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Emerging Hardware Prototyping Technologies as Tools for Learning

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ABSTRACT Integrating hardware prototyping platforms such as Arduino, Raspberry Pi or BeagleBone Board in education is becoming more prevalent as the number of courses utilizing such platforms is continuously increasing. In this work, we conduct an analytical investigation on the plurality of courses that utilize or integrate hardware prototyping platforms. We examine curriculum and instructional material (e.g. course syllabi or outlines) through publicly available web informational resources (e.g. search engines). We use this data to determine the degree to which these platforms are used as effective learning technologies in existing courses. We further use this data to determine hardware platforms integration statistics and distribution based on the number of courses, types of platforms employed and institutions using them as learning technologies. This statistical data can be used to help determine the current status of the utilization and adoption rate of hardware prototyping platforms into courses. In this paper, we present evidence that hardware prototyping technologies are employed as tools for teaching and learning. Based on examining forty five universities worldwide, we determine that there are on average nine unique courses per university which utilize or integrate a variety of these platforms into courses. We also determine that 75% of these courses are Science, Technology, Engineering, and Math- (STEM-) based while 25% are Non-STEM. We further use our findings to provide insights on the extent to which educational institutions are utilizing these platforms as learning technologies and applying project-based or experiential learning approaches as part of their curriculum development.

INDEX TERMS Computer aided instruction, experiential learning, project-based learning, engineering education, computer science education, education, courses, Internet of Things, curriculum development, educational technology, STEM, learning technologies.

I. INTRODUCTION

The utilization and integration of hardware prototyping platforms such as the Raspberry Pi (RPI), Arduino (ARD), BeagleBone Board (BBB), among many other platforms into courses for enhancing the student learning experience is becoming more prevalent [1]. These inexpensive computing devices are considerably getting into the hands of students to ideate, create and innovate in course-related activities. Hardware prototyping platforms have also made considerable progress into being integrated by instructors in Science, Technology, Engineering, and Mathematics (STEM) and Non-STEM courses. Although there are no formal statistics on the number of hardware prototyping platforms used in education, figures show that the widespread use of these platforms is continuously increasing.

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Adafruit Industries, an open-source hardware company and one of the resellers of the Raspberry Pi, has reported selling over twenty-five million Raspberry Pi computer devices in 2019 [2]. Sony UK TEC has reported in 2017 that it manufactures in excess of 15,000 Raspberry Pi products per day (or 5.5 million per year) for the Raspberry Pi Foundation, the maker of this device [3]. According to the Raspberry Pi Foundation, 27 million Raspberry Pi devices have been sold in total including six million in 2018. Comparing this figure to the worldwide PC shipments reported by Gartner, the Raspberry Pi share is approximately 2.2% of the global PC market (based on the last quarter of 2018) [4].

Single-board computing devices have become practical apparatuses that are used by individuals, manufacturers and businesses. For example, the Raspberry Pi is a credit-card sized single board computer that can be connected into a monitor or TV and helps individuals across all ages for learning a mixture of programming languages such as Scratch, C++ and Python. It can also be used to connect sensors and actuators for developing Internet of Things (IoT) applications. There are many examples that employ hardware prototyping platforms in creating home and industrial applications [5]–[8].

A single-board computer (SBC) represents a complete computing device built using a single circuit board [9]. A single-board microcontroller (SBM) is a microcontroller that is built on a single circuit board [10]. A SBM provides all the necessary circuitry for controlling tasks such as a microprocessor, I/O circuits, clock generator, data storage, memory, among others [10], [11]. It is common to use a single-board microcontroller (e.g. Arduino) or a single-board computer (e.g. Raspberry Pi, BeagleBone Board) for developing hardware prototyping applications.

Hardware prototyping is a process that typically includes a moderately rapid cycle of prototyping and development with the goal of having a working functionality or functional system designed based on specific requirements. Hardware prototyping platforms (e.g. SBC or SBM) help designers transform their ideas into prototypes that demonstrate the intended functionality or system using elements that are not essentially in their final form factor.

In this paper, we generalize SBM and SBC as both being part of hardware prototyping platforms (HPP). This generalization is due to the fact that hardware prototypes can be developed or built using SBC or SBM and sometimes even both. Furthermore, regardless of the board type (i.e. SBC or SBM), single-boards are generally hardware prototyping platforms that share common uses such as general electronics and wearable development [29], IoT application development, home automation, among many others. Although there are variations among the different types of SBCs and SBMs that exist (e.g. Raspberry Pi 3 versus 4, or Arduino Uno versus Mega), our study focuses on measuring the extent to which hardware prototyping platforms in general are integrated into the curriculum.

Stemming from the fact that these low-cost single-board computing or microcontroller devices can support experiential or project-based learning approaches, instructors are exploring ways to integrate these platforms into the curriculum. The ability to utilize these platforms in creating a wide range of applications facilitates or enhances the students' learning and promotes proactive thinking. This is prompting instructors to think of creative ways to integrate prototyping platforms into computer science and engineering courses by providing students these tools for developing practical solutions and exploring real-world problems.

The widespread usage and integration of prototyping tools and boards into courses and research is becoming evident. At the time of writing this paper, a search query executed on Google Scholar, as an illustration, for exact matching of the keywords "Raspberry Pi" and "classroom" yields over 4,700 publications. Another search query for the keyword "Raspberry Pi" on IEEE Xplore shows over 2,500 publications and over 3,000 publications for the keyword "Arduino". Although such results do not provide a measure of the degree to which these tools have been integrated into the classroom or research projects, they do provide a high-level overall metric of how prototyping platforms are associated within courses or research projects.

