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## Development and testing of a platform aimed at pervasive monitoring of indoor environment and building energy

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### Abstract

The interest of the building energy sector is leaning towards the measurement of building actual performance, as regards both indoor environment quality and energy consumption. Sensors and central elaboration units aimed at monitoring indoor environment and HVAC system parameters can also provide the basic infrastructure for further applications such as predictive and neuro-fuzzy controls. However, the cost of such systems is high, so they are mainly used in large buildings. This paper describes the main features and expected applications for a low-budget monitoring platform currently under development and tuning. In particular, the monitoring system was developed based on electronic prototyping platform Arduino and on sensors and devices usually available in the retail market of electronics. The monitoring platform has been designed with the following characteristics in mind: replicability, full remote control, portability, versatility, reliability and affordability.

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### 1. Introduction

The rapid development of domotics and building management systems (BMSs) in the building energy sector is stimulating interesting perspectives about the chance to record data from a large amount of buildings, besides usual indoor environment and HVAC system monitoring. Moreover, additional applications might consist in the collection of large quantities of data from which statistical figures about the indoor environment management and energy

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consumption in buildings could be inferred. For instance, such data might be used to derive building energy evaluation models based on actual energy consumption measurements. However, such applications would require an even higher number of buildings for the achievement of reliable figures and related correlations and that would require long time because of the limited amount of (usually expensive) BMSs installed and because of the difficult synthesis of different data formats resulting from BMSs developed by different manufacturers.

In the frame of this research activity, a low-cost wireless measurement platform is being developed, together with the instructions and schemes aimed at hardware construction and software implementation, in order to aid researchers, professionals and technicians in the replication of this platform.

The hardware developed in this research consists of:

- Monitoring Hubs (MHs)
- Monitoring Units (MUs)

Each MH coordinates measurements, supplies energy to up to three MUs, logs measured values on SD cards and uploads/downloads data and settings through Wi-Fi connection. Each MU is managed by the hosting MH and contains all the circuitry needed for measuring a specific parameter. MHs are developed in order to manage many different kinds of MUs and their settings and management behaviour will be defined by the user through a web interface.

Of course, some projects aimed at the development of low cost monitoring platforms already exist. For instance, Open Energy Monitor [1] is a project aimed at the development of open-source energy monitoring tools in the field of energy use and monitoring. Furthermore, WiSensys [2] is a wireless, easy-to-install and ready-to-use sensing system with data logging capability, designed for a variety of sensors, such as temperature, humidity, CO<sub>2</sub> and energy sensors. Also Shah and Mishra [3] developed a customized Internet of Things (IoT) enabled sensing and monitoring platform to monitor temperature, relative humidity and light in the context of building automation. Harfield and Rattanongphisat [4] propose a monitoring platform empowering users to make intelligent decisions about energy efficiency, by sensing temperature, humidity, power and occupancy information about a room and providing services aimed at energy saving and comfort maximization. In the same field but focusing more to energy awareness, Bouhafis and Rajabi [5] present an energy monitoring system offering consumers the possibility to monitor the energy utilization of their appliances and built over a sensor network's open platform.

Another relevant context for the development of such platforms consists in the monitoring of environmental conditions. For instance, Smart Citizen Platform [6] is a platform aimed at promoting the participation of people by sharing measurements of temperature, humidity, light, sound, CO, NO<sub>2</sub>. In the same context, AirSensEUR [7] is an open source platform developed by the Joint Research Centre and a SME specialized in IoT, for monitoring ambient air quality using low-cost sensors. Schima et al. [8] describe the development of a monitoring system covering data collection, data processing and data integration as well as data provision within one infrastructure able to acquire temperature and humidity in space (GPS) and time (real-time clock) as a built in function.

More monitoring platforms have been developed for other contexts, such as civil infrastructure, as shown in [9] and [10], and gardening, with the Open Garden platform [11], allowing the control of the state of the plants by sensing several parameters. Finally, general purpose IoT platforms [12] and health-related IoT platforms are increasingly spreading.

However, most of these sensor platforms are mainly targeted to customers as final users. For this reason, they are mainly marketed through a corresponding web shop and may include customers-oriented services. The measurement platform under development, instead, is mainly aimed at researchers, professionals and technicians in the field of building management and conservation, with the aim to provide very detailed information for the development of basic wireless and web-managed measurement platforms. For this purpose, there is no need to provide web shops or products, but the project will mainly consist in a blog containing detailed instructions and drawings for MHs and MUs development and installation. Measurement networks aimed at research activities are usually designed for the specific scope, with no further extension to other fields. Only Ali et al. [13] are working in this perspective. However, wireless capabilities are in progress in their sensor network, whereas this research activity has been planned since the very beginning with wireless networking in mind.

