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Building a Smart Laboratory Environment at a University via a Cyber-Physical System

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Abstract—Contemporary activities in laboratories have become versatile and complicated, and can be significantly affected by the environment of the laboratory. Thus, a smart laboratory environment is needed to interpret and manipulate (implicit) environmental quantities, for improving and retaining the performance of laboratory activities. This paper presents a deployment of a cyber-physical system (CPS) gathering and acting on relevant information about physical quantities in laboratories. In particular, the proposed CPS can measure, analyze and regulate the thermal comfort. Improvements have been proposed to enhance the functionality of the system. Evaluations of an on-site deployment indicate the functionality of the proposed CPS.

Keywords—environment regulation; cyber-physical systems

I. INTRODUCTION

Cyber-physical systems (CPSs) are systems that contain numerous distributed, linked and autonomously operated sensor nodes and actuator nodes [1], [2]. Generally, CPSs can be used to gather adequate information about the physical environment via sensors, and eventually provide useful and prompt services for people via actuators. Meanwhile, from the system perspective, computation, communication and control are tightly integrated in CPSs, in order to manipulate cyber/physical/information quantities. Results showed that CPSs can be used for various applications [3], [4]. However, CPSs were seldom used in improving and retaining performance of learning activities in schools.

On the other hand, learning in higher education has become versatile, integrated and context-aware [5]. In particular, working activities in laboratories have become sophisticated and highly complicated. For examples, people have to work with different hazardous chemical substances (i.e. solvents, catalysts, reagents and products), and use environment-sensitive equipment. Therefore, a smart laboratory environment is needed for productive and effective laboratory activities.

Different learning technologies have been proposed to integrate different tools and services from a mobility perspective and an anytime-anywhere perspective [5]–[8]. However, existing technologies are mainly about manipulating direct data obtained from experiments. In addition, the environment of the laboratory can significantly affect the result of experiments. Therefore, a proper interpretation and manipulation of (implicit) environmental quantities in laboratories can lead to a more facilitating environment for

activities carried out in laboratories. This issue has not been explored by researchers and yet, is significant. Recently, a preliminary wireless sensor network (WSN) had been proposed for collecting information of physical quantities in a laboratory [9]. However, the WSN cannot convert measured data into meaningful knowledge through statistical analysis, and it also cannot provide services to regulate the environment instantly because of the absence of actuators in the WSN.

In this paper, we describe how a smart laboratory can be constructed via a CPS. In the proposed system, the CPS is used to gather and act on relevant information about the thermal comfort for people and equipment in laboratories. In order to improve the performance of the system, mechanisms for habit-based control, low-volume communications and statistical analysis have been proposed. In this paper, after the introduction of smart laboratories in Section II, requirements of a smart laboratory environment as well as the discussion of computation, control and communication in the CPS are discussed in Section III. The performance evaluation of the developed CPS is shown in Section IV.

II. REGULATING THERMAL COMFORT IN A SMART LABORATORY

A. Roles of a Smart Laboratory

The main purpose of a smart laboratory is to enhance the efficiency of working activities. In particular, a smart laboratory should be able to

- 1) detect hazards, such as fires and accidental spill of chemical and bacteria;
- 2) monitor long-term health of staffs and students, as well as conditions of equipment and the environment;
- 3) track the existence of equipment for maintaining safety and security; and
- 4) regulate the environment to reduce consumption of power and other resources without deteriorating efficiency of research activities.

In order to achieve aforementioned outcomes, different physical quantities should be regulated. Examples of design concerns and relevant physical quantities are shown in Table I.

B. Regulating Thermal Comfort in Laboratories

In the application of monitoring laboratory, the major relevant physical quantity is thermal comfort. A poor thermal comfort condition can lead to dissatisfaction and discomfort,

and eventually a reduction in work performance and concentration [10], [11]. Factors determining thermal comfort include air temperature, radiant temperature, air speed and relative humidity (RH). For example, a range of operative temperature and RH that meet the thermal comfort criteria can be found in [12]. In particular, people become uncomfortable when the RH of the environment is lower than 25% or higher than 60%. Reliability of equipment can also be affected by temperature and RH. For example, low RH may cause problems with static electricity, which may cause damages to static-sensitive equipment and materials as well as may cause fires and explosions when working with flammable liquids and gases. Meanwhile, when RH is high (e.g. >70%), there may be condensations on surfaces of instruments, which leads to corrosions and moisture-related deteriorations. Therefore, these quantities should be examined and moderated automatically in the laboratory.