Apart from the many examples illustrating the use of prototyping boards into classrooms or research [12]–[29], there exists no study, up to our knowledge at the time of writing this paper, which provides a thorough investigation into the degree to which these platforms have been used in educational institutions. Many of the existing research efforts attempt to provide illustrations or examples of the usage of such platforms with primary focus on factors such as improving student engagement, enhancing the student learning experience, reinforcing traditional theoretical ideas with practical hardware applications [21], [25], [26] or conducting research projects [30].

In addition, existing studies do not provide statistical evidence or significance for measuring the utilization of these prototyping boards at a global institutional level. For example, a recent study surveyed courses that integrate Arduino in embedded systems' courses and found that Arduino proved to be very promising educational platform in embedded engineering [31]. However, the study is limited to embedded systems courses and the engineering discipline.

There are a number of reasons that may contribute to the lack of statistical evidence at a broader scale including, but not limited to, the following: (a) the complexity associated with the collection of data that pertains to courses which utilize these platforms (e.g. targeted web crawlers), (b) course resources that reside on learning management systems that are not publicly accessible (e.g. Canvas or Blackboard) and (c) defining quantitative metrics to effectively determine the degree to which these platforms are integrated into existing courses. Although statistics show that these boards are becoming increasingly popular at the global level as evidenced by the numbers or figures provided by resellers or manufacturers of these devices, it is imperative to identify the context in which these platforms are integrated within STEM and Non-STEM education.

Based on the above, we conclude that there is an apparent need to define and determine the status or the degree of integration of these single-board devices into STEM and Non-STEM courses. To this extent, we conduct a study that focused on the data collection and analysis of course information to be used for determining the current status or impact of utilizing hardware prototyping platforms within courses. In this work, we make the following contributions:

- We examine a subset of educational institutions as our initial seed list for crawling and data collection.
- We run several experiments on a dataset consisting of the plurality of course resources that can be accessed on the web today for forty-five educational institutions.
- We analyze result sets and present various statistics including how many courses utilize prototyping platforms, which platform is more frequently used than

others and learning technology trends in employing these platforms.

- We examine and investigate the extent to which these platforms with their current varying degrees in terms of types are integrated into the curriculum across STEM and Non-STEM fields.

The rest of this paper is organized as follows: Section II describes the related works. Section III describes materials and methods used throughout this study. Results and evaluation are discussed in Section IV. Section V discusses some of the challenges and constraints. Section VI discusses the evidence of using emerging technologies as tools for learning and teaching. Finally conclusion and future work are discussed in Section VII.

II. RELATED WORK

With emerging paradigms such as the Internet of Things (IoT), cyber-physical systems, ubiquitous computing, cloud computing, among others, applying project-based or experiential learning approaches in courses becomes inevitable. For example, teaching students application layer IoT protocols such as HTTP, CoAP, WebSockets, MQTT, XMPP, DDS or AMQP may well require students to develop solutions or ideas for solving real-world problems that involve the application of a number of these protocols. Empowering students to find solutions to these real-world problems, from an educational standpoint, requires best practices or techniques to be adopted for integrating the tools that enable students to develop these solutions. In the following sections, we identify major emerging technology trends that have been adopted in recent years across many educational institutions.

A. HARDWARE PROTOTYPING PLATFORMS

A number of hardware manufacturers have recently begun creating their own single board computers. For example, Asus launched in 2017 the Asus Tinker Board that is compatible with the second-generation of the Raspberry Pi models [32]. Novasom Industries manufactures SBC platforms that focus on industrial and advanced multimedia or networking applications [33]. The Banana Pi is an open-source hardware and software platform developed by Shenzhen SINOVOIP that uses the Allwinner System on Chip (SoC) [34].

The Arduino platform stemmed as a project at the Interaction Design Institute Ivrea (Italy) in early 2000s [35]. The main goal of the Arduino is to facilitate the creation of working prototypes by novice users having minimal or no digital hardware background. BeagleBoard.org Foundation develops the BeagleBone [36]. Intel developed the Intel Galileo, an Arduino compatible development board based on Intel's x86 architecture [37]. Altera Corporation develops a FPGA prototyping board (e.g. Terasic DE10) [38]. These are only few of the many examples that exist today with respect to hardware prototyping platforms. Surveying a list of these platforms in its entirety is beyond the scope of this paper. However, we identify some platforms that are commonly used in the classroom to conduct our investigation for this research study.

Due to the fact that there exists a wide range of manufacturers and suppliers for processors and microcontrollers, there is a wide selection of SBMs and SBCs that can be used across many types of applications. For example, some of the existing SBMs are based on Intel microcontrollers (e.g. Intel Galileo) whereas ARM boards are based on the ARM7 microcontrollers and the MSP430 boards are based on Texas Instruments (TI) microcontrollers. However, these boards vary in terms of operating voltage, memory, clock speed, number of I/O pins, microcontroller or processor type, network interfaces, I/O ports, among many other hardware and software features.

Although there is a wide variety of SBMs and SBCs that exist, deciding on which board to use for prototyping is not an easy task. However, there are a few hardware prototyping platforms that have become popular in recent years and widely used in home and industrial applications or robotics. To this extent, in this study we limit our investigation based on the board type used in courses including Arduino [35], Raspberry Pi [39] and BeagleBone Boards [36]. We describe the rationale that has driven this selection in more details in Section 3.

