From Embedded Systems to Cyberphysical Systems to the Internet of Things: Consequences for STEM Education

Janusz Zalewski, Dahai Guo, Robert Kenny and Xiaoxue Wang

Abstract**—**The paper presents experiences with student projects aiming at gradually acquiring practical command of programming skills in the areas of embedded computing systems, cyberphysical systems, and the Internet of Things (IoT). Three projects are described, one per each domain: Google glass as an example of an embedded system, networking a 3D printer as an example of a cyperhysical system, and using a smatwatch to collect medical data and make them available to doctors and patients, as an IoT device. Finally, the impact of the results of these projects on STEM education is discussed.

Keywords**—**Cyberphysical Systems, Embedded Systems, Internet of Things, STEM Education.

I. Introduction

STEM education relies on introducing awareness of Science, Technology, Engineering and Mathematics, collectively called STEM, and teaching respective skills and knowledge that would enhance students competitiveness on the job market when they graduate. The central motivation in this approach is a widespread belief that STEM focused education contributes to the innovativeness in product development and as such has a significant impact on strengthening the economy and making it more competitive globally [1].

In addressing this challenge, the Florida Gulf Coast University's (FGCU) Software Engineering Department has developed over recent years a sophisticated undergraduate software engineering lab for use in embedded and cyberphysical systems and related project courses [2]-[3]. As a result, a number of teaching modules have been put in place, with emphasis on developing complex systems, studying their properties, and providing web-based access to the lab.

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With the evolution of the Internet and emergence of the Internet of Things (IoT), new issues come into place, which have to be addressed in courses on Embedded Systems and Cyberphysical Systems. This paper looks into the extension of traditional courses of that sort, to meet the challenges of the IoT technologies. It offers a hierarchical approach to designing and implementing respective curricula, with project emphasis.

At the lowest level, there is a need to prepare students to understand the measurement and control aspects of embedded systems. This is addressed in Section 2. Next, once the students have understanding of measurement and control aspects, the networking element is introduced, in a course on Cyberphysical Systems. A respective project example is outlined in Section 3. Finally, given that the students acquired respective background in two lower level courses, the next stage involves actual IoT applications with the use of a cloud, which is presented in Section 4. This is summarized in the Conclusion section, which ends the article.

II. Embedded Computing in STEM

A. Need for Integration

It has been argued in the previous paper [3] that one of the key factors in STEM education should be the integration of all four disciplines, which can be accomplished via the use of student projects. Such an integrated approach to STEM is very rarely seen in current teaching practices at the undergraduate college level [4]. In particular, math and technology disciplines can be viewed as the basis of respective activities, and science and engineering draw from the support of math and technology, developing respective concepts at the higher levels. In this view, science disciplines essentially rely on inquiry and discovery, while engineering activities apply scientific concepts to construction of respective artifacts.

As a fertile example, a concept of feedback control is used to illustrate the idea. The feedback principle, illustrated in Figure 1, is one of the most fundamental concepts in nature and technology. In essence, every biological system, including a human being, exists due to the application of a feedback principle, which results in self-regulation. The same is true of social systems where self-regulation is essential to their survival and prosperity. In engineering, the first documented use of a feedback principle took place in the IV-th century

B.C., with the invention of a water clock. A more contemporary example is a thermostat, which is a device operating on the very same principle of feedback control.

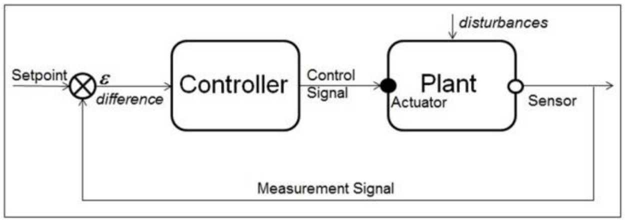

Fig. 1. Feedback control system principle.

In contemporary applications, due to the development of technology, a simple control system expands into a more involved embedded system configuration, with interfaces to the user, the database and the network, as shown in Figure 2.

