# Building-CPS: Cyber-Physical System for Building Environment Monitoring

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## Abstract

The application of Cyber-Physical System (CPS) with Building information modeling (BIM) presents a powerful paradigm for effectively monitor and utilize existing energy use for optimization, analysis, and calculation to minimize environmental impact. The work presented in this paper documents an experiment of a building environmental monitoring system that can monitor and query physical sensor information in real-time, and by collecting environmental data to a central database. This work utilizes lightweight micro-controller computers, low-cost sensor modules, and open-source software system as a generic, reproducible CPS-BIM integration platform. It provides a cost-effective, open-source, scalable data integration system for building environment monitoring using open standards. The paper also discusses the use of underlying data communication protocols MQTT, BIM integration methods. As a proof of concept example of air quality monitoring in a residential area is studied. This work is an initial step towards CPS implementation in the AECO sector (Architecture, Engineering, Construction and Operation), which allows an affordable use of available technologies, including internet of things (IoT), machine learning to combine them with open BIM systems.

Keywords: Cyber-physical system (CPS), Building information modeling (BIM), Building environment monitoring, Energy efficiency

## 1 Introduction

Extensive research has shown that buildings generate approximately 33% of the world's energy consumption and are also the largest contributor to CO2 emissions (OECD/IEA 2013). In Europe, Buildings in the EU account for about 37% of final energy consumption, and it is growing at a rate of 1.5% annually (Pérez et al. 2008). Given this situation, the monitoring of building environment can not only maintain an adequate indoor air quality and thermal comfort environment but also a crucial step forward in energy retrofitting. The most productive way to retrofit building energy is to precisely control the usage from the source, which requires accurate measurements and extensive knowledge of existing building environment.

With technological advances in electronics and wireless communications, sensors can be distributed and remotely deployed to communicate. However, this still requires technical support from electronic engineering specialists, thus a scalable and replicable sensor data monitoring framework can fill this gap. The Raspberry Pi offers technical support for this framework, which is a Linux-based microcontroller computer designed to facilitate a wide range of applications from education to industry with low cost hardware and open-source software. Most of the research is based on Arduino platform, and they all have various application limitations as well. For example, there is no open source software platform used to enable the transfer and replication of the technology (Suryadevara & Mukhopadhyay 2012). (Ali et al. 2016)has using an offline database does not allow for real-time readings and calculations of sensor data. As electronic technology evolves, Raspberry Pi has more advantages compared to Arduino: 1) Can run a full range of operating systems, including Ubuntu, Windows 10 IoT Core. 2) More comprehensive hardware interfaces including USB, Ethernet, and HDMI. 3) More powerful computing level. 4) offers a wide range of sensor support accessories. Therefore, the Raspberry Pi-based CPS-BIM system will become mainstream in the future use cases. The primary aim of this paper is to propose a conceptual framework based on open-source software that balances performance and cost for building environment monitoring.

In this study, seven distributed sensor agents including temperature and humidity sensor, noise sensor, air quality sensor, vibration sensor, fire detection sensor are used together to monitor the building environment in multiple aspects, to establish a building physical entity data hub. Then the sensor data is transmitted to the time series database called InfluxDB through the communication protocol MQTT. Meanwhile, the BIM model is uploaded to the BIM web-viewer for sensor location identification and sensor data query.

A practical application case demonstrates the effectiveness of the proposed framework in building a queryable environmental data system for buildings using CPS and BIM. The proposed platform for data collection, model presentation, and data visualization enables a certain degree of innovation in building energy efficiency management.

## 2 Background

### 2.1 Cyber-Physical System and the Building Industry

Cyber-Physical System (CPS) is a paradigm that mainly focuses on the fusion of physical world and cyberspace. Over the last decades, CPS plays a key role in the transformation within the Industry 4.0 effort in Europe (Zezulka et al. 2016). CPS provides new ideas and potential solutions for solving legacy problems in multiple domains (Smarsly et al. 2017). In the sector of industrial manufacturing, intelligent transportation, smart grid, medical industry, CPS system has demonstrated its applicability and potential benefits (Krogh et al. 2008). The digital transformation is being accepted by the building industry, it presents the possibility of dynamic data gathering and real-time data exchange in the building life cycle (BuildingSMART International 2020). The Gemini Principles (Centre for Digital Built Britain 2018) proposes a digital-based data management framework to guide the national digital twin. However, the exploration of CPS benefits and applicability to the AEC industry is still at the initial stage (Yuan et al. 2020). The physical entity data is difficult to describe in the IFC format which commonly used in the AEC domain. On the other hand, the individual CPS systems often lack contextual information. The idea that the application of CPS in the AECO sector could enhance the performance in multiple areas. CPS was proposed to monitoring temporary structures (TSM) that integrate the virtual model with physical model in the jobsite (Yuan et al. 2020). CPS-SMS is a cyber-physical-system-based safety monitoring system that used to decrease the safety risk in blind hoisting in metro and underground constructions (Zhou et al. 2019).