B. MAKER SPACES AND TECH CAMPS

Over the past few years, a maker movement has been emerging [30], [40]. Thanks to advancements in 3D printing technologies, laser cutting and open-source hardware prototyping platforms that are contributing to this maker movement. Using the US News and World Report's Best Undergraduate Programs Ranking in 2014, Barrett *et al.* found that out of 127 colleges, 35 colleges have created maker spaces [41]. A maker space is a designated space that enables makers to perform creative activities and provides them with the necessary equipment or tools (including raw materials) [30].

Apart from maker spaces, a number of companies are devoted to provide learners at young age an opportunity to learn about new technologies. Through short and intensive course trainings, students attend tech camps to develop their software or hardware skills using emerging tools [42], [43]. As these tech camps are becoming increasingly popular for children (ages 7-18), there is an apparent technology learning trend which utilizes or integrates hardware prototyping platforms into the curriculum [1]. In the following section, we identify a number of universities that have been adopting these platforms in their curriculum.

C. INTEGRATING TECHNOLOGIES IN CLASSROOMS

Universities in recent years have started adopting courses that integrate hardware prototyping platforms [23]–[29]. In this section, we identify some examples that illustrate their usage. At the Utah Valley University, students use the Arduino to develop senior design course (capstone) projects as part of the computer engineering program or to model electromechanical systems [44]. At the University of Granada, introductory programming courses are offered using an experiential or a project-based learning approach by integrating Arduino devices [45]. A course in the area of embedded electronics utilizes Arduino- and Raspberry Pi-based kits to teach students the basics of the Internet of Things (IoT) at Florida Atlantic University [20]. Another course in embedded systems at Miami University encourages students to utilize Arduino platform for their course projects [46]. The authors in [46] have found that students' projects involving the Arduino platform outperform in terms of creativity those projects that did not involve Arduino kits.

At the University of Buffalo, a course in real-time and embedded operating systems provides students with Arduino, Raspberry Pi or a drone to complete course labs or projects [19]. The integration of hardware prototyping platforms is not limited to engineering courses but spans across other domains such as arts, humanities, among others. For example, the Center for Digital Arts and Experimental Media at the University of Washington offers a course titled 'E-textiles & Wearables for Art & Design' teaching students how to design interactive wearables through the use of smart materials and hand-created electronics while integrating the Arduino platform [47]. Another course at Harvard University titled 'Electronic Music Composition' explores hardware prototyping platforms as tools for enhancing instruments and methods of making and shaping sounds [48].

As part of their integration of this platform in engineering courses, some educators are investigating the challenges involved in including hardware prototyping platforms in the engineering curriculum [49]. Another study investigated the students' outcomes based on the integration of Arduino in a design-based module for undergraduate students [50]. In [51], the authors studied the outcome of students learning through the integration of open-source platforms in wireless scenarios.

There are additional examples exhibiting the integration of hardware prototyping platforms in an effort to improve students' learning outcomes [12]–[15]. Researchers at Case Western University have been investigating the impact of a technology enhanced classroom curriculum [16]. At an Internet of Things bootcamp at MIT, students were provided with Arduino, Raspberry Pi and sensor kits [15]. In [17], an engineering course at the University of Maryland integrates Arduino and Raspberry Pi as part of student-driven projects in an attempt to strengthen the students' understanding of mechatronics concepts while extending them to the Internet of Things domain. A computer science course in robotics focuses on the use of Raspberry Pi as an essential component of the course design and technology learning objectives [20]. A course at Portland State University in electrical engineering integrates a data acquisition device called LabJack in teaching students MATLAB programming [21].

While there exists significant research efforts that identify the effectiveness of using these platforms in education, this paper investigates the extent to which hardware prototyping platforms such as Arduino, Raspberry Pi and BeagleBone Board are used within courses offered by educational institutions worldwide. In addition, this paper analyzes which platform is commonly used in courses and assesses whether this integration is limited to STEM or Non-STEM courses. Additionally, this research study identifies the degree to which these platforms are integrated through applied or non-applied approaches. Furthermore, we provide statistical analysis relating to the distribution and adoption rates of this integration within courses. In the following section, we describe in details the methodology we adopted for generating our dataset that we used further in our experiments.

III. METHODOLOGY

The aim of the current research study is to identify any relationship between the utilization and integration of hardware prototyping platforms and the curriculum of computer science, engineering and other fields of study. Our study is not limited to specific fields. We mainly focus on the utilization and integration of these platforms as part of the course components (e.g. projects, assignments, labs, etc.). We designed our quantitative research as descriptive since we measure the data once. To this extent, we considered quantitative methods that emphasize on actual measurements and statistical numerical analysis of data that can be collected. We use this data to measure the degree to which institutions are using these platforms. We describe two main goals of our research study as follows:

- First, identify the relationship between hardware prototyping platforms and their utilization within courses across different fields of study.
- Second, collect data using structured mechanisms from existing sources over the web to be able to generalize concepts more broadly and investigate relationships between hardware prototyping platforms and their utilization in courses offered to students across different fields.

To achieve these goals, we applied a practical approach to build the dataset needed for identifying relationships. To this extent, we built a framework called Crawl, Extract and Analyze (CEA) for this purpose. The procedure of our research using CEA consists of: (1) building a repository for the course syllabi of a large number of courses available over web resources including search engines indices, university websites, and educational portals; (2) build mechanisms for extracting information pertinent to this study; (3) analyze retrieved course information by examining course syllabi, geographic location, STEM or Non-STEM related, discipline, types of hardware prototyping platforms employed, among others. Figure 1 provides a graphical representation of the CEA framework that we implemented for the purpose of this study in addition to the steps we applied for the design, collection and analysis of our system. The following sub-sections describe the details of each of these components, their responsibilities and the implementation details.