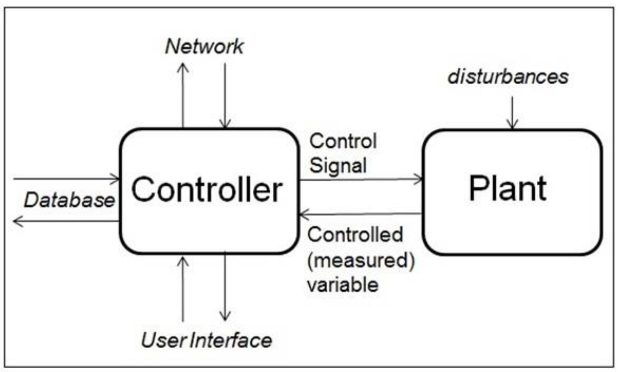

Fig. 2. Illustration of a modern embedded system.

B. Wearables

A specific kind of embedded devices are wearables, such as smartwatches, helmets, sewable microcontrollers, etc. They have I/O channels to contact the environment and some computing and wireless capabilities, making them suitable for all sorts of personal applications.

Wearable technology opens up a world of new possibilities because of the personalization that is achieved by being consistently physically connected to the device. Some examples include access to an individual's location with increased accuracy and biological data, such as, heart rate or body temperature. This allows a device to keep a more accurate profile of an individual that cannot be realized by manually entering data into an app's profile section or within an approximation with an external object, such as, a smartphone.

One specific wearable technology is focused on sports medicine to prevent injury and compile personal stats reports. For example, Riddell's SpeedFlex helmet with InSite Impact Response System [5] uses sensors to determine if an impact is a trauma risk and sends an alert if that impact exceeds the allowable limit. Another device of that sort is eyewear, such as the Google Glass. At one point [6], Google Glass has been used to enhance simulation-based training of medical students and medical residents in a hospital setting.

C. The Google Glass

Google Glass is a wearable which was initially unveiled in 2012 at the Google I/O conference. The user is able to directly interact with the device through a combination of voice, touch, and head/facial movements. It is equipped [7] with a 5 megapixel camera able to take photos and record videos in high definition 1280 x 720 resolution (720p), 1 gigabyte of memory, and 16 GB persistent storage. A Google Glass can be controlled via the MyGlass application on an Android phone or tablet and communicated with via Bluetooth.

Although sales of the Google Glass in the Google Play store were discontinued early 2015, it is worthwhile to document a student project with this device as an example of developing skills for programming embedded devices.

One of these areas for potential wearable utilization is in the field of educational technology. Wearables may one day be as ubiquitous in the classroom as laptops and desktops but that is only if these devices manage to add value over traditional pedagogical methods. One application could be for learning simple algebraic operations, such as addition, subtraction, multiplication and division. Points could be earned based on the number of correct answers and the length of time taken by the user.

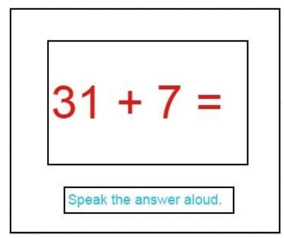

Fig. 3. Barebones sketch of Google Glass math app.

The objective of this project was to explore educational technology applications for the Google Glass, specifically as it relates to learning early math skills. A basic sketch of the addition mode of the application is shown in Figure 3 and the software architecture is illustrated in Figure 4.

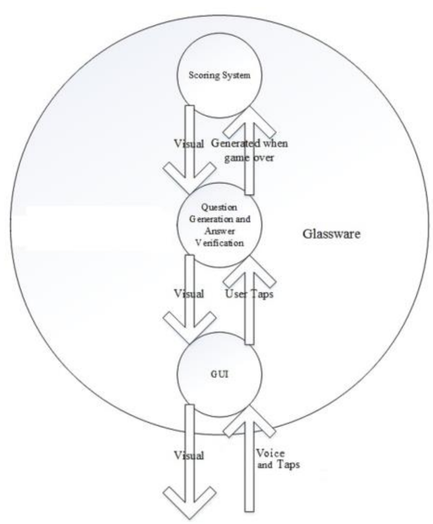

Fig. 4. Software architecture for the Math Glassware.

