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Review article

A systematic literature review on prototyping with Arduino: Applications, challenges, advantages, and limitations

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ABSTRACT

Arduino, an open-source electronics platform, has become the go-to option for anyone working on interactive hardware and software projects. An Arduino board (such as the Uno) connected to a breadboard with plugins such as inputs, sensors, lights, and displays can be controlled by a code written in the Arduino development environment. How to achieve this is by prototyping with Arduino. Prototyping with Arduino has grown in popularity with the increased use of the Arduino platform. Prototyping with Arduino, however, is not an easy task for nonprogrammers with interest in the field. With increased public interest in the field will come a need for accessible information. This paper presents a methodical literature review intended to intensively analyze and compare existing primary studies on prototyping with Arduino. We found about 130 of such studies, all peer-reviewed and published within the last 15 years, including these years (2015–2020). These studies were tediously and carefully chosen through a three-step process. In this paper, a cautious analysis of selected studies was followed by a clear description of the methods applied. The methods were categorized according to the success rate of the studied prototypes. Results obtained can be used in researches on the best technique to adopt while prototyping with Arduino. They can also be used in electronics researches and by individuals who wish to obtain a guide on prototyping with Arduino despite lacking grounded knowledge of the subject matter.

Contents

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1. Introduction

Any study on prototyping with Arduino that does not mention microcontrollers would be judged to be incomplete. Microcontrollers have found widespread use in homes, offices, and research environments. In simple terms, microcontrollers are embedded systems which when in a device control the actions and features of that device [1,2]. Most often, they control one dedicated task in the device and not all of the device's functions. Microcontrollers have both a software and a hardware component [3]. Microcontrollers are microcomputers now popularly known as single board computers [4,5]. But microcontrollers should not be confused with microprocessors which are used for general-purpose computing whereas microcontrollers are designed for a specific purpose [6].

Microcontrollers can be found in implantable medical devices, process control systems, automobile engine control systems, remote control systems, industrial instrumentation devices, voltmeter, office equipment, electronic appliances, power tools, and toys [4]. Most of these devices and products are automatically controlled, have dedicated input devices and tiny LED/LCD display outputs.

Their consumption of very low power is microcontrollers' biggest selling point and explains why a very big percentage of the applications in most facets of the electronics manufacturing industry is being implemented as embedded computer systems such as microcontrollers [7]. Microcontrollers are also loved for their reusability, cost-effectiveness [8], and dependability. All microcontrollers are programmable [9].

While many systems exist for building microcontrollers [8], Arduino has proved to be the most effective. Arduino, an open-source hardware and software enterprise and user interaction community, has been manufacturing microcontroller-based Arduino boards since 2005 [10]. These development boards are also known as Arduino Modules can be used for microcontroller development. Arduino makes the procedure of working with microcontrollers simpler while offering huge benefits to teachers, students, and hobbyists when compared with similar systems. Unlike other microcontroller development platforms, Arduino boards are moderately inexpensive. There is also the possibility of uploading a script ton the Arduino board's EEPROM and it would execute without the board being interfaced with computers or some software outside the Arduino system. This gives ensures it can function independently and with a high degree of accuracy and portability [11]. Arduino boards also have an accessory of microcontroller-based kits that are useful in building digital devices and interactive entities that not only sense but control real-life objects [6,12]. An Arduino itself contains a microcontroller, such as an Atmel ATmega328p or ATmega168, and relies on this microcontroller in the development of prototypes and projects [13,14]. Arduino has a simple, easy-to-understand, easy-to-use syntax that makes it perfect for the kind of individuals that are naturally lovers of C, simplified C++, and Processing namely, hobbyists, students, and amateur innovators [15,16]. Arduino, then, is a conglomeration of microcontroller and other needed parts like crystal, on-board power supply pins, bootloader. All of these are necessary for successfully building executable programs in the Arduino IDE.

An Arduino board allows users to experiment on innovative ideas they wish to bring to life. The controller in the Arduino board can be programmed with the Arduino IDE. In reality, programming with Arduino means reprogramming this microcontroller. There are inbuilt LEDs on the board, as well as extendable pins where external modules such as USB can be attached to. It is the in-built microcontroller that controls the functions of the LEDs and sensors that are attached to the board through its pins.

Arduino exists in many variants [17] including Arduino Uno, Arduino Due, Arduino Mega, and Arduino Leonardo [18] and has been used in many fields such as mining [19–33] Systems Design, controllers [34], General Purpose Applications [35–37] and use, remote sensing [38–41] Hardware Communication [42], Software Prototyping, Oceanographic research [43,44] and Programming Education [45–49] and [50].

1.1. Steps in prototyping with arduino

Generic steps in prototyping with Arduino, irrespective of the variant being used or the type of project being prototyped [51], usually includes the following (cp. Fig. 1):

1.1.1. Ideation/problem definition

during this stage, the idea of the project is birthed, a need for such a project is discovered and the project the finished project is supposed to solve is defined. From this stage, a picture of the successfully prototyped project is imagined.

1.1.2. Conceptualization

After the idea had been birthed and problems defined, a concept is built around the idea. This is a simplified view of the project [Gruber]. How exactly should it work? Would computations be necessary for generating the final output? What is the process the finished product would go through before producing an output? Are theories necessary, what should be the theory behind the operations of the imagined system?