TABLE I. EXAMPLES OF CPS FUNCTIONS IN A SMART LABORATORY.

Concern	Students/Staffs	Facilities	Relevant physical quantities
Utilizing resources	Recommending of nearby resources	Saving energy; Managing and tracking available resources	Air pressure; Air movement; Light intensity; Temperature; Particulates; Current; Power; Moisture
Ensuring safety	Sparking alert; Recording attendances	Monitoring infrastructure; Sensing and alert; Broadcasting hazards; Identifying users	Rotation; Acceleration; Collusion; Vibration; Existence; Orientation
Protecting health	Health monitoring	Tracing and authenticating dangerous materials; Preventive healthcare; Monitoring thermal comfort	Toxic gas; Particulates; Relative humidity; Air movement; Light intensity; Temperature

Fig. 1. The deployment of the CPS in the laboratory. The black square, black circles, black triangles, grey squares and white rectangles denote the base station, sensor nodes, actuator nodes, wall structures and laboratory benches, respectively.

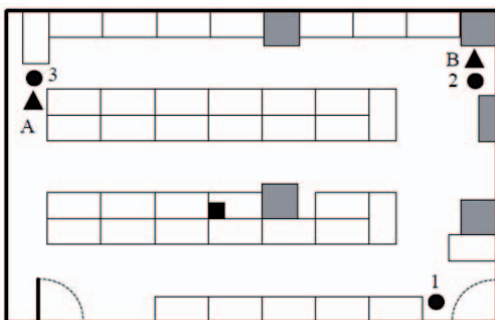
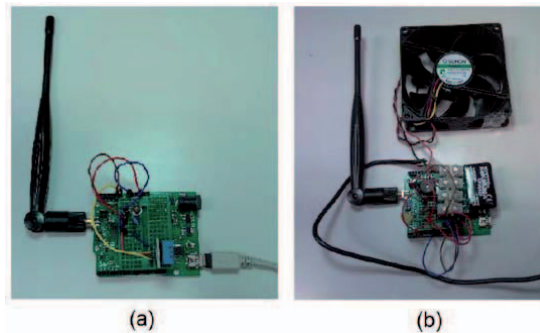


Fig. 2. Implemented prototypes of nodes for the proposed CPS: (a) sensor node, and (b) actuator node.



III. DEVELOPMENT OF A SMART LABORATORY VIA A CPS

In a CPS, measured physical quantities are processed by the microcontroller in the sensor node, and are transmitted to the base station via the wireless transceiver in the node. After system-level analysis, control signals are then sent from the base station to actuator nodes. Finally, actuator nodes introduce motions and regulate the environment.

A. Deployed Environment

The proposed CPS has been deployed in a project laboratory in a university. In one semester, about 150 students had to use microprocessor boards as well as peripheral sensors and actuators to design engineering machines [13], [14]. The floorplan of the laboratory and positions of deployed nodes are shown in Fig. 1. Since many students had to work at the same time before the end of the semester, and main vents were not distributed evenly, there were areas with poor ventilations and thermal comfort. Therefore, CPS is deployed for monitoring and regulating thermal comfort of the laboratory.

B. Challenges of Deploying CPSs in Laboratories

There are a few challenges in the deployment of CPSs in general environments, such as power supply for the system, processing of measured data, and communications between nodes. In laboratories, there are a few requirements for the deployment of CPSs:

- Nodes should be placed seamlessly, such that nodes can measure realistic environments and provide effective services as well as prevent destructions by impact with equipment and human activities.
- Most power plugs had been occupied by existing equipment, therefore only the base station can be powered by a power plug. Meanwhile, nodes are usually powered by portable battery packs.
- Wireless communication may be blocked or deteriorated occasionally because of physical obstacles (e.g. wall structures) and electromagnetic obstacles (e.g. instruments and computers).