III. Cyberphysical Systems in STEM

A. Emergence of the Discipline

With the ubiquity of the Internet, embedded systems have expanded into, so called, cyberphysical systems, which offer not only direct connectivity with the physical environment but also networking of all the interfaces illustrated in Figure 2. This fact has to be taken into account in education and publications started to appear documenting related courses [8]-[9], curriculum development [10], including textbooks [11].

Examples of cyberphysical systems, such as modern software intensive embedded systems, are used in the most demanding real-time safety-critical applications, for instance, flight control, particle accelerator control, road vehicle control, etc. They are all distributed and for proper operation require very different programming techniques than traditional systems. Typical STEM curricula, however, rather rarely include respective methodologies of software development for such systems. Possible reasons for this situation include:

- difficulties with acquiring, operating and maintaining appropriate hardware and system software
- necessity of acquiring specific knowledge of device architectures and low-level programming techniques for this hardware and system software, and
- need of significant attention to technical support, rarely available at the school or college level.

B. 3D Printer as an Example of a Cyberphysical System

3D printing has sparked somewhat of a modern day industrial revolution. With its wide variety of applications that touch virtually every industry, the interest in 3D printing is only rising. Prototyping, modeling, prosthetics, and plastic duplicating are just a few of the possibilities that 3D printers can bring to the average consumer today, and the same is true for their more industrial (and more capable) counterparts. In the past couple of years, more affordable 3D printers have become available to the public, and today, there are countless brands, sizes, and printable materials that have flooded the market. The Tiko 3D printer [12] is just one example of a product designed and marketed for the average consumer.

The need for this project arises from safety concerns as well as educational needs. While 3D printers are sophisticated machines, they function in environments not entirely suitable for the production of quality prints. Oftentimes, this is made apparent when a lengthy print job has been scheduled. While smaller prints may be finished in under half an hour, most prints usually take up much more time – too long for someone to sit around and monitor. For that reason, networking and visually monitoring 3D printers for the purpose of remote control is advantageous.

Prints may fail due to miscalibration, inconsistencies in temperature, or a host of other possible issues. Unless the printer has been stopped by the user, it will continue to run its code forcing it to continuously extrude material wastefully. This project addresses the issue of education and safety, using the Lulzbot TAZ 5 3D printer [13].

C. Networking a 3D Printer

The objective of this project was to expand the user's ability to interact and to interface with the 3D printer. Specifically, the goal is to facilitate a remote (network) communication between the user and the 3D printer for the sake of safety and education. The user will be able to monitor active prints and remotely take action if it is necessary in order to terminate a print, to move the hot extruder end away from danger, or to shut down the hot extruder end and hot bed. The TAZ 5 can exceed temperatures of 240℃ for the extruder, and the hotbed alone can reach past 100℃. The focus is on these main safety mechanisms, which are essential to the goal of the project.

While this specific 3D printer can function in an untethered configuration, the Raspberry Pi single-board computer has been used in order to facilitate the network connection for remote control. Figure 5 visualizes this relationship. The Pi works as the server tethering the printer as well as relaying live visual data to be accessible on the Internet - via the Raspberry Pi's onboard Apache server. The outer server handles incoming Internet connection requests and tunnels them to the Raspberry Pi which is on its network.

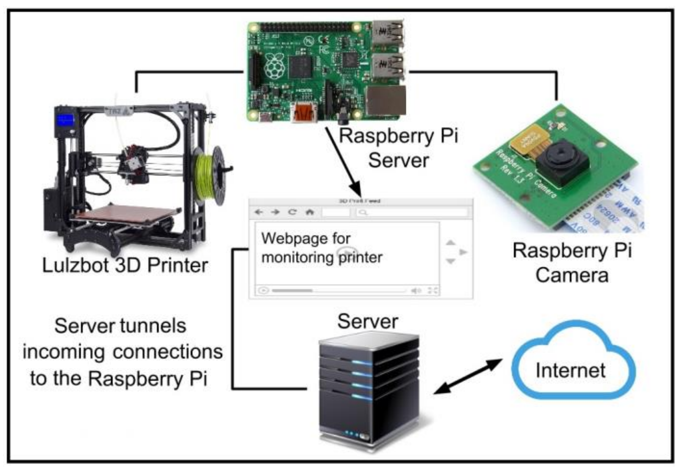

Fig. 5. Physical diagram of 3D printer connectivity.