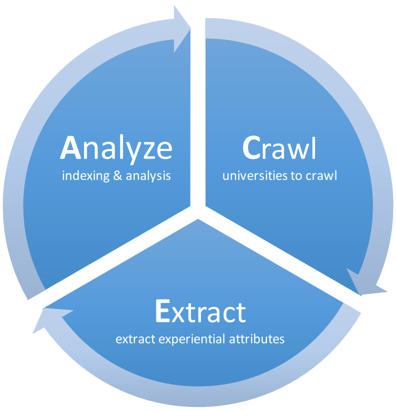

FIGURE 1. Our proposed CEA framework.

A. DATA SOURCE AND SAMPLING METHOD

Data collection is an integral part of this study as it enabled us to perform data analysis. Unfortunately, there is no single repository that provides a comprehensive list of sources for accessing course syllabi. Furthermore, there are a number of search engines that exist (e.g. Google, Baidu, etc.) which are geographically distributed and employ different languages for performing search queries. Therefore, prior to applying the essential tools for collecting data, it is necessary to first build a set of resources that provide a list of course syllabi which can then be used for our experiments and avoid the complications associated with randomly collecting them via existing search engines.

Due to the fact that collecting all possible courses at the global level is not countable and the limitations associated with arbitrarily or unmethodically searching for course syllabi through existing web resources (i.e. search engine indices), we followed a focused approach for our data collection. Through this approach, it is necessary to identify a countable measure or mechanism that enables us to find a seed list of universities that we can then use to discover the course syllabi we need to collect. To this extent, we used a sound sampling method that is discrete to obtain reliable results in our statistical study and avoid self-selection or bias.

For obtaining the source of the data needed for this study, we used existing web resources that provide a repository of world universities to create a seed list of universities. UniRank provides a comprehensive alphabetical listing of world universities [52]. We imported this list into a database to store: (a) university name, (b) country and (c) URL of the website of the university. To build a list of universities that we wish to crawl, we randomly selected forty five samples from this seed list. Through this random sampling technique, we avoid bias and subjectivity in selecting universities to be examined such that we only focus on extracting data from identified URLs without considering factors such as size of the universities (i.e. in terms of faculty/staff/student population), financial budgets, location, among many other factors.

Based on this initial seed list, we use our crawler to crawl for course-related information (e.g. syllabi) for courses that utilize hardware prototyping platforms. Our targeted crawler is designed to identify potential web resources (e.g. html files, PDF documents, etc.) where these platforms are used. Then, we analyzed the course syllabi to identify relevant information pertaining to this study. Because we are able to obtain a list for tertiary institutions (e.g. universities, colleges, polytechnic), we were able to collect relevant data for this research study which is stored within the publicly available syllabi resources. Unfortunately, following the same strategy for secondary and primary institutions was not feasible due to the scarcity of the publicly available course syllabi resources on the web.

We identified through our crawl component of the CEA that the total number of course syllabi per institution varied since this number is mainly dependent on how many courses we could identify or discover over the web per host. Our crawling strategy included filtering crawled documents and identify only those that are relevant for the purpose of this study. To this extent, we collected data from a total of 422 relevant course syllabi discovered on hosts representing the forty five randomly selected institutions. We determined that the total size of course-related data equaled to 321MB.

B. DATA COLLECTION AND ANALYSIS

Following the process of collecting and storing extracted information relevant from the plurality of discovered course syllabi representing the forty five institutions, we then examine each syllabus and extract properties based on what we define as Experiential Attributes (EA). Some of these attributes are fixed (e.g. course name) while others are variables (e.g. hardware platform type). We measure these variables quantitatively such that we are able to identify relationships. As part of the analyze step, we perform additional indexing based on the collected data such as parsing content and analyzing course information. This step helps us identify critical information that will be needed for the analysis of our study. The experiential attributes include: (a) institution name, (b) course name, (c) course number, (d) hardware platform type, (e) usage type and (f) STEM indicator.

The institution name can be of any of the forty five universities collected in the previous stage. The course name and number are used for referencing. The hardware platform type can be any of the following labels: (a) "ARD" for Arduino, (b) "RPI" for Raspberry Pi and (c) "BBB" for BeagleBone Board. Categorizing hardware prototyping platforms into any of these three labels was based on the analysis we performed across course syllabi examined for the forty five institutions. The usage platform is used as an indicator whether the course uses an experiential (empirical) or referenced (unempirical) method.

An experiential or empirical indicator demonstrates that the knowledge acquisition of utilizing or integrating a hardware prototyping platform in the course is possessed through observation or experience using the platforms. An experiential indicator is generally associated with a course project, activity or lab involving an applied learning approach or developing a tangible prototype or model using these platforms. A referenced (or unempirical) is a course that encourages students to explore the use of hardware prototyping platforms without gaining tangible experience on using them.

Finally, a STEM indicator can be either 1 for a STEM course or 0 for a Non-STEM course. STEM stands for Science, Technology, Engineering, and Mathematics. The STEM indicator is used to identify the discipline of the course being examined at a broad scale. To categorize courses based on type, we examine each course and identify the department or school offering the course. Then, we use this information to identify whether the course is associated with a STEM or Non-STEM field. We believe that identifying this information provides a degree to which these hardware prototyping platforms are integrated into courses across different fields of study while also determining the extent to which these platforms are applied into a learning process that promotes more complex, deeper understanding of course topics [53].

IV. RESULTS

In this section, we present results and statistics from collected course-related information following our focused process in our CEA framework described in Section 3 spanning across three-seven months. The total number of courses we collected information about is 422, the majority of which were collected through search engines. Table 1 provides an overview of our dataset with respect to the platform used across courses and the corresponding course types.