To conclude, the CPS system can complement BIM systems in some ways, which can be summarized as follows (Cardin 2019):

- It can be integrated with the information of the physical environment, recording environmental information through sensors and interacting through actuators.
- It should be connected to the network and other cyber-physical system to complete data interaction, as well as further services.
- It should efficiently serve a specific application domain and enhance the capabilities and possibilities of the entire environment.
- It should be equipped with multiple user models including human-machine and machine-to-machine interfaces.

### 2.2 Communication protocols

Communication protocols can serve as an efficient bridge for several physical entities' information transmit. Depending on the application domain, there are many specialized communication protocols, such as, MQTT, BACnet, LonWorks can be used (Wang et al. 2004)

Message Queuing Telemetry Transport (MQTT) is one of the real-time IoT communication protocol standard introduced by IBM. MQTT is specifically designed for lightweight computing devices that can effectively interact with network data while working in low-bandwidth network environments (Ansari et al. 2018). Thus, the remote sensor and control equipment can communicate with the server in a timely manner. MQTT message transmission mode is based on client-server message publish/subscribe. Meanwhile, MQTT runs on the TCP protocol and provides network connection guarantee of orderly, reliable and bidirectional connection for network devices. As an extensively used IoT communication protocol, MQTT has the following important features:

- The lightweight structure can save more resources and reduce the burden of data transmission, that's the most crucial reason why this communication protocol can be widely used in industry, in building automation systems.
- The protocol is easy to implement on both M2M (Machine to machine) communication and WSN (Wireless Sensor Network) communication through the MQTT message broker.
- It supports three levels QoS (Quality of Service) for message delivery.
- It can adapt to multiple network protocols, such as TCP, LoRaWAN, Bluetooth.

CPS has greatly changed the digital transformation of the building industry. It enables physical objects to make smart and intelligent decisions according to the unpredictable environment, while the Internet of Things communication protocol will make the hundreds of thousands of sensing, execution, communication, and processing capabilities possible. GeoMQTT[1] can be an option when the cyber physical system has to be associated with spatial properties matters.

### 2.3 Building Environmental Quality Evaluation

With the growing environmental concerns, the Energy Performance of Buildings Directive (EPBD) 2010/31/EU has proposed a variety of measures by focusing on energy efficiency and implementing smart solutions and digital technologies to reduce building energy consumption. The measures include the promotion of smart technologies based on automation and control systems, development of almost zero-energy buildings, the issuance of energy performance certificates, the establishment of new strategies in each EU country, electronic mobility in buildings, and the provision of financial assistance to improve the energy efficiency of buildings (EPBD 2020). The calculation method for energy in the evaluation criteria usually refers to the total annual or monthly energy consumption value, while energy savings can be achieved through a combination of different measures, including building renewal, high-performance windows, etc., but the most economical way to save energy is to precisely control the usage from the source. In this case, an efficient and comprehensive monitoring system allows us to perform source control with better accuracy, where the basic measurements include light, ventilation, temperature and humidity, and human occupancy, etc. It also provides the groundwork for the next step of building energy usage database, energy usage model, and optimization model. However,current research (Kiss & Szalay 2020) in the field of combining BIM with energy efficiency focuses on the optimization of building entities (including envelope, building service systems), while lacks tools that can integrate 2D/3D models and monitor building operational energy efficiency.

## 3 Methodology

### 3.1 Workflow framework

Considering the lack of real-time physical sensor information in existing BIM data, this study proposes a prototype system that can be used for real-time environmental monitoring from building to city scale. This part introduces an overall framework for capturing distributed physical device data using CPS (Figure 1). In order to solve the problem of existing data islands, the application of CPS to transmit real-time sensor physical information into BIM system can

[1] http://geomqtt.org/protocol.html

enrich BIM information to a large extent and improve the completion degree of BIM system. At present, due to the high price of sensors, complex models, lack of proprietary software support and other problems, and has not been very good development in the field of building automation. At the same time, BIM has gradually become an important platform for information delivery and building facility management, which is rapidly expanding. Therefore, it is an important research goal for us to combine building environmental data with BIM platform. In this study, low-cost portable sensors, open-source IoT device communication protocol, time-series database, and visualization platform will be used to build an Internet of Things infrastructure supporting Internet collection. This CPS based data framework enables:

- Generate real-time information about the building environment from microsensors, including (temperature and humidity, air quality, noise, vibration, lighting, etc.)
- Transmit data over long distances based on communication protocols and interact with commands.
- Integrate and sort out the acquired sensor data, and transfer it to the central database for storage.
- Provide a visual client for users to visualize data for further use.