Among the requirements for connecting the printer to the Internet were the following:

- the Raspberry Pi (RPS) shall be able to broadcast live images of the 3D printer on the network
- the RPS shall be able to establish full connectivity to the 3D printer in order to provide full control of it through one of its compatible applications, which means the ability to:
  - move the extruder head motors
  - terminate a print in progress
  - shut off both the extruder and the hotbed
- the RPS shall be able to accept a remote (LAN) connection to a user seeking to take full control of the printer.

There were also additional requirements on the Graphical User Interface (GUI). With this, the context diagram for software development is shown in Figure 6.

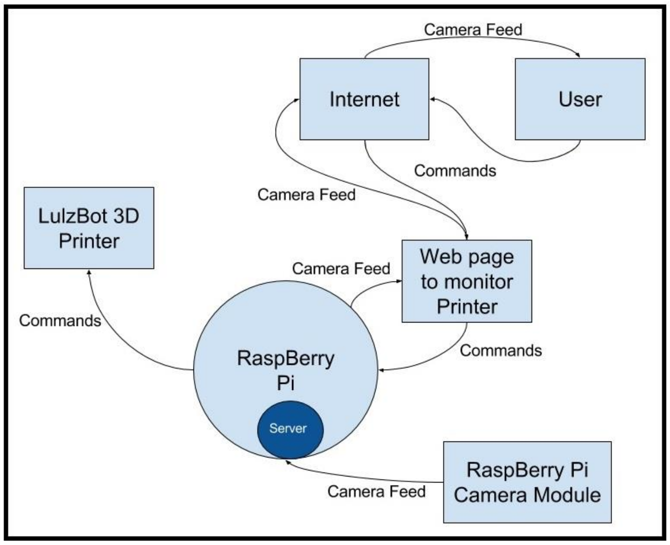

Fig. 6. Context diagram for software development.

Following the requirements, the software for Raspberry Pi can be separated into four main functionalities: listening to user commands, sending commands to the 3D printer, packaging up the live camera feed, and finally, embedding the camera feed onto the web page for viewing. While the software development is too lengthy to be described here in more detail, the resulting GUI, as designed for remote user interaction, is shown in Figure 7.

Although from its description the project looks like a sophisticated software engineering endeavor, in fact, it offers additional value for all STEM disciplines, for example: biological science and bioengineering – to teach shaping human and animal bones, technology – to teach principles of mechanical design, and math – to master solution of simple or more complicated equations mapped onto specific three-dimensional curves.

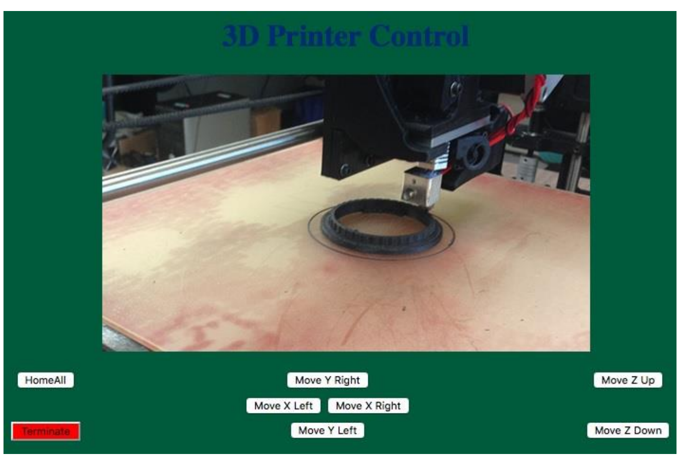

Fig. 7. GUI screenshot of live feed with print in progress.

Practical exercises or experiments in any STEM discipline can be organized by starting with small demos, how to move the camera to observe the printer's operation, to more sophisticated, involving printer programming to perform specific tasks.