The measurement platform under development is the subject of this paper. In particular, Section 2 summarizes the main characteristics of the measurement platform under development and Section 3 shows an illustrative measurement taken by means of the first MH and MU developed in the frame of this research activity.

## 2. Methods

The monitoring platform is being designed with the following characteristics in mind:

- Replicability, achieved by the use of components easily available on the market of electronics as well as by the open source approach, implying a source code repository and the development of detailed documentation to illustrate each phase of hardware construction;
- Full remote control, achieved by the implementation of data upload and device control through Wi-Fi network;
- Versatility, achieved by the development of hardware (and corresponding software) modules able to expand the number of parameters that may be measured;
- Reliability, achieved through easy-to-use connection sockets as well as through circuitry and devices limiting the measurement uncertainty;
- Affordability, achieved by the selection of low cost hardware components and the avoidance of commercial and side costs;
- Portability, achieved by software strategies and hardware aimed at increasing battery life.

The hardware under development in the frame of this research consists of monitoring hubs (MHs) and monitoring units (MUs). Each MH consists of the following main parts:

- 1 microcontroller unit consisting in a very common microcontroller, named ATmega328P and currently used in Arduino Uno Rev. 3;
- 1 energy supply unit (battery and voltage regulator);
- 1 SD card reader/writer;
- 1 Wi-Fi module consisting in a cheap and diffuse ESPRESSIF module, named ESP-8266, connecting with the Wi-Fi network, at user-defined time intervals, to upload the measurements logged in the SD card mentioned above and to download the measurement settings defined by the user through a basic RESTful service;
- Circuitry needed for the management and energy supply of (up to three) Mus.

Moreover, the next release of MHs will be integrated with LM4040 voltage reference and 24 bit Analog-Digital Converter (ADC) TI-ADS1252 for accurate reading of low value analog signals.

As mentioned above, MHs are developed in order to manage many different kinds of MUs and their settings and behavior will be user-defined from the web. In fact, in the frame of this research activity, not only the software needed for a proper management of the MHs and MUs is under development, but also basic RESTful services able to log recorded data and transmit user-defined settings to the MHs. Currently, the RESTful service is written in Python and is hosted on a PC operating as a server. The RESTful service will manage the following databases:

- Database of MHs: Each MH will be characterized by a set of characteristics, here included a unique identification code, dates of relevant modifications and general technical specifications;
- Database of MUs: Each MU will be characterized by a set of characteristics, here included a unique identification code, dates of relevant modifications, calibration curves and other general technical specifications;
- Database of settings: The database of settings includes the main data to be exchanged with the MHs for their convenient operation, in particular:
  - o For each channel of the MH:
    - Unique identification code of the connected MU;
    - Relevant measurement options, i.e.:
      - Time interval of each measurement;
      - Sensor warm-up time, to be used for detectors relying on sensor warming up;
      - Number of readings per measurement;
  - o State of charge of the MH onboard battery;
  - o Level of MH Wi-Fi signal;
  - o Time interval for Wi-Fi connection, in order to save battery by limiting the use of the Wi-Fi module.
- Database of measures. This database receives and stores the measurements from each MH and includes simple post-processing, e.g. the use of calibration curves.

The limited amount of memory available on the microcontroller and the long-run battery target made it necessary to limit the code and actions to be performed by the microcontroller, preferring, where available, the measurement of the sole raw data, which are going to be post-processed by the RESTful service.

Due to the high number of soldering consequent to such a versatile MH architecture and in order to increase the reliability of the platform, printed circuit boards (PCBs) are currently under development, as shown in Fig. 1, where the main components of the master board consist of ATMEGA328 microcontroller (J30), microSD unit (SD), connectors for connections with slave boards, with reference to both shared circuits (U1\_PC, U2\_PC and U3\_PC) and to specific connections (U1\_PS, U2\_PS and U3\_PS), whereas RX\_TX, J85, “cer”, “Crys” and “power” provide alimentation and proper operation of the microcontroller.