1.1.3. Prototyping

This involves building a sample of the finished product [52]. A prototype translates theories into specifications for a real, working system [53]. The imagined ideas, now conceptualized are built into an observable framework; a rough set of clickable screens one capable of having the user/developer move around it to simulate interaction; high definition screens with code-like prototypes and eventually the project up and running in actual codes. Prototypes of software are initially alpha grades being that they are the first version of the project to run until they have been modified to contain all the required features. Once all the features are incorporated, the prototype becomes a beta software, ready for testing and subsequent deployment for public use. These two types of prototypes capsulate the general idea behind a prototype, that is, a version needed by system analysts and users to evaluate the built system to enhance effectiveness and performance [54].

The final stage, prototyping, does have stages itself. These are the communication, design, modeling, and deployment stages [55] (see Fig. 2).

At the communication stage, the project requirement and outlook of the expected final product are communicated to the developing team by the idea initiator. The design is important in building the prototype. The design stage requires the depiction of the input and output features of the project under review, focusing on the features of the project that are easily observable and implementable and not just abstract, non-implementable wishes of the idea initiator. During modeling, the goal is to put the conceptualized idea in a form it is clearly understood and the expected product imagined. After this stage, the idea initiator and other critical stakeholders of the project should see what has been built so far and agree whether it is good enough or requires improvements in certain places. Finally, the product from the modeling stage is deployed to the production environment and eventually shipped to the expected users.

At the heart of this paper, are the following objectives:

(1) a thorough review of researches already conducted in the field of prototyping with Arduino

(2) highlighting the challenges of research, and

(3) the motivation of more individuals to prototype with Arduino and enjoy the many benefits of using it to build microcontrollers which in turn could be used to solve a whole range of problems.

Much effort was concentrated on reviewing the application domains of Arduino. A detailed analysis of the prototyping steps is outside the deliverables of this review. Moreover, the methods applied within these phases are generic and generally independent of the application domain.

2. Methods

A systematic literature review (SLR) is the assessment of all existing research materials on a particular research topic of interest and an accompanying generalized interpretation of the results from the assessed research works. The methodology for a systematic literature review (SLR) is well established. The processes involved in an SLR are grouped into three main parts, and these include:

1. Outlining of the research questions,
2. Conduction of a thorough search procedure to find important publications, and
3. Mining essential data, useful for answering the outlined research questions, from the identified publications [56] and [57].

These steps and methods were exactly what was adopted in this review.

2.1. Research questions

The following four research questions were defined for our systematic literature review:

RESEARCH QUESTION-1: **Arduino Board variants:** *What are the different variants of Arduino boards? What are the technical specifications (width, breadth, weight, number of digital and analog IO pins, memory, processor, etc.), advantages, and limitations of each variant? What is the specific application of each variant?* (The goal here is to get a quantitative overview of Arduino boards and a description of each variant as obtained in the reviewed literature.)

RESEARCH QUESTION-2: **Application Domains of Arduino:** *What are the various application domains of Arduino prototyping? What are the advantages, challenges, limitations of using Arduino for prototyping in each application domain?* This question interrogated the areas where Arduino could be used in prototyping problem-solving devices. There happen to exist over a thousand such areas, so we had to constrain ourselves with a limited number of domains.

RESEARCH QUESTION-3: **Alternatives to Arduino:** *What are the other alternative prototyping boards to Arduino? What are their strengths and weaknesses?* Arduino is not the only type of prototyping board in the market. This research question seeks to identify these alternatives and to conduct a comparative analysis of the capabilities of each board.

RESEARCH QUESTION-4: **Hardware components and software packages used when prototyping with Arduino**: *What are the commonly used Hardware components (Sensors, connectors, accessories, and other devices) in prototyping with Arduino? What is the commonly used software for data storage, analysis, and output?* Here we identified the hardware components of an Arduino board and the software packages that work with these hardware components to prototype projects.

2.2. Data sources and selection strategy

Many strategies exist for the identification of data sources in systematic literature reviews like this one. But for our review, we combined the backward and forward snowballing strategies in identifying relevant primary studies (as shown in Fig. 3). The reason we adopted this approach because such a snowballing search technique allows the accumulation of a relatively complete census of relevant literature. Again, literature so acquired is not always limited to a single research methodology, a single set of journal articles and conference papers, or a particular geographic location. The snowballing strategy needs in its operations a starting set of publications usually publications in the research field's leading journals. Publications that have been cited several times and by varied categories of researches are also acceptable. A manual search on Google Scholar was used to identify our starting set of five publications (as illustrated in Table 1). Google Scholar is a popular tool for finding research papers and scholarly written textbooks, journal articles, and conference papers. It is widely used in the intelligence community because eliminates bias in favor of against a particular publisher in the set point of the sampling procedure. But the existence of a publication on Google

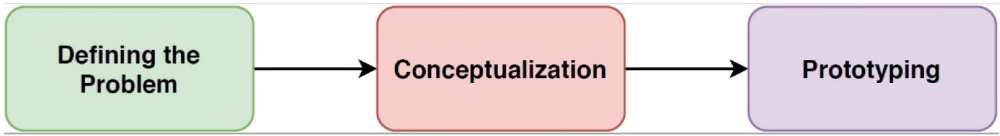

Fig. 1. Generic steps in prototyping with Arduino.