IV. Internet of Things in STEM

A. The Emergence of Technology

Among new information technologies, the Internet of Things (IoT) is definitely making its way into teaching and learning, but there is very little experience or information how to use it effectively in education, especially, in STEM education. It is the fact of the matter that the IoT is a disruptive technology in many industries and in business in general, but also in education. Actual numbers may vary by source but the consensus is that the volume of IoT connected devices will grow somewhat unpredictably to billions of units in the next decade. So will grow the market value, likely reaching trillions of dollars in the same period.

The early and later corrected predictions are both shown in Figure 8. As summarized in [14], current estimates include the following numbers of devices by 2020:

- 28 billion, as corrected value by Ericsson (by 2021)
- 30 billion, corrected by former CISCO executive
- 30.7 billion by IHS Markit
- 28.1 billion by International Data Corp., and
- 30.7 billion in a study by Gartner.

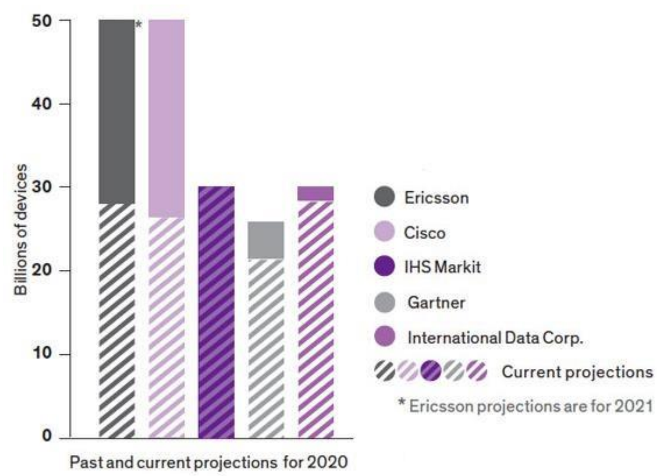

Fig. 8. Past and current projection for the number of interconnected devices (adopted from [15]).

Thus, it is clear that with numbers this big, the education, including STEM education, will be heavily impacted. Therefore, given the pervasive nature of IoT, it is necessary to address the educational aspects of the problem. Teaching how to design, implement and use the IoT is essential to all STEM professions.

B. The Principles of Technology

The IoT does not appear to have a single, widely adopted, definition. However, one particular definition should appeal more to the professionals, since it comes from an engineering society and reads as follows [16]:

„Internet of Things (IoT) is a system consisting of networks of sensors, actuators, and smart objects whose purpose is to interconnect "all" things,

including everyday and industrial objects, in such a way as to make them intelligent, programmable, and more capable of interacting with humans and each other."

There are a number of characteristics, which can be attributed to the IoT. The most important ones are its architectural components, which can be listed as follows:

- smart devices at the user end
- communication infrastructure for connectivity
- computing cloud to provide data storage, and
- analytics tools at the cloud level.

As shown in Figure 9, there are multiple devices ("things", some smart) at the user end, a communication infrastructure with devices accessing the cloud directly or via intermediaries, such as local gateways, and service providers in the cloud equipped with appropriate analytical tools. These are the critical constituents of the IoT, forming its architecture compliant with the one adopted by Intel [17].

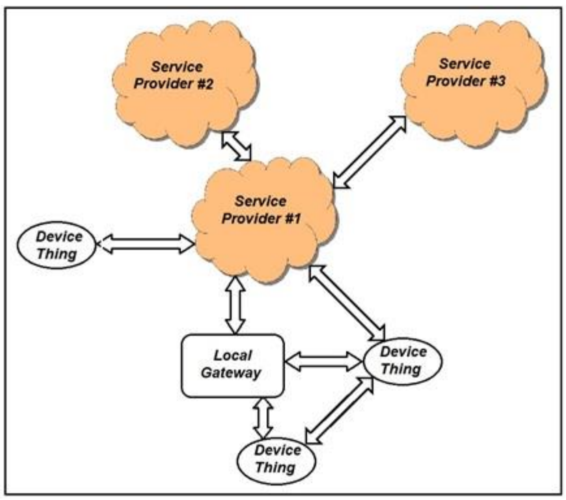

Fig. 9. Overall architecture of the Internet of Things.