TABLE 1. Our dataset for courses offered between 01/12-02/20.

Platform	Number of Courses	
	STEM	Non-STEM
Arduino (ARD)	196	78
Raspberry Pi (RPI)	102	21
BeagleBone Board (BBB)	19	6
Total Number of Courses Per Type	317	105
Total Number of Courses Overall	422 courses	

Nearly all of the courses we examined were offered at least once between the period of January 2012 and February 2020, 76% of which were offered between the years of 2016 and 2020. We only considered unique courses in our seed list such that courses that are offered across multiple terms are treated as one offered course regardless of the term. This is due to the fact that we are interested in determining the total number of unique courses offered by educational institutions. By removing course recurrences, we avoid considering the same course multiple times which provides a more accurate reflection of the overall total number of courses that we are investigating in our seed list.

A. COURSE DISTRIBUTION BY TYPE

We first examine the total number of STEM and Non-STEM courses in our dataset. We have found that 317 courses integrate hardware prototyping platforms into a STEM-related curriculum as opposed to 105 non-STEM courses. Figure 2 presents the percentage of each course type based on our dataset collection of 422 courses for the 45 selected universities. Figure 3 presents the course distribution by platform and type.

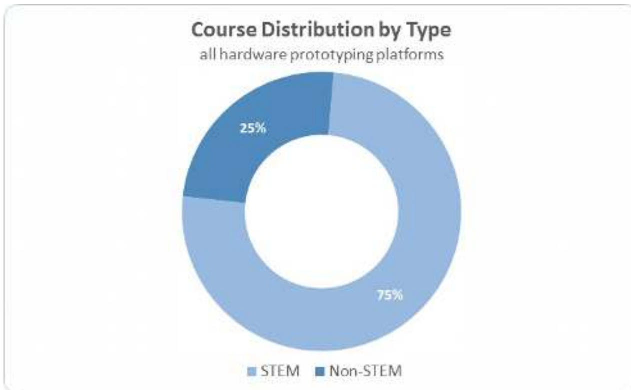

FIGURE 2. Proportion of STEM and non-STEM courses.

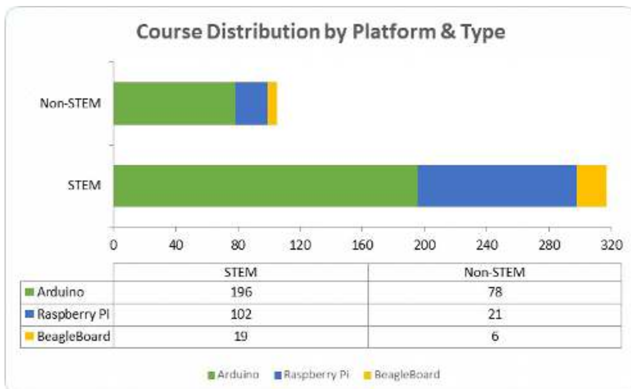

FIGURE 3. Distribution of STEM and non-STEM courses by platform and type.

Although Non-STEM courses constitute 25% of the courses that utilize hardware prototyping platforms in one form or another, STEM courses constitute triple this percentage value being 75% which provides an extent of the usage of these platforms in STEM fields and the application of the experiential learning approach applied within these courses. This is an indicator that although STEM courses utilize single boards, a significant number of Non-STEM courses also utilize these boards into courses.

B. COURSE DISTRIBUTION BY PROTOTYPING PLATFORM

As part of our analysis of the course syllabi, we divide the categories on the basis of the platform applied for the courses. Table 1 shows that 196 STEM courses use Arduino, 102 use Raspberry Pi and 19 use BeagleBone Board. In contrast, only 78 Non-STEM courses use Arduino, 21 use Raspberry Pi and 6 use BeagleBone Board. In fact, 65% (or 274 courses) of the total courses we analyzed utilize or integrate Arduino in the curriculum. Raspberry Pi was the second common platform with 29% (or 123 courses) while BeagleBone Board has 6% (or 25 courses) of the total number of courses examined. These statistics show that Arduino is not only the most commonly used hardware prototyping platform for STEM courses but also for Non-STEM courses. We believe that this finding provides a degree to which this platform is used or applied as a teaching and learning tool across both STEM and Non-STEM courses.

Figure 4 presents the course distribution for all hardware prototyping platforms that we considered. Figures 5 and 6 show the course distribution based on the platform for STEM and Non-STEM courses, respectively. Statistics show that Arduino remains the most preferred or utilized hardware prototyping platform across both STEM and Non-STEM curriculum integration, followed by Raspberry Pi. We further examined any correlation between the integration of the hardware platforms and course types (i.e. STEM and Non-STEM) and have found a correlation coefficient of 0.96.

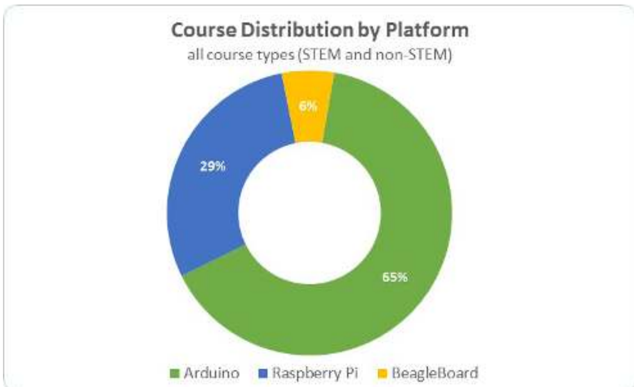

FIGURE 4. Course distribution by platform.