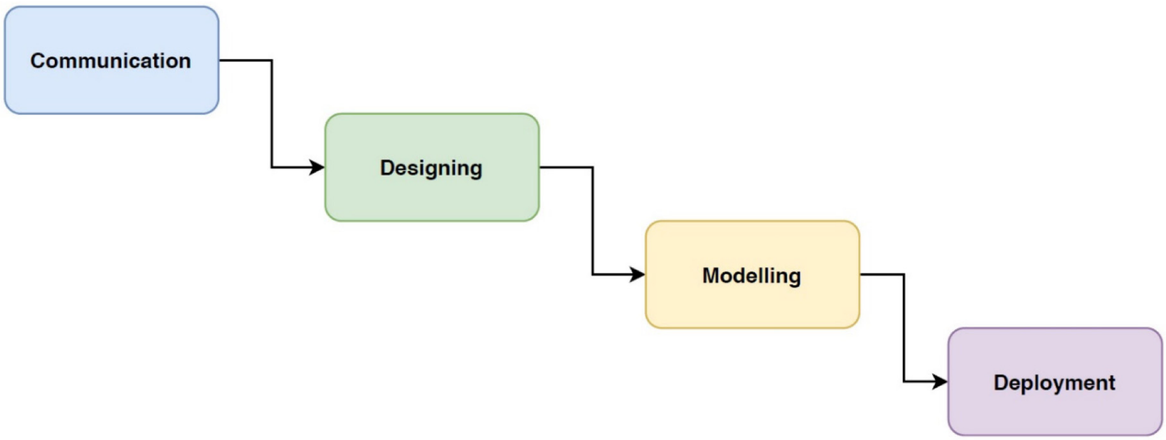

Fig. 2. Final processes in the prototyping phase of prototyping.

Scholar is in itself not enough to judge the credibility of the publication or ascertain that it is scholarly enough. To confirm if our initial set publications already identified from Google Scholar were scholarly enough and good enough for our systematic literature review, we had to be sure they appeared in at least one other scientific repositories. Popular scientific repositories for such check include:

(a) ACM Digital Library,
(b) Elsevier ScienceDirect®,
(c) IEEE Xplore®, and
(d) Thomson Reuters Web of Science™.

All of these repositories are reputable enough to publish low-quality publications. The existence of the selected publication is not only Google Scholar but also one of these repositories is clear proof the publication is high quality and therefore fit to make a list of the publications that would possibly make the final cut. We also applied backward snowball selection to all the publications selected and confirmed to exist in any of the above-listed repositories. Backward snowball selection here refers to a recursive consideration of all the referenced publications in all the papers already identified from our manual search on Google Scholar. This is complemented by forward snowballing to further increase the references needed for our review.

Forward snowballing was carried out by scurrying through Google Scholar citations to identify similar publications that provide answers to our research questions especially publications from all the studies that cited any of our already included publications.

To make the final cut and be used in our study, we subjected the publications to further assessment other than being listed in the repositories. This assessment was based on the criteria that the paper title is expected to comply with a certain pattern. This pattern went thus: P1 AND (P2 OR P3 OR P4 OR P5 OR P6) AND NOT (P7) where

P1: (Arduino* OR Arduino board* OR microcontroller OR embedded system OR Arduino components*)
P2: (prototype OR prototyped OR prototyping OR prototypes)
P3: (applications OR appliances OR uses OR domain)
P4: (advantages OR comparison OR benefits OR selling point)
P5: (challenge OR challenging OR setbacks OR shortcomings)
P6: ("prototyping with Arduino" OR "computing platform")
P7: (Microprocessor OR Computer* OR "Arduino Algorithms").

It was by using these search strings that we were able to eliminate some existing works which though related to our study is irrelevant to us. This way we successfully handled the huge amount of obtainable work and concentrated our efforts on crucial studies that dealt with prototyping with Arduino, its applications, advantages, challenges, and limitations. Following this, we removed all studies that appeared in the list but had previously been scrutinized in another backward or forward snowballing operation.

After this, we removed every study that was found to be missing on any of the literature depositories listed above. Whatever studies that were left after this became candidates for the systematic literature review. These were then subjected to further backward and forward snowballing. At last, neither backward nor forward snowballing yielded new papers leading to the termination of the search process. This way we got a candidate list of about 193 primary studies. Throughout the whole selection process, we ensured seminar papers in workshops and symposia including working notes and papers with four pages or less, were left out since we needed high-quality peer-reviewed papers. Also disqualified were review papers that are not primary studies. We focused on papers published in the last 15 years including this year, that is between 2005 and 2020. This is because Arduino only came into existence in 2005 and prior papers on related topics such as those on microcontrollers may not contain the most recent researches in prototyping with Arduino except if a revised edition was recently published. Eventually, 130 primary studies that fully complied with the established criteria were used to source the results presented in this systematic literature review.

2.3. Data extraction

Data were gotten from the selected primary studies to answer the questions posed by our research questions. The data extracted to answer all the research questions, be they RESEARCH