C. Hardware of Nodes

An implemented sensor node and actuator node of the proposed CPS are shown in Fig. 2. In the proposed CPS, Arduino-compatible and transceiver-embedded microcontroller

platform Zigduino is used in nodes. Sensors are installed in sensor nodes for measuring humidity, temperature and light intensity. Meanwhile, 2W electrical fans, electrical buzzers, light emitting diodes are installed on actuator nodes for notifying and introducing motions. Furthermore, since actuators consume a large power for operations, a separated battery pack is used for operations.

TABLE II. THE CONFIGURATION OF DUTY CYCLE ADJUSTMENT: (A) SENSOR NODES, AND (B) ACTUATOR NODES.

Condition	Laboratory activities	Initial duration (sec.)	Increment of duration in each time step (sec.)	Max. duration (sec.)
Normal	Existed	15	5	30
Normal	Not existed	30	10	300
Abnormal	Existed	5	0	5
Abnormal	Not existed	5	5	60

D. Communications between Nodes

Sensor messages (i.e. messages *from* sensor nodes) and actuator messages (i.e. messages *to* actuator nodes) are sent through the wireless network. Generally, a sensor message contains its sensor node number, measurement readings and a checksum. Furthermore, urgent messages further contain reserved codes to indicate abnormal conditions, such as sensor failures. Meanwhile, an actuator message contains the recipient actuator node number, action code and a checksum.

For reliable communications, a message acknowledgement mechanism and a disconnection alarm have been introduced in the system, such that the system can notify technicians for diagnosis if the node is not working. For example, if a sensor node cannot successfully transmit messages to the base station, the sensor node will be self-classified as "disconnected". Meanwhile, the base station also monitors the traffic of communications between nodes.

E. Computations for Analyzing the Environment

Since characteristics (e.g. reliability and redundancy) of machine-generated data are different from human-generated data, processing algorithms have been used in sensor nodes, such that spikes and irregular tendencies of measured data can be detected by sensor nodes directly, without processing through the base station. This can simplify the notification process as well as reduce the traffic of redundant data communication. Meanwhile, computation algorithms have been installed in the base station to perform system-level analysis, generate histograms and relevant statistics (i.e. minimum, maximum, (running) average and standard deviation of measured data), and eventually provide meaningful and evidence-based services for the laboratory.

F. Habit-based Mechanisms for Power-Aware Control

Sensor nodes and actuator nodes are mainly powered by 7.2V 3Ah battery packs that cannot be replaced frequently. Meanwhile, by changing the node into "sleeping mode" in unnecessary situations, current consumption of the Zigduino board can be reduced by >99%. In other words, power consumption can be significantly reduced. Therefore, power-aware control operations are the major concern in the CPS.

In the proposed system, adaptive operation control mechanisms are proposed for sensor nodes and actuator nodes. A summary of the configuration of duty cycle is shown in Table II. To be specific, the adaptive control mechanism of sensor nodes adjusts the duty cycle, based on

- long-term habits of laboratory activities;
- existences of current laboratory activities;
- existences of current abnormal environment condition;
- the status of current node operation.

For example, if the environment does not change, the duty cycle can be prolonged gradually until the duty cycle reaches a pre-determined maximum duty cycle. Meanwhile, the maximum duty cycle can be longer if there are no activities or abnormal conditions in the laboratory. On the other hand, besides the wireless transmitter, other parts in actuator nodes are deactivated. Actuator nodes are only activated when an interrupt is received from sensor nodes or the base station.

Besides aforementioned control mechanisms, different techniques have also been used in the system to avoid unnecessary power consumption:

- Sensors are switched on only when an interrupt from the microcontroller is received.
- Measurement data from sensors are verified in the sensor node via checksum verification before transmission, such that nodes only transmit low-volume meaningful information to the network.
- A message acknowledgement mechanism and a disconnection alarm are introduced to avoid unnecessary communications (e.g. communications with faults) in the wireless network.

IV. EVALUATION OF THE SYSTEM PERFORMANCE

In this section, we evaluate the proposed CPS from perspectives of computation, control and communication.