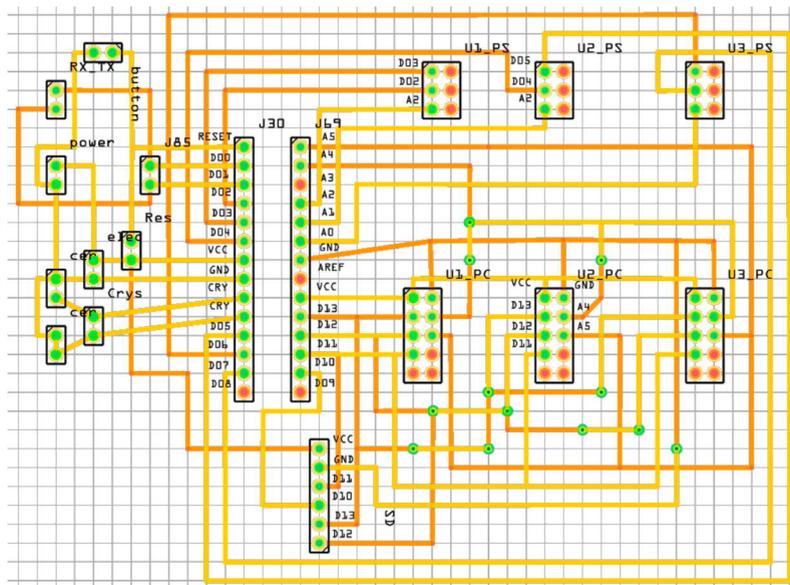


Fig. 1. Scheme of the Monitoring Hub.

On the other side, each MU is fed and managed by the hosting MH and contains all the circuitry and devices needed for measuring a specific parameter. In particular, the MUs listed in Table 1 are programmed for development in the frame of the present research activity, classified with the current development status level (“Developed”/“Under Development”).

Table 1. MUs programmed and current development.

Parameter	Details about the sensor	Sensor placement	Development status
Temperature	DHT22	Onboard	Developed
	Thermocouple	External	Under development
	Resistance Temperature Detector (RTD)	External	Under development
	IR sensor	Onboard	-
	Globethermometer	Onboard	-
Relative humidity	DHT22	Onboard	Developed
Illuminance	TSL2561	Onboard	Developed
Water level	RB-02S048	External	Under development

<b>Water flow meter</b>	-	External	-
<b>Air velocity</b>	Hot wire	Onboard	-
<b>Pressure</b>	-	Onboard	-
<b>AC Current</b>	YHDC SCT Family	Onboard	Developed
<b>CO<sub>2</sub> concentration</b>	NDIR sensor	Onboard	Developed
<b>Methane concentration</b>	-	Onboard	-
<b>Ammonia concentration</b>	-	Onboard	-
<b>Dust concentration</b>	-	Onboard	-
<b>Smoke presence</b>	DYP-ME0010	Onboard	Developed
<b>Movement</b>	IR	Onboard	Developed
<b>Sound level</b>	-	Onboard	-
<b>Pulse counter</b>	-	External	-
<b>Distance</b>	IR sensor	External	Developed
<b>Strain</b>	-	External	-
<b>Access management</b>	RFID reader	External	-

Up to three MUs can be connected with the hosting MH, by means of DA-15 connectors. Each connector is provided with 16 pins (including the connection to ground), which are used for enabling any MU to fully connect and be powered by the connected MH, as follows:

- I. Power supply through:
  - a. Power supply connection at 5V (Pin 01)
  - b. Onboard MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor)
  - c. Digital signal for MOSFET activation (Pin 10)
  - d. Possible 5V-to-3.3V step-down voltage regulator, depending on the sensor voltage requirement
  - e. Connection to ground (Pin 02)
- II. Data connection through:
  - a. Serial Peripheral Interface (SPI): Master Output Slave Input (MOSI, Pin 03), Master Input Slave Output (MISO, Pin 04), Serial Clock (SC, Pin 05) and Slave Select (SS, Pin 11)
  - b. Inter Integrated Circuit (I2C): Serial Data (SDA, Pin 06) and Serial Clock (SCL, Pin 07)
  - c. Analog channel (Pin 12)
  - d. Digital channel (Pin 13)

In particular, pins in common among the MUs are grouped between pin 01 and pin 07, while the pins specific for each MU are grouped between pin 10 and pin 13.

This way, each MU port is compatible with any kind of sensor, while the specific MU circuitry and the MH source code enable specific behaviors for each MU sensor kind. In particular, the activation of the convenient source code for the specific MU parameter reading takes place based on the user's specifications communicated through the RESTful service. This way, the user may select the specific device code, so the corresponding calibration curves and measurement settings will be used. That enables both complete remote control and no cost for the onboard control panel, thus lowering the cost for the platform development.

Also for MUs, corresponding PCBs are developed, as illustratively shown in Fig. 2, where the DA-15 connector used as an interface between the MUs and the hosting MH is named U1 and U2.