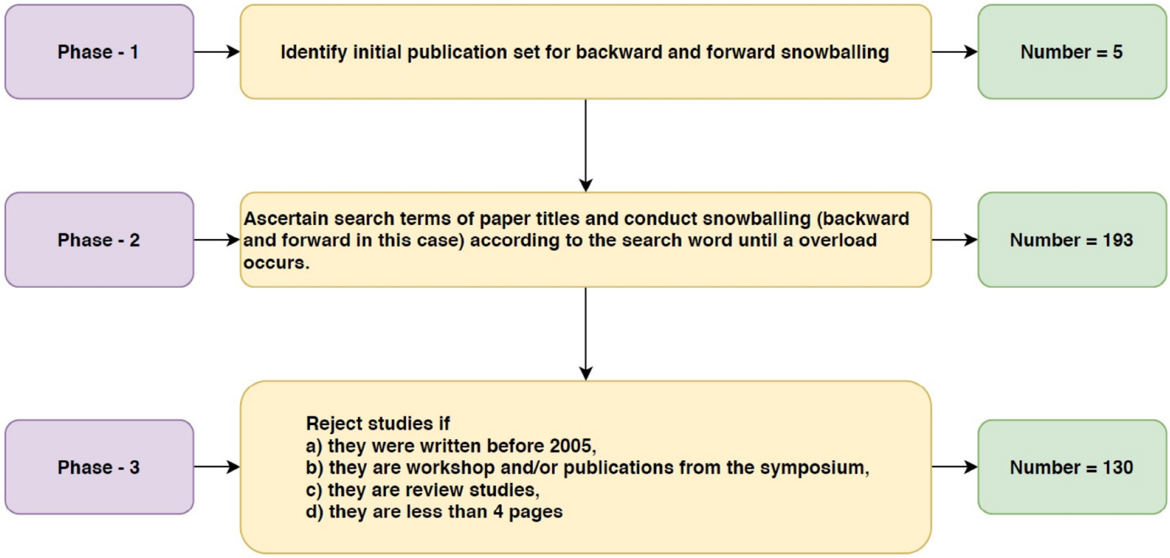

Fig. 3. Selection Process of the literature used in the study.

Table 1
Seeding of a set of papers for backward and forward snowballing in the review.

Author, Year	Journal/Conference	Title	Year	Σ References	Σ Citation
(Ariagi, Ade, & Ritzkal, 2020) [58]	Journal of Robotics and Control (JRC)	Information System Prototyping of Strawberry Maturity Stages using Arduino Uno and TCS3200	2020	33	1
(Badamasi, 2014) [13]	2014 11 International Conference on Electronics, Computer and Computation (ICECCO)	The working principle of an Arduino. 1-4. 10.1109/ICECCO.2014.6997578.	2014	7	160
(Budiman, Tarigan, & Winata, 2020) [59]	Journal of Physics: Conference Series	Arduino UNO and Android Based Digital Lock Using Combination of Vigenere Cipher and XOR Cipher.	2020	12	12
(Nayyar & Puri, 2016) [18]	3rd International Conference on Computing for Sustainable Global Development	A review of Arduino boards, Lilypad's and Arduino shields	2016	12	56
(Vivek & Lee, 1995) [7]	In Proceedings of the 1995 Asia and South Pacific Design Automation Conference (ASP-DAC '95). Association for Computing Machinery, New York.	Power analysis of a 32-bit embedded microcontroller.	1995	16	49

Notes: the number of citations is based on figures from Google Scholar as accessed August 2020.

QUESTION-1, RESEARCH QUESTION-2, RESEARCH QUESTION-3, or RESEARCH QUESTION-4, are associated with the methodology suggested by particular literature as illustrated in Table 2. A careful analysis of all primary studies was instrumental in successfully extracting all necessary data for the SLR. A template to be used for the collection of the information needed for the data extraction was designed in line with what is in Table 2. The authors of this review shared the responsibility of extracting the data and filling them into the template. They also worked together to double-check all extracted information irrespective of the person responsible for extracting that particular information. They then raised objections and discussed disagreements with the person that extracted the information. In some cases, they could not reach a consensus amongst themselves and had to involve other researchers for possible resolution of the disagreement as well as further discussion of the area in contention.

2.4. Threats to validity

A couple of threats to the validity and legitimacy of this systematic review were identified. These threats were mostly in two aspects. These study selection bias and likely inaccuracies in the cause of data extraction and analysis. Being that the process of selecting studies depends on the search strategy adopted, the chosen literature sources, the criteria for selection, and the quality criteria certain limitations are bound to occur. Firstly, as detailed by [57], multiple databases are usually used for literature searches in studies like this. Moreover, it is always necessary to make available a clear, but concise, certification of the deployed search strategy to make it easier to replicate the search at some later stage of the study. In our study, we incorporated a filter of the titles of publications in an initial stage and used a predefined search string. The need for a predefined search string stems from our intention to only examine primary studies that are dwelt on our topic of discussion: Prototyping with Arduino, Applications,

Table 2
A streamlined summary of the data extraction pattern.

RESEARCH OBJECTIVES
RESEARCH QUESTION-1
- Arduino Board Variants[a] (Arduino Uno, Arduino Due, Arduino Mega, Arduino Nano)
- Technical specifications of each variant[a] (number of digital and analog IO pins, memory, processor, etc)
- Advantages of each variant[a]
- Limitations of each variant[a]
- Specific applications of each variant[a]
RESEARCH QUESTION-2
- Application Domains of Arduino[a] (systems design, general-purpose applications, home automation, etc)
- Advantages of using Arduino for prototyping in the reviewed domains[a]
- Challenges of using Arduino for prototyping in the reviewed domains[a]
- Limitations of using Arduino for prototyping in the reviewed domains[a]
RESEARCH QUESTION-3
- Alternatives to Arduino Board[a] (Raspberry Pi, BeagleBone, Sharks Cove, Waspmote)
- Strengths and weaknesses of each of the alternatives[a]
RESEARCH QUESTION-4
- Hardware and software used in Arduino
- Hardware components[a] (Sensors, connectors, accessories, microcontroller, etc)
- Software packages used[a] (Arduino IDE, software for data storage, analysis, and output)

[a]Multiple values possible.