C. Overview of Using the IoT in Education

Prospects of using IoT in education, in general, are articulated the most vocally, among others, by computer companies, which sense a big business just around the corner. Such examples are CISCO [15] and Intel [18], which beyond hidden advertising provide valuable insight into the use of IoT in education. For example, CISCO considers the following key factors for successful implementation of IoT in education: security, data integrity, and education policies [15]. Intel [18] advocates that IoT has the potential to trigger enablers to create the "synthesizing mind", which include: programming (commonly understood as "coding"), science, and making (in a sense of "makers movement").

There is, however, an independent study by the British Computer Society [19], which emphasizes the enormous significance of IoT in education for the future:

"The impact of the Internet of Things is likely to be revolutionary in all areas of education. This will be a consequence of speed of deployment, ubiquity, global scale, low cost and connectivity of billions of intelligent sensors and actuator devices generating unprecedentedly huge amounts of data. The interconnectivity and cutting across silos will place more demand on hybrid skills throughout ICT and beyond."

With respect of using IoT in higher education, the industry is definitely taking the lead. Most notably, in a special issue of Educause Review [20], executives from Salesforce, Google, Extreme Networks, IBM and CISCO present their views on the IoT impacts on higher education, followed by some sobering thoughts of one of the Information Technology directors at a major U.S. university:

"*The IoT and IoT systems have the potential to provide substantial value to higher education institutions. But the implementation of those systems creates seams with our existing IT and information management ecosystems.*"

The academic research falls far behind the industry and there are only a handful of studies analyzing impacts of IoT on higher education in the forthcoming years. In one paper [21], the author lists a number of changes the educators and administrators will face due to the introduction of IoT, including: changes in teaching and learning, experimental and practical changes, need for a change in management, etc.

Another article [22] focuses on presenting the needs for adopting IoT technology on campus in e-learning, calling it smart i-campus. It points to a number of issues facing those who implement the i-campus, related mostly to the use of new technologies, but omitting completely the changes in pedagogy resulting from adopting the new approach. Another paper [23] presents academic experiences on learning the IoT technology for purposes of e-business courses. The described model relies on using cheap, general-purpose boards based on Raspberry Pi and Arduino microcontrollers. The authors outline the course structure and its pilot implementation, sharing their first experiences and feedback from students.

For use of IoT in engineering education and specific impacts on this area, please see [24].

D. Remote Health Monitoring

The Software Engineering program at the authors' institution aims at creating a full IoT specialization. For the time being, prospective specialization courses have been defined and are in the process of approval. They are all based on projects, of which one is describe here. Each project has a small embedded device, sensor or/and actuator, and targets a specific cloud platform. The choice of both the device and the platform is given to students with instructor's approval.

The specific project involves using a Moto 360 smartwatch [25] to implement a person's monitoring health parameters for use by a doctor and a person themselves. Initially, only one parameter, heart rate, was measured, but a completely operational system was implemented, with full connectivity to a Google Cloud, as shown in Figure 10.

Fig. 10. Connectivity of the smartwatch with Android and cloud.

For STEM education, it is essential to demonstrate in each project a practical usefulness, which in terms of the design means usability, as illustrated in Figure 11. By reading the user's heart rate and sending the data via smartphone to the health monitoring server, which stores the history of all the information it receives, the application allows a doctor and a patient to stay in touch over a secure network, regarding all actions necessary to monitor health.

Fig. 11. Practical usefulness of the smartwatch solution.

V. Summary and Conclusion

The paper described a hierarchical way of using student projects in teaching courses on embedded systems through cyberphysical systems through the Internet of Things, with application in STEM disciplines. From the use of simple embedded devices, such as a temperature controller, to much more complicated, but still at this level, such as a Google Glass, every STEM discipline can find interesting examples of applications matching student interests. The situation gets more complicated with the use of the Internet, which leads to expanding the projects to cyberphysical systems and the IoT, however, many of the reported experiments have been found to fit the specifics of respective STEM disciplines.

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