from Keithley Instruments KEI2100 [11]. All solar radiation measurements used to develop laboratory insolation simulator were made

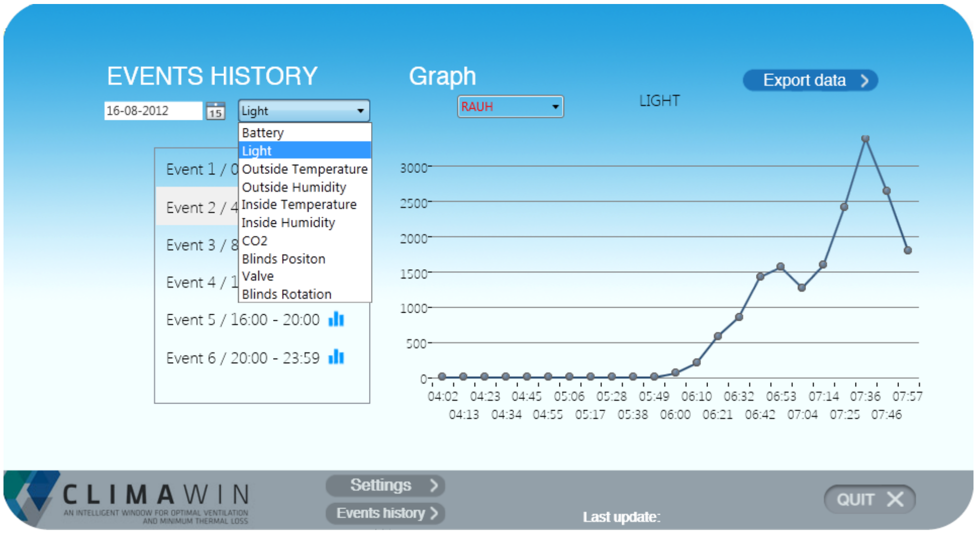

Fig. 7: GUI interface to access remote database

with the radiometer HD2101.1 from Delta Ohm [12].

VI. Conclusion and Future Work

The ClimaWin is a multi disciplinary project with several scientific areas playing together to achieve a common goal: increase the buildings energy efficiency.

Based on the restrictions presented and the results achieved in the previous section, it is safe to conclude that the ClimaWin system is highly energy-aware since in that scenario very few USB charges are enough to power the system throughout the year, with optimal solar exposition.

The prototypes were assessed at Fraunhofer IBP (Institute for Building Physics) and all the gathered data was successfully stored to our remote database through the router's daemon application. These tests were carried out during four weeks and they demonstrated all functionalities provided by these smart green windows. In Fig. 7, the GUI interface to access the remote database is depicted. This interface allows the selection of the individual window, the time frame of the gathered data, the data source and allows to export this data to an excel spreadsheet. Also in Fig. 7, the evolution (16th August 2012, from 4:00am to 8:00am) of outside light is showed. Likewise, it is possible to analyse gathered data regarding the battery level, inside and outside temperature, inside and outside humidity, blind and valves positions, and CO_2 information.

In summary, the results obtained at Fraunhofer IBP are an evidence of the successful design of the ClimaWin window' concept, demonstrating the suitability of these smart green windows to meet the requirements of modern buildings in terms of energy efficiency and indoor air quality.

As future work the prototypes will be adapted for market production, and a few features will be added, such as auto-calibration of sensors and the incorporation of more green energy sources for system energy harvesting.

VII. Acknowledgements

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