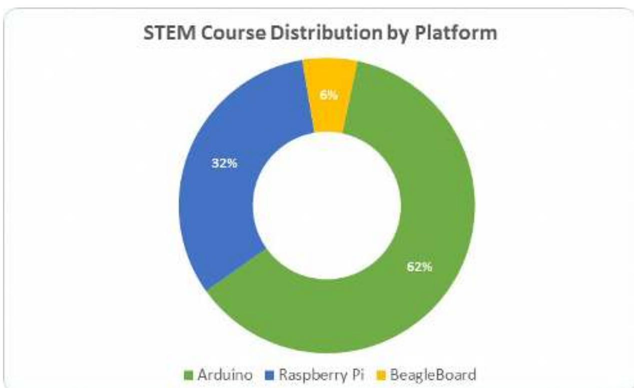

FIGURE 5. STEM course distribution by platform.

C. COURSE DISTRIBUTION BY USAGE

As discussed in Section III.B, we categorized the usage of the hardware platform as either experiential (empirical) or referenced (unempirical). An experiential usage translates into an applied learning approach that encourages and engages students into gaining skills and experience by performing practical or hands-on learning. To this extent, we analyzed the dataset based on the course usage of the platform. Our dataset shows that 322 courses (or 76%) of the overall 422 courses required students to work on activities or projects that follow an experiential learning strategy. Figure 7 demonstrates the ratio of this categorization.

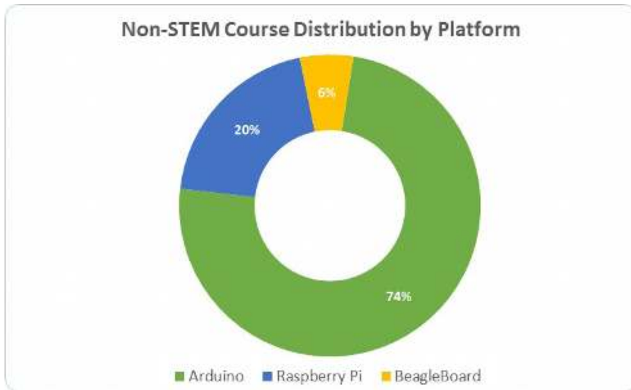

FIGURE 6. Non-STEM course distribution by platform.

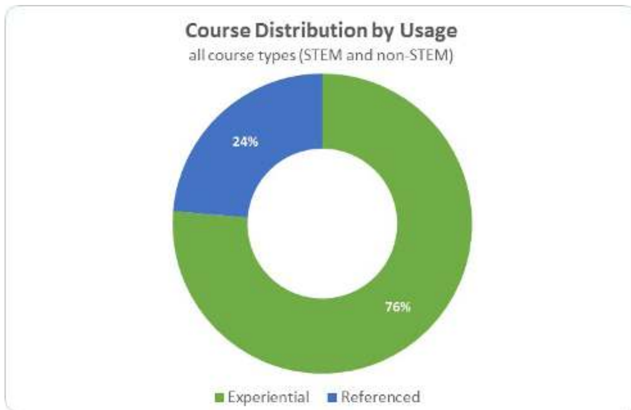

FIGURE 7. Course distribution by usage (experiential or referenced approaches).

As presented in Figure 7, there is a significant number of courses that utilize an experiential learning strategy for integrating hardware prototyping platforms into courses compared to that of the referenced approach.

We further analyze the course distribution by usage across each platform and results are presented in Figure 8.

As can be seen in Figure 8, Arduino maintains the highest, widely or commonly used platform across both usage types, experiential and referenced. This is an indicator that instructors require or recommend the usage of Arduino across both course usage types (i.e. experiential and referenced). Out of the 322 courses classified as experiential, 218 courses used Arduino, 87 used Raspberry Pi and 17 used BeagleBone Board. Out of the 100 courses that are categorized as referenced, 56 courses recommended the usage of Arduino and 36 courses recommended the usage of Raspberry Pi. From the 422 course syllabi, we observed that the majority of

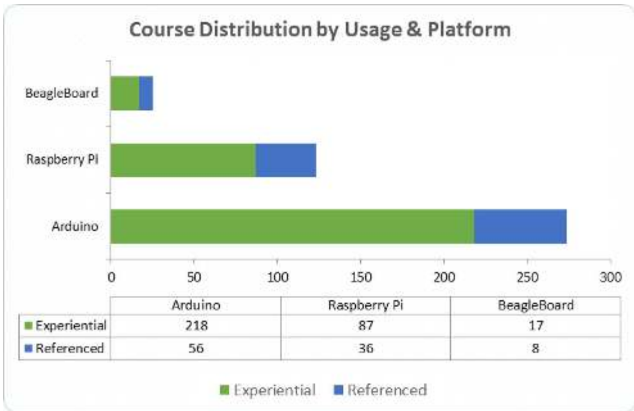

FIGURE 8. Course distribution by usage (experiential and referenced approaches) and platform (ARD, RPI and BBB).

Non-STEM courses have a primary focus on digital arts or digital fabrication. We also observed that the majority of the courses that utilize BeagleBone Board are primarily related to areas such as embedded system and microcontrollers.

We further investigated the percentage difference between Arduino and Raspberry Pi for both experiential and referenced usage types. We determined that 27% of the courses in the experiential category integrate the Raspberry Pi into the curriculum whereas Arduino constitutes 68% of this category. We also determined a similar trend in the referenced category in which 56% of the courses in the referenced category recommending students to explore Arduino compared to 36% for the Raspberry Pi. Regardless of a course being classified as STEM or Non-STEM, this could be an indicator that although many instructors recommend their students to explore the Raspberry Pi in the referenced approach, Arduino becomes a more preferred choice for instructors when recommending a platform for students to explore.