A. Detecting and Regulating Abnormal Environment Conditions in the Laboratory

Sensor readings had been analyzed to detect the onset of thermal comfort deterioration and to restore the laboratory environment in a real-time manner. Readings in abnormal conditions are shown in Fig. 3. In the study, a water vapor source had been placed at Time (I) near the sensor, in order to imitate a hot and humid environment. The source is then removed at Time (III). Based on received messages, the base station noticed that the abnormal condition at Time (II). Therefore, the electrical fan of the actuator node had switched on to provide adequate air ventilation for a regulation. The environment had been regulated after about one minute. Compared to the original environment, the regulated environment has a similar temperature and a slightly higher relative humidity. On the other hand, if the ventilation was not introduced by the CPS, the condition of the environment deteriorated, and thus significantly affected the performance of research activities and eventually the safety of people in the laboratory. This example shows that the proposed CPS can

effectively detect and restore deteriorations of thermal comfort (and other physical quantities) in the laboratory.

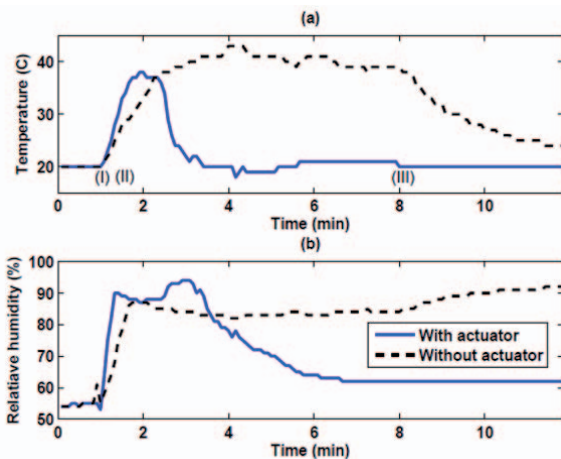
B. Power Consumption of the Sensor Node with the Adaptive Control Mechanism

The adaptive operation mechanism had been evaluated by an example shown in Fig. 4. In each cycle, the sensor node as well as actuator node switched on and off based on the determined duty cycle. The figure shows that in a 1.8-hour surveillance, the sensor node with adaptive duty cycle mechanism switched on 63 times, which is about 4.9% times of the standard sensing (i.e. sensing for every five seconds). In the example, the proposed system with the adaptive control mechanism consumed 945J energy during the operation, which is about 1.9% energy consumption of the original system. The excessive power consumption of the original system is caused by unnecessary operations in low-risk situations (e.g. environments without laboratory activities). The examples show that the adaptive control mechanism can effectively prolong the lifetime of the system. Thus, the system can be placed in areas without continuous power supply.

C. Large-scale Network Performance Analysis

The system collected 90-hour communication traffic for the evaluation of network performance. In the evaluation, one sensor node had been deployed for monitoring. In the study, 32431 sensor messages had been collected from the base station. Among received sensor messages, 31432 messages had valid readings, i.e., the mean system reliability is about 96.91%. All measurements showed that the laboratory was in a normal condition (e.g. no “hazards”). Results indicate the system had successfully delivered a high proportion of valid transmissions in spite of dynamic channel conditions.

Fig. 3. Obtained readings in abnormal situations with an actuator and without an actuator: (a) temperature, and (b) relative humidity.

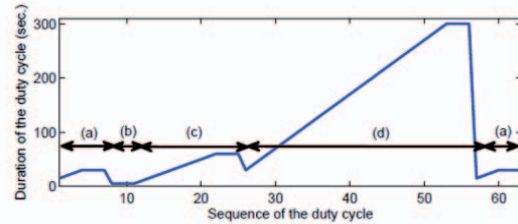


V. CONCLUSION

This paper presents a deployment of a CPS for smart university laboratory environment. Techniques have been proposed for solving issues of power-aware adaptive control, computations for providing meaningful services, reliable data communication between nodes. Evaluations showed that the

deployed CPS can regulate the thermal comfort. The developed system can also be used to regulate other relevant physical quantities shown in Table I, for a comprehensive smart laboratory environment.

Fig. 4. The duty cycle of a sensor node with an adaptive sensing mechanism. (a), (b), (c) and (d) indicate normal conditions with laboratory activities, abnormal conditions with laboratory activities, abnormal conditions with no laboratory activities and normal conditions with no laboratory activities, respectively.



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