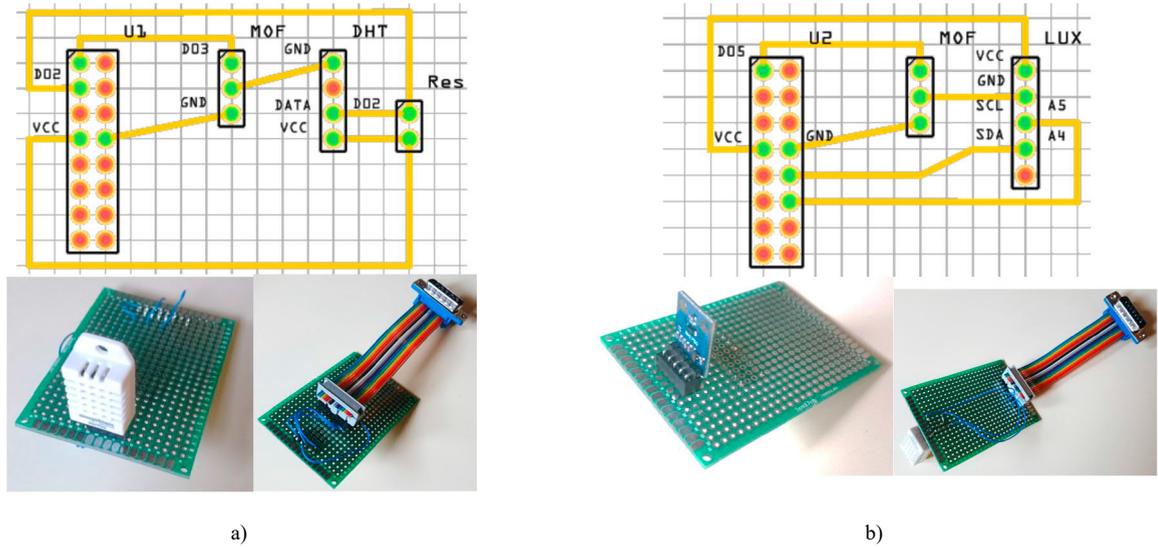


Fig. 2. Schemes of two illustrative Monitoring Units: DHT22 temperature and relative humidity unit (a) and illuminance unit (b).

### 3. Results

As a first demonstration of monitoring campaigns performed by means of the measurement platform under development, the profile of CO<sub>2</sub> concentration resulting from a short-term campaign is shown in Fig. 3. This is just the first attempt of monitoring campaign, but two MHs are going to be installed in a historical building, for the monitoring of temperature and relative humidity, aimed at preservation purposes. In this case, the platform will be tested as regards battery life and reliability on the long-term.

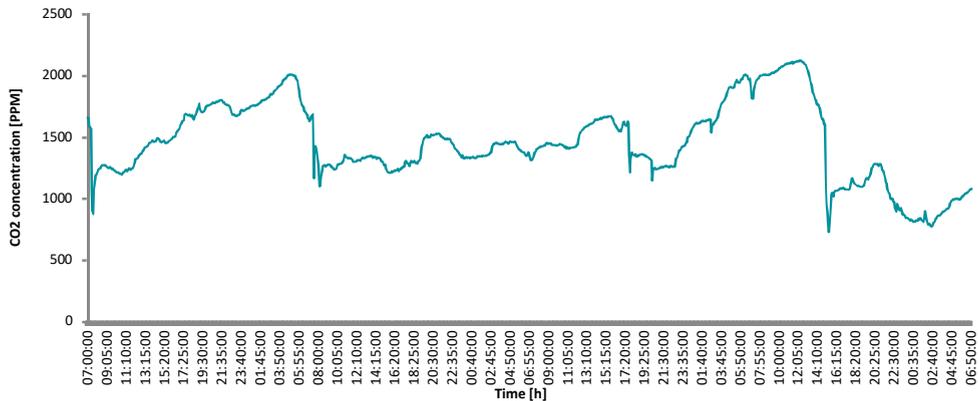


Fig. 3. Illustrative profile of CO<sub>2</sub> concentration measured during a short term monitoring campaign.

### 4. Conclusions

The present paper shows the status of a research activity aimed at the development of budget measurement platforms, presenting its background architecture. Even if the tests currently performed are still not sufficient for a complete verification of the design choices taken, the developed platform looks very promising, thanks to its versatile architecture that is enabling the developers to connect the Monitoring Hub (MH) with a number of

Monitoring Units (MUs) aimed at very different measurement purposes. However, longer tests are going to be performed, in historical buildings, and that will be the chance for a first test about reliability and battery life under real world conditions. After these tests, the MH and the MUs schemes and source codes will be improved and made available to researchers, professionals and technicians, in order to test the developed platform in other contexts and bring together further improvements.

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