Advantages, Challenges, and Limitations. To that end, we focused on publication titles that could be said to have hit the nail on the head in terms of the words used. Those that rather had unrelated terms like "building sensors with a computing platform" will automatically be filtered out. We have also limited our choice of publications to those written in the English language excluding by default relevant studies that are not written in the English language. These publications are also by requirement expected to only be journals and conference papers whose papers do not number less than four in pages, written in the English language, remember. There is no gainsaying that if our net had been cast wider more results could have been found. Excluded gray literature including those of Ph.D. and Master's theses, technical reports, working notes, white papers, workshop, and symposium papers could have provided fertile ground for relevant ideas, ideas perhaps missed in the publications that eventually made the cut. Luckily, we did spread our net quite wide in the community of the type of publications we wanted for our systematic literature review so much so that a large number of publications studied revealed more information than we initially set out to find, answered all our research questions and gave new insights. It is also worth saying that some of the excluded gray literature such as Ph.D. and Master's theses end up being published in journals or as conference papers. In this case, these papers may have already been considered not in their natural form but in a form acceptable to our stated criteria for selecting publications. Excluding them, therefore, helps us avoid duplicating primary studies within a literature review. We also recognized ab initio that inaccurate data extraction is a possible threat and so we set out to mitigate against it right away by developing a specialized template for data extraction. To also reduce inaccuracies during data extraction, prompt resolution of disagreements between data checker and extractor was deemed a priority. Researchers weighed all the contentious issues and chose the best line of action at every point.

3. Results

In this section, we report the aggregated results per research question based on the data we extracted from primary studies.

3.1. Variants of arduino boards (RESEARCH QUESTION-1)

Here we considered the different variants of Arduino boards that are currently in existence. A whole number of boards were identified from a couple of the publications that formed our primary study [60,61], and [11]. Several variants of Arduino boards are available in the market, but only a handful are most often used by engineers and hobbyists (see Fig. 4). Some of these commonly used Arduino boards include (see Fig. 4):

3.1.1. Arduino UNO

The UNO is perhaps the most popular Arduino board in the market and the industry. Powered by an Atmega328 processor that operates at 16 MHz, the Arduino Uno board is widely used. Its 32 KB of program memory, 1 KB of EEPROM, and 2 KB of RAM does not make it the board with the most storage space but users seem to love it just the way it is, as well as forgive its shortcomings in having only 14 digital I/O, 6 analog inputs, and both 5 V and 3.3 V power rails.

The Arduino UNO does have a pin header arrangement that is quickly becoming the industry standard for development boards. This pin header makes Arduino Uno compatible with most development board shields on the market. The shields, explained later, are connected to the boards through the pin header to enhance the capabilities and increase the functionalities of the Arduino board.

Every Arduino Uno comes with a power jack. A power jack is important because it allows the Arduino Uno to be powered by an external wall wart. An alternative means of connection to a power source known as VIN does also exist. The VIN option is available for connecting the UNO to batteries.

At 69 mm in length and 54 mm in width, the physical dimensions of the UNO make it a small development board that can easily fit into many projects. The presence of four screw holes allows designers, hobbyists, and engineers to securely fit them into place.

3.1.2. Arduino due

The Arduino Due, which together with Arduino Mega has the largest board of all the variants of Arduino boards is the only Arduino board that is powered by an ARM processor, the AT91SAM3X8E Cortex-M3, and does indeed operate at a higher speed than others — 84 MHz.

Unlike the Arduino UNO and Arduino Nano that operate at 5 V, the Arduino Due operates at a lesser 3.3 V. The voltage may be small but reduces overvoltage which if not checked usually leads to damaged boards. With 512 KB of ROM and 96 KB RAM, the Arduino Due has a relatively large memory space compared to

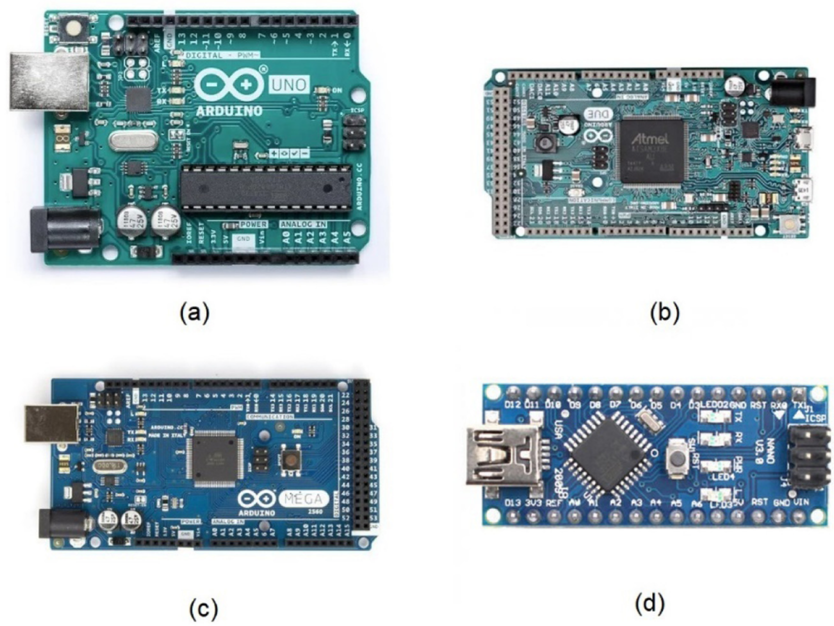

Fig. 4. Arduino Variants. (a) Arduino Uno, (b) Arduino Due, (c) Arduino Mega (d) Arduino Nano.

other boards. Although the absence of EEPROM coupled with the fact that it is Arduino's most expensive board also gives enough room for Due's criticism. In its favor, the import Arduino due has 54 digital I/O pins, 12 PWM channels, 12 analog inputs, and 2 analog outputs. It also has a large number of pin headers which are important for connecting to Due's many digital I/O. It does specifically have a pin-l that is compatible with most Arduino shields. Software compatibility with the Due, however, is not always certain.