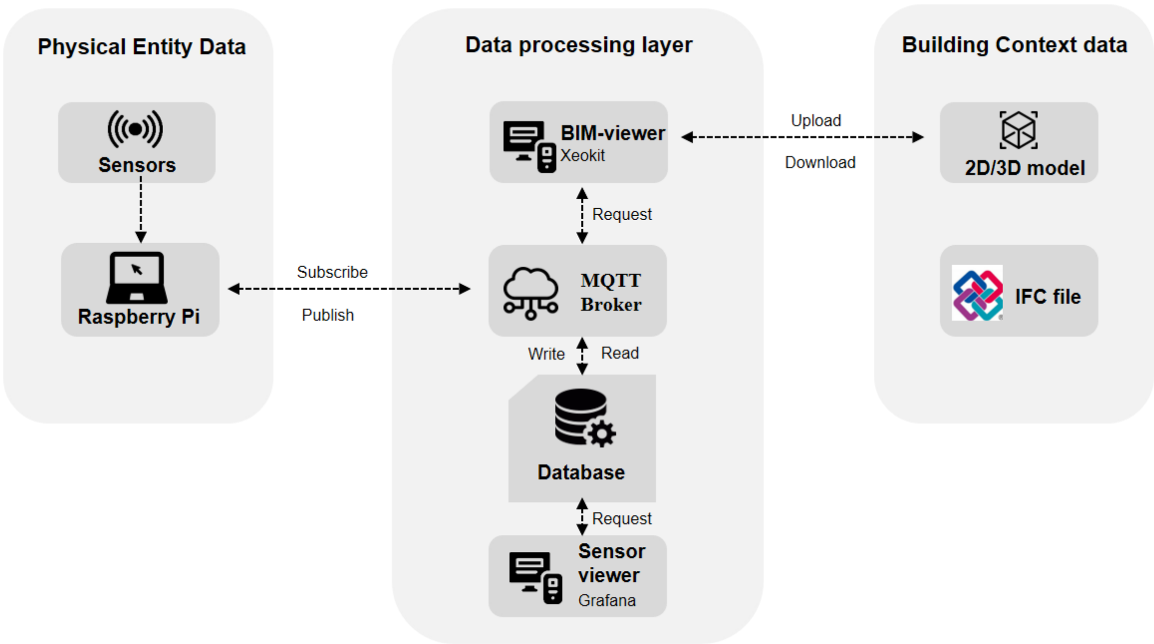


**Figure 1.** Framework of the building environmen monitoring system work with CPS and BIM

## 3.2 Data acquisition

In the data framework, this study will use Raspberry Pi 4B as the data agent to collect micro sensor data. As Raspberry Pi has GPIO (General-Purpose Input/Output) interface, it can be easily connected to various hardware and sensors compared to ordinary computers. Raspberry Pi is cheap, easy to get and small, with a 4B model costing about 40 euros. Raspberry Pi is a single chip computer based on Linux system, and equipped with WiFi module to facilitate data transmission.