In addition, this finding may be attributed to many factors including, but not limited to, ease of use of the platform, cost, availability of instructional material, accessibility, ease of integration into various topics or disciplines, among many others. While our study does not focus on examining these factors, we believe it is worthwhile investigating these results as they do provide valuable information as the preferred choice of hardware prototyping platform in STEM and Non-STEM courses.

D. RELATIONSHIP OF TRENDS BY TYPE AND PLATFORM

As part of our observations, we examine the relationship of the current trends of contribution by universities in STEM and Non-STEM courses. That is, we would like to determine whether the trend of integrating hardware prototyping platforms in STEM courses (variable 1) is related to the trend of the same integration but in Non-STEM courses (variable 2).

First, we examine the correlation between courses that integrate Arduino to those courses that integrate Raspberry Pi across all of the forty five universities we examined (e.g. the entire seed list). This includes both STEM and Non-STEM courses. We did not include BeagleBone Board into this analysis due to the fact that it has a significantly low number of courses compared to the other two platforms. As a result, information about BBB would not add any statistical value to our analysis since we are focusing on the top learning technology trends.

We consider any trend relationship between the integration of Arduino and Raspberry Pi across all universities examined. We compute the correlation coefficient which was found to be $r = 0.62$ and compute the p-value which was found to be 0.0001. The correlation coefficient is closer to +1 and the p-value suggests that the sample results are not likely to occur by chance when a linear correlation does not exist. We have found the correlation coefficients to be more closer to +1 when considering the trends of all courses to (a) Arduino ($r = 0.93$, p-value = 5.5E-20) and (b) Raspberry Pi ($r = 0.80$, p-value = 5.6E-11).

We further consider the relationship between trends in the contribution of the universities in STEM courses. In particular, we focused on courses that integrate Arduino and Raspberry Pi for this observation. We have found a correlation coefficient of $r = 0.70$ and p-value = 1.2E-07 for universities with STEM courses that integrate Raspberry Pi whereas there exists a significant positive correlation between STEM-based courses and integration of Arduino ($r = 0.70$, p-value = 1.7E-07). The correlation coefficients are closer to +1 and the p-value suggests that these trends are unlikely to occur by chance. That is, there is a significant positive correlation between STEM courses and the type of platform.

We also considered the correlation between the platform and the usage (i.e. experiential versus referenced). We observed that there is a more significant positive correlation between experiential usage with Arduino compared to that of the Raspberry Pi platform type. We have found a correlation coefficient of $r = 0.86$ of Arduino and experiential type (p-value = 4.5E-14). The correlation coefficient of $r = 0.71$ with p-value = 1.2E-07 for Raspberry Pi and experiential type across all examined 45 universities. This observation aligns with the earlier findings that suggest that Arduino as being the preferred or more popular hardware prototyping tool integrated into courses.

V. CHALLENGES AND CONSTRAINTS

The web provides a framework or foundation for searching informational resources which can vary in terms of data formats. These resources may not always be publicly accessible. For example, institutions use learning management systems (LMSs) such as Blackboard, Canvas, Moodle, among many others. Access to these LMSs is often restricted and therefore content may not be publicly accessible. This makes the process of finding course syllabi that we can use for our study a difficult and challenging task. To overcome this, we applied a number of crawling methods to be able to collect as many course syllabi as possible and expanded our search strategy to also include curriculum and course description catalogs. In addition, based on our analysis we determined that although access to educational resources through LMSs may be restricted, institutions generally host copies of course syllabi for majority of offered courses which are publicly available or accessible. Hence, this enabled us to collect sufficient data required for conducting our research study.

Furthermore, there is a constraint in the way search queries can be constructed or executed. This is due to the fact that search engines integrate the geographical location of the user performing the search request for obtaining relevant search results [54], [55]. This can be a constraint since performing a search query from a specific location (e.g. United States) may only yield course syllabi pertaining to a particular geographic location (e.g. Seattle, USA). To overcome this limitation, we applied a distributed technique such that search queries are not constrained by a specific geographical location in order to avoid subjectivity during the data collection process.

Although the information we analyzed for the 422 course syllabi from forty five institutions around the world, the number of courses that we may be able to collect for other institutions will likely to yield a much larger number of courses. As we collect more information about courses that integrate hardware platforms in the curriculum, we will likely have more insights about the extent of this integration. However, one of the main goals of our research study is to investigate the degree to which this integration exists across a number of institutions.

Results from our study show that across all of the forty five educational institutions, the likelihood that an institution does not have a number of courses that integrate hardware prototyping platforms in one form or another is very minimal. Therefore, adding more course syllabi will provide more insights but will unlikely contradict our findings that hardware prototyping platforms are clearly becoming a technology learning trend at an educational institutional level that is reaching a wide variety of courses across STEM and Non-STEM fields. These findings also strongly suggest that these platforms are not only being used at the commercial level but also applied or used as tools for teaching and learning in academia.

Apart from the limitations regarding the collection of more data, there are some challenges associated with the parsing of the course syllabi. Due to the fact that these syllabi represent a large number of courses which are authored or structured differently, parsing and extracting information (i.e. experiential attributes) is not an easy task. Some of the limitations we encountered include: (1) identifying whether a course follows an experiential (or empirical) approach or a referenced approach; (2) identify associations between a hardware prototyping platform and course labs or projects; (3) determining if a course is a STEM or Non-STEM related; (4) some courses may be taught by different instructors and are subject to revisions over time; and (5) determining any associations between the integration of hardware prototyping platforms and attributes of pedagogy (e.g. reflective practices, innovation and creativity, among others.). To this extent, a number of judgements were employed by multiple individuals to avoid any subjectivity in identifying the experiential attributes.