3.1.3. Arduino mega

The Arduino Mega compared be with the Arduino Due in many ways. One, it has the same size and also because it also has 54 I/O. But unlike the Due, the Arduino Mega is not powered by an ARM processor but rather by an ATmega2560. The processor has a clock speed of 16 MHz. It has a relatively modest storage space consisting of 256 KB of ROM, 8 KB of RAM, 4 KB of EEPROM. It operates at 5 V and is easy to use not least because several electronics operate at the same 5 V.

The Arduino Mega has 16 analog inputs, 15 PWM channels, a header pinout that is just like that of the Due. Its hardware is compatible with Arduino shields but sometimes lacks software compatibility.

3.1.4. Arduino nano

On the surface of it, the Arduino Nano is a mini Arduino Uno. This is because the Arduino nano is an Arduino UNO shrunk into a very small profile. But a great advantage lies in its minuteness. This small size makes the Arduino Nano a very good fit for projects that need their weights reduced for some reason. It also makes it easier for the Arduino Nano to be securely kept in tight spaces. Previous versions of the Arduino Nano used ATmega168 which could be said to be half of Arduino Uno's Atmega328. Current versions have reverted to the full ATmega328 processor and operate at the same 16 MHz as does the Arduino Uno.

Just like the Arduino UNO, the Arduino Uno has 32 KB of program memory, 1 KB of EEPROM, 2 KB of RAM as well as 14 digital I/O and 6 analog inputs and both 5 V and 3.3 V power rails.

But unlike the UNO, the Nano cannot connect to Arduino shields despite having pin headers. It does use its pin headers for breadboard prototyping and in PCBs with the use of a socket. Arduino Nano boards are the cheapest Arduino board option in the market. This makes them cost-effective for large projects.

Comparing the variants of Arduino boards.

The physical dimensions of the Arduino Nano are the smallest of all the variants and therefore make the Nano a very portable device. The UNO is a medium-sized development board yet it is still small enough to be mounted to many projects including remote-controlled devices such as RC cars and boats. The Mega and Due are by far larger boards. Hence, they are difficult to use in space-restricted applications.

For projects requiring high processing power, it will be best the Due, which has a potent ARM core and enormous RAM/ROM, is used. While the Mega is a large Arduino with plenty of GPIO, its CPU speed is still the same as that found on the UNO and Nano (partly because they all belong to the same Mega family). The Arduino Mega, therefore, offers no speed advantage.

The UNO and Nano use the same processor, the Atmega328. This means that in terms of hardware and peripherals the UNO and Nano are identical. If a project requires plenty of GPIO, Due and Mega are the best options to choose from. An application that does not require a strong CPU but needs sufficient GPIO which can best be prototyped with Arduino Mega.

With 12 analog inputs and about 2 analog outputs, the Android Due is the leader in the prototyping and development of analog projects. Others can also be used but they are by nature not as effective (see Table 3).

Finally, we compare the different Arduino boards by looking at certain key factors:

1. Physical dimensions
2. Processor and CPU power
3. I/O capability
4. Voltage
5. Memory size
6. Kinds of projects best suited for, etc.

Table 3
Summary of Arduino boards and applications.

Name of the Board	Dimensions (mm)	CPU Power & processor	I/O capability	Voltage	Memory Size	Kinds of Projects best suited to prototyping	Components
Arduino Uno	69 × 54	16 MHz ATMega328	14	5 V	32 kb + 1 kb EEPROM + 2 KB RAM	Desktop prototyping, used with Arduino shield	IoT sensors, simple robot controller, RC cars, simple game consoles, device testing
Arduino Due	101.52 × 53.3	84 MHz AT91SAM3X8E	54	3.3 V	512 KB ROM + 96 KB RAM	High-performance prototyping with superior analog I/O	Data processor for data from multiple sources, home automation, the machine controller
Arduino Mega	101.52 × 53.3	16 MHz ATMega2560	54	5 V	256 kb ROM + 8 kb RAM + 5 V 4 kb EEPROM	High I/O requirements with more memory space	DIY bench tools, multi device controlling, machine controller, home automation
Arduino Nano	18 × 45	16 MHz ATMega328	14	5 V	32 kb + 1 kb EEPROM + 2 KB RAM	Low cost, minor profile, simple projects	RC planes, portable electronics, sensor gathering

3.2. Application domains of arduino prototyping (RESEARCH QUESTION-2)

Different Arduino boards are prototyped with by hobbyists, developers and innovators to develop solutions for problems in different fields. These fields are as varied as the applications of prototypes made with Arduino are limitless (See Fig. 5). From systems designs [62] and [63] to hardware communication [64] and [65], Healthcare [66,67], Education [68,69] and [70]; and Mining [71], Arduino remains a popular choice for prototyping solutions. We looked at available literature on eleven of such application domains namely System design [8,63] and [62]; general purpose application [72,73], and [74]; hardware communication [64,65] and [75]; software prototyping [76,77] and [78]; home automation and general automation [79,80] and [81]; agriculture [82,83] and [84]; healthcare [85,86] and [87]; mining industry [88,89] and [71]; energy [90–92] and [93]; defense [94–96] and [97]; and education [60,98,99] and [100] (see Fig. 5).