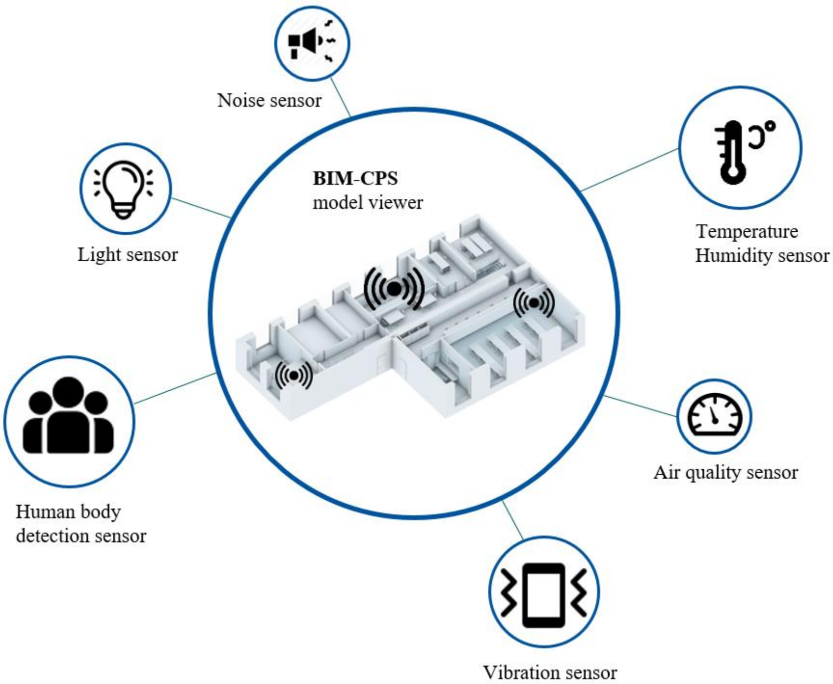


**Figure 2.** Sensor nodes in the building entity

The Raspberry Pi communicates with the sensor through GPIO, and receives data continuously through the programming cycle. All sensor data is converted into MQTT messages for delivery and published to the managed MQTT broker mosquitto [2] to subscribe to different sensor information by different topics. In the building environment monitoring experiment, this study adopts 7 kinds of sensors to obtain basic environmental information, including temperature and humidity sensor, noise sensor, air quality sensor, vibration sensor, fire detection sensor, lighting sensor and human body detection sensor.

## 3.3 Data Integration Approach

The universal Cyber-Physical System mainly contains physical entity information. If the Cyber-Physical System is to be applied to the AECO field, additional 2D/3D model information needs to be added to it. In the current research, it is difficult to find an organization both providing access to its building system's database or internal webpage and allowing the deployment of the data agent with sensors. Thus, the study of BIM-CPS needs to be divided into two parts: model and sensor data. Xeokit BIM viewer[3] is an open-source 3D BIM viewer, it runs on web server, and loads model from the local file. As an open-source 3D graphics SDK, Xeokit BIM viewer provides technical support for CPS implementation. In the AECO domain, the model usually needs special commercial software to view, operate and modify, which greatly affects the efficiency of collaborative work. Xeokit's component toolkit makes it easy to capture models on the Web and store the data on your own server. It can load multiple building model data formats to work together, including: IFC (2x3 and 4), GLTF, OBJ, STL, 3DXML, XKT, and BIMserver. From there, the

[2] https://hub.docker.com/_/eclipse-mosquitto
[3] https://github.com/xeokit/xeokit-bim-viewer112

user can view the large model in the browser, mark the location of the view sensor in the model, and communicate with the sensor via MQTT for real-time information.

## 4 Case study

In order to verify the realizability and reproducibility of the BIM-CPS framework, a pollutant gas detection program in residential area is used as a case study. Roads are an important part of the urban transportation system and urban form, and the traffic volume on them has shown an upward trend in recent years. In different areas of urban blocks, road, ventilation, illumination, traffic flow and other factors will cause the difference of air quality in residential areas. Vehicle exhaust (VE) is the most important cause of air pollutants, it mainly contains HC, CO, CO2, NOx, and other pollutants that present serious air pollution to the adjacent residential area environment (Keyte et al. 2016). The aim of this case study is to applying the monitoring framework proposed in the previous section to environmental pollution monitoring in residential areas.

**Table 1.** Application of the CPS-BIM platform

| **Application** | Pollutant gas monitoring in residential areas |
|---|---|
| **Value proposition** | Monitoring vehicle exhaust emissions on the road, predicting air quality in residential environments, and improving air quality through appropriate initiatives (such as adding catalysts to specific road sections). |
| **Description** | Using micro sensor to monitoring environment data, providing sensor metadata for the next step of prediction, calculation and optimization of the environment model. |
| **Independent variables** | Location, Airflow, light, traffic volume |
| **Output data** | Time stamp, Sensor observation metadata (Air quality) |

The first part of this work is to determine the composition of the pollutant gas to be tested, so as to select the appropriate sensor and accessories. The second part is to set up the time series database Influx DB[4]. The third part is to set up the user visualization terminal, set up the reminder, warning and statistical calculation for the data. The MQ-7Sensor, the MQ139Sensor, the MQ-135 Sensor, the PCF8591 conversion module, the buzzer are selected to detect HC, CO, CO2, NOx. This type of gas sensor detects by heating a built-in chemical. When the target detection gas is present in the environment where the sensor is located, the conductivity of the sensor increases as the concentration of the gas in the air increases.