Hardware prototyping platforms are no longer resources used by hobbyists or individuals. Results from our study show that a significant number of educators are starting to integrate these platforms in one form or another into their courses and as part of their curriculum. The depth of this integration may vary, however, it is apparent that all forty five institutions we analyzed are all using these platforms in many different ways. Due to the fact that course syllabi contain textual information which are often stored in documents, these documents can potentially be indexed by search engine crawlers. Through search engines, it is then possible that users are able to perform search queries in order to discover course syllabi documents that are disseminated throughout the web. However, crawling such documents is often a complex process, time consuming and requires special consideration to the structure of these documents.

The ability to identify the extent of the integration of hardware prototyping platforms in education is a challenge. Although search engines are examples of data repositories that may contain such information, the inability to access course information directly through educational institutions acts considerably as a deterrent for the widespread of determining the extent of this integration. Nonetheless, with current possible methods for collecting data accessible through existing web informational resources, we are able to identify the extent to which emerging hardware prototyping technologies are used as tools for teaching and learning activities.

VI. INTEGRATING EMERGING TECHNOLOGIES AS TOOLS FOR TEACHING & LEARNING

In our study, we investigated the distribution of courses that integrate hardware prototyping platforms based on course type (i.e. STEM or Non-STEM), by platform (i.e. Raspberry Pi, Arduino or BeagleBone Board), by usage (i.e. experiential or referenced approach) and other learning technology trends we were able to find. Results provide an overview on the current status of integrating hardware prototyping platforms today. An intriguing result is the fact that integrating hardware prototyping platforms is no longer limited to a small number of courses.

Table 2 presents a summary of our findings on courses that were examined for the randomly selected forty-five institutions. Results show that on average, there are 9.38 courses per institution that utilize one or more hardware prototyping platforms. The average of ARD is 6.09 which is more than double that of RPI (2.73). This is an indicator of the popularity or the degree to which ARD is integrated into the courses when compared to that of RPI and BBB. Furthermore, we note that there exists at least one course per institution that uses one of these platforms. In addition, the average number of courses for STEM is more than three times higher when compared to that of Non-STEM. This result aligns with our findings that STEM courses constitute 75% of the courses we have examined while 25% are Non-STEM.

Results from our experimentation also suggest that hardware prototyping platforms such as Arduino and Raspberry Pi

TABLE 2. Summary of findings on courses examined for forty five institutions.

Platform	Courses			
	Average	Min	Max	Median
All Platforms*	9.38	1	27	9
ARD*	6.09	0	19	6
RPI*	2.73	0	9	2
BBB*	0.56	0	3	0
Experiential**	7.16	1	24	7
Referenced**	2.22	0	11	2
STEM**	7.07	1	21	6
Non-STEM**	2.31	0	14	0

* *(regardless of type, usage)*
* *(regardless of platform, type, usage)*

are becoming useful tools for teaching and learning. The observations we determined while examining relationships between hardware prototyping platforms, usage and types proof that the results we have obtained from this study are significant and demonstrate factual evidence that these trends are unlikely to occur by chance.

VII. CONCLUSION

Emerging paradigms such as the Internet of Things have contributed to the cohesiveness and intersection between computing with other areas. This has led to a growing interest among students into learning more about new cutting-edge technologies. This has also been prompting educators to consider applying nontraditional teaching methods for improving the students' learning process and promoting proactive thinking within classrooms. One promising technology trend that is becoming apparent in teaching and learning is the integration of hardware prototyping platforms such as the Arduino or Raspberry Pi into the curriculum. Identifying the extent of this integration was not of critical importance when the number of courses integrating them was few or limited. However, due to the increasing popularity of these platforms across the education community, determining and investigating the extent to which these platforms are used in education as tools for teaching and learning becomes inevitable.

Our experiments show that the integration of hardware prototyping platforms is no longer constrained to Science, Technology, Engineering, and Mathematics (STEM) fields. In fact, our results show that 25% of the courses which integrate or utilize these platforms are Non-STEM. Furthermore, results show that 76% of the courses we investigated apply an experiential or a project-based learning approach.

Our study also demonstrate that the forty five randomly selected educational institutions offered on average nine unique courses that utilize or integrate one or more hardware prototyping platforms in their curriculum over the past five-six years. Results also show that Arduino constitutes 65% of the total number of courses followed by the Raspberry Pi with 29%. This is a strong indicator that Arduino is among the top or most preferred emerging hardware prototyping technology used as a tool in teaching and learning.

Based on our experiments, we also have found that there exists a strong correlation between the number of courses that utilize Arduino and Raspberry Pi across all of the universities we examined. Such course statistics may provide instructors or educators additional methods to further examine the potential of integrating such platforms at a wider scale in an effort to engage students and promote their proactive thinking within and outside the classroom environment. Our results demonstrate that integrating hardware prototyping platforms such as Arduino or Raspberry Pi used as tools for teaching and learning is becoming an apparent learning technology trend.

Furthermore, we believe that this paper provides an eye opener to researchers, educators and industries manufacturing these prototyping tools of the extent of the integration for such platforms in academia. We also believe that our study provides a motivating factor for other researchers to explore the benefits or impact of integrating hardware prototyping platforms on the overall students' learning process. For future work, we plan to extend our research work to collect more courses across a larger segment of universities worldwide and identify the extent to which these platforms are reflecting or enhancing pedagogical approaches or learning activities.

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