3.2.1. Systems design

Arduino, as well as other computing platforms such as Raspberry Pi, can be used for systems design. [62] describes how Arduino could be used to design overall system architecture as well as the hardware and software components of a wireless sensor network. They conclude that systems such as Arduino are specially adapted for systems design because they are low cost [8] and highly scalable. Due to Arduino's scalability, in designing wireless sensor networks, the types of sensors and the number of nodes can be easily amplified at the developer's discretion. This particularly makes Arduino suitable for the design of a wide variety of environmental monitoring applications. This was confirmed by [63] which also used Raspberry Pi and Arduino to design a wireless sensor network for environmental monitoring applications.

3.2.2. General purpose applications

Arduino platforms have wide uses in almost all facets of life. Design and implementation techniques that are based on open-source approaches [101–103] made available on platforms such as Arduino are now deployed in building digital twins for smart manufacturing [72]. Metrological information is important for scholars and stakeholders involved with environmental management. To such people, a sonde, a system for transmitting metrological information and about just any other information, is very important. These sondes can be used to gather information from very deep boreholes by lowering them into the borehole. They can also be attached to a balloon or an aircraft and carried into the upper atmosphere for information. Today, however, these systems are quite expensive to design and implement but with the aid of Arduino, a cheap sonde for coastal applications that is based on Arduino can easily be prototyped and built [74]. This system was built on Arduino Mega and Arduino Uno boards and found to deliver efficiently. Arduino can also be deployed in building a system that automatically controls the laboratory sterilization process [104]. [105] too described how an embedded platform such as Arduino can be used, in conjunction with an artificial neural network, to build a Quantitative recognition of flammable and toxic gases.

[106] also detailed the use of Arduinos and 3D-printers in building research-grade weather stations and ecological devices. Several other application of prototyping with Arduino exists.

3.2.3. Hardware communication

Arduino can be used to prototype systems for hardware communication. Hardware communication has to do with devices that transmit data in form of digital and/or analog signals from one a source device to a target device through telephony technology, network interface cards, Wi-Fi technologies, and devise access points. Hardware communication in satellites have proved to offer useful data in better understanding our world and helping communication itself. Hardware communication devices are ever in need because of the many things they can achieve and platforms to prototypes such devices are darlings in the engineering community. Arduino happens to sit at the top of this pile, ranking first in the list of computing platforms used for prototyping hardware communication devices. This is even made more so by the fact that Arduino is a low-cost alternative for technical instrumentation and research [64]. This means that researchers in hardware communication such as those building a high-temperature information gaining system for stellar energy applications will prefer to use Arduino than more expensive alternatives [65]. Several of the other application domains where prototypes made with Arduino boards have found wide use also involve some level of hardware communication. Studies such as [75] developed integrated systems that depended on hardware communication to monitor gases, track activities in mines, and incorporate cloud computing into technical operations. In connecting different sensors such as MQ9, and MQ4 to an Arduino board in achieving their goal of building the system, [75] systems much like similar ones used Arduino massively in prototypes applications that needed some element of hardware communication including network interface cards, Wi-Fi devices, and access points.

Fig. 5. Some of the application domains of Arduino.

3.2.4. Software prototyping

Quite frequently, different kinds of software are prototyped with Arduino. [76] discussed what they considered the standard for analysis, demonstrating, and regulation of aeration systems in the non-large-scale mine in which Arduino was chosen as the go-to platform for software prototyping. With Arduino, similar conditions as in existing underground mines were replicated. Sensors were used to measure the airflow and the transfer function of a typical ventilation system was computed with experimental data. [77] described a system for forecasting carboxyhemoglobin levels as a pointer for on-time setting up of self-contained self-rescuers in case of fire in underground mines. This system was to be modeled in the Arduino platform and integrated monitoring and analyzing approaches. Further applications of Arduino in software prototyping were found in [78] where a state-of-the-art use of the T-Ray imaging unit for crack recognition and mine security was proposed. He showed how Arduino could be used to build the proposed system, to simulate crack identification in mines through the systematic mapping of variations in dielectric properties and thermograph images at a time.

3.2.5. Home automation and general automation

Prototypes of home automation devices, as well as those of automation in other fields, can be made with Arduino. intelligent smart home automation and security systems that now disrupt the market and offer alternatives to households are now prototyped with Arduino [79]. Households are wary of systems, be they refrigerators or Siri, that increase their utility bills. This makes [107] that produced an energy-efficient home automation system an answer to the prayers of many. The system described, and prototyped with Arduino, can smartly schedule tasks and keep members of the household abreast of the schedule of activities, who is to do what and when. [108] also tried solving households' energy problems by designing an established protocol for smart home energy management systems and prototyping the same with Arduino Uno.