In this experiment, when the Digital Output (DO) pin of the gas sensor module is connected to the General-Purpose Input/Output (GPIO) of the Raspberry Pi, the MQ sensor is programmed to detect the presence of the target gas; at the same time, the analog output (AO) of the gas sensor is converted into a digital signal by PCF8591 and the change of the digital signal is observed. The MQ-7 sensor is used to detect CO; MQ-139 sensor is used to detect NOx, HC; MQ-135 sensor is used to detect CO2. In order to transfer and reuse the data in a real-time manner, we need to create a time series database named sensor_data in InfluxDB. The meta data from the microsensor is transferred to the sensor_data database via MQTT protocol and it will automatically generate the measurements including timestamps and sensor observation data. Finally, a dashboard is created in Grafana[5] to visualize the data from the sensor_data database, which can be set up with multiple heat map representations of the data and allows for some basic calculations.

[4] https://hub.docker.com/_/influxdb
[5] https://hub.docker.com/r/grafana/grafana

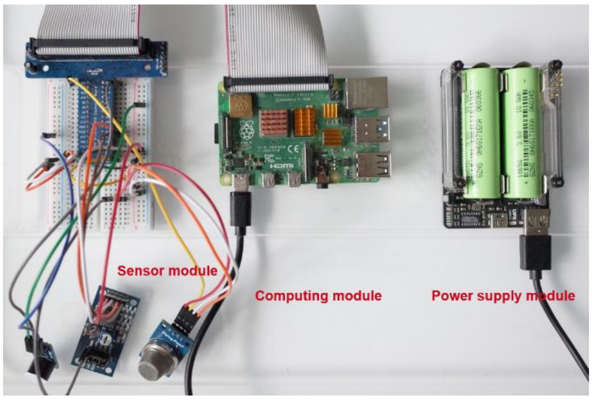


**Figure 3.** Raspberry Pi 4B work with micro sensors.

```python
from influxdb import InfluxDBClient
import datetime

def send(dat):
    client = InfluxDBClient('192.168.2.112', 8086, 'root', 'root', 'gas_sensor_db')
    #client.create_database('gas_sensor_db')

    current_time = datetime.datetime.utcnow().isoformat("T")
    body = [
        {
            "measurement": "sensor",
            "time": current_time,
            "tags": {

            },
            "fields": {
                "GAS": dat
            },
        }
    ]
    res = client.write_points(body)

    result = client.query('select * from sensor;')
    print("Result: {0}".format(result))
```

**List 1.** Passing sensor data into the database

This framework establishes a database of physical entities that provide data support for smart building environments management. A prerequisite for advanced AI intelligence analysis (such as machine learning) is sufficient sample dataset, thus to make correct energy prediction and optimization models. Meanwhile, micro sensors distributed in space for better privacy protection instead of wearable sensors and image recognition means.

The residential environment is critical to the health and well-being of the occupants, statistical studies of vehicle exhaust (VE) provide an accessible historical data platform for urban regional planningand the resolution of pollutant gas emissions. This research proves its potential in provides database for further research, such as adding catalysts to road materials to degrade pollutants according to the level of environmental requirements in different regions (Hu et al. 2017), and using historical environmental data for the development of life-cycle costs (LCC) prediction tools (Gao et al. 2019).

## 5 Conclusion and future work

### 5.1 Conclusion

In this study, we propose a real-time, open-source, low-cost solution for monitoring the building environment based on BIM and CPS systems. The solution uses an economical and lightweight Raspberry Pi and sensors to obtain the physical environment data, then uses the MQTT communication protocol to transfer the data to a time-series database for storage. A web-based BIM viewer is used as a visual dashboard to interact with the 3D building model to subscribe the sensor data through the MQTT protocol via websockets. A preliminary case study of pollutant gas monitoring in a residential area was used to demonstrate the feasibility and application potential of the solution. This physical entity monitoring system, built through the proposed framework,


**Figure 4.** Custom dashboard for data visualization, caculation, early warning

enables initial innovation in smart building environments. The research in this area also offer promising applications in practice, including providing a platform for governments to achieve innovations in optimal energy retrofitting, for enterprises and factories to provide more economical energy solutions and automated control system, and for campuses and educational institutions to provide a better quality environment for users.

## 5.2 Future work

As this work is only an initial step, future research can go in various directions. Pollutant gas monitoring is an area that calls for attention, it requires semantic interoperability solutions. The semantic web technologies allow for a unified definition of heterogeneous spatial property data, while the IoT can deal with the dynamic data stream. Few studies have explored regarding pollutant gas monitoring in the building sector. This work requires the development of the semantic models for the air pollution monitoring sector, which including the reuse and modification of the existing models (Including SSN, SOSA, SAREF).

Another focus should lie on further develop the micro sensor sensing performance. For example, simultaneous localization and mapping (SLAM) technology can be implemented to realize sensor perception and output position information at the same time, so as to increase the sensor perception range. The development of sensor data transmission networks should also be noted, which is the basis for dynamic and collaborative work of IoT devices.

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