Robots have also found wide uses in households especially in automation and in helping carry out household functions that were hitherto carried out by humans [109]. System's like the one in [80] which illustrated the design of a miniature smart home device that was prototyped with Arduino, tapped into robotics to solve household problems while using Arduino to make the prototypes. Others adopted cutting edge technologies while not forgetting to use Arduino for prototyping and simulation. This category is [81] which built a smart home device based on IPV6 and ZIGBEE technology but prototyped with Arduino.

Innovations in the Internet of Things (IoT) have also extended what is possible as far as home automation is concerned. IoT has varied uses in this regard and the number keeps increasing every new hour. [110] did show a way internet of things could be deployed in building a home control (automated) and monitoring system that uses an Android-based smartphone and was prototyped with Arduino. Another Android-based system was presented in [111]. The smart home system described made use of an android application. The prototyping of the system was with Arduino Uno.

Outside the home, automation has also found wide uses in many other ways and with Arduino, more and more solutions can be prototyped daily. Such solutions include the one in [Kumar] that illustrated the localization and tracking of unmanned vehicles and how this can be prototyped with Arduino computing platforms. Such an automation process was also extended to mine operations and aerial systems. [66], for instance, proposed an internet of things based automation system that could be used to ensure safety and monitor mines operations. [112] on the other hand, described how unmanned aerial systems prototyped with

Arduino systems could be used for the mapping of legacy uranium mines. Similar automated systems exist for applications in other areas.

3.2.6. Agriculture

Food insufficiency amidst an increasing global population has forced many stakeholders to look for alternatives in increasing food production as well as revenue for farmers and foreign earnings from agriculture exports for countries. This need for alternatives birthed precision agriculture. Precision Agriculture sometimes referred to as satellite agriculture is a concept in farming management which aims to observe, measure and then respond to field variability in crops by making use of a decision support system (DSS) with the overall goal of maximizing outputs from the farm while at the same time utilizing farming resources optimally. Precision agriculture has found uses in diverse areas in agriculture including soil management, crop variety selection, yield prediction, and fruit harvesting. Luckily, innovations in Arduino computing platforms have co with innovations in precision agriculture tools [82]. Today several of the tools needed in agriculture can safely and cheaply be prototyped with Arduino. Several studies detail these application areas of Arduino prototyping in agriculture. [83] described a system for observing soil moisture that used IoT enabled Arduino sensors with neural networks in refining soil management for agriculturalists and to forecast periodic rainfall for anticipating forthcoming yield in North Karnataka-India. Similarly, [113] proposed using Arduino to build a system that could be deployed in observing the water content in the soil while determining multiple soil–air–vegetation factors. [82] Proposed in great detail how Arduino could be used to prototype a system that can monitor environmental parameters that are usually needed in precision agriculture. Also, [84] proposed a computerized system for observing soil moistness and directing irrigation with low-cost open-source microcontrollers. These are the same microcontrollers in Arduino boards.

With smart farming becoming an area of intense research, the need has arisen for applications that will translate research findings and proposed systems into real-life solutions. [114] stepped in to provide a detailed illustration, prototype, and implementation of a smart farming solution that made use of Arduino and data mining.

Beyond precision agriculture and smart farming, [115] showed how a low-cost open-source LED system namely Arduino could be deployed for microalgae cultivation. [116] developed some Arduino-based geographic information tools for landscape ecology. [117] developed an easy-to-use and low-cost device for recording photosynthetically active radioactivity that was prototyped with Arduino. Finally, [118] described a cheap, open-source, robotic data gathering on the farm. Such data is without question helpful in accomplishing a variety of farming operations.

3.2.7. Healthcare

Breakthroughs in expert systems have produced a plethora of studies looking at solutions that can make the work of a doctor easier in some cases or replace a doctor in others. Expert systems must often take advantage of mobile technologies in smartphones and other smart devices including those running on the internet of things. [119] surveyed IoT and Arduino based patient health monitoring systems. [120] prototyped on Arduino and Android-based M-Health solution for diabetes mellitus patient. Biomedical instrumentation is more successful when prototyped with Arduino [121]. What Arduino can be used to accomplish in healthcare are limitless. [86] described a continuous health monitoring system for a photovoltaic array that used Arduino microcontroller. [87] also proposed using Arduino UNO and wireless GSM for prototyping and implementing a health monitoring system for patients. [122] on the other hand is an Arduino based e-health system that measured health functions such as heart rate, body temperature, and body temperature and used the information gathered to diagnose health risks and provide interventions in real-time.

Different Arduino boards can be deployed in building wearable systems [123]. Such systems can monitor the health status of the wearer at any point and offer health and safety tips. Some can monitor the person's temperature and some could be used to see if vital organs, such as the heart, are not functioning properly. Table 4 summarizes the literature on some wearable systems. These studies were based on miners and their need to have devices that could help monitor their health status as well as the safety of the mining environment. [66], described a system that monitors air quality and air density in an environment. With such a system, an unsafe system can very easily be known.

3.2.8. Mining industry

The Arduino computing platform has found wide use in the mining industry. [16,22,23,49,71,131], stated that Arduino's capability to acquire information from as many sensors as possible, transmit data with the aid of communication devices, and control devices with the aid of actuators have made it possible for it to be an important tool in building an initial prototype of an autonomous mining device.

[88] designed an intelligent helmet that could be used by mine workers with the aid of Arduino. [89] presented at a conference a case study of a low-cost environmental observation system for non-metallic underground mines by suggesting how open-source hardware and software specifically Arduino are useful to the mining industry. Several other studies focused on the application of Arduino to different operations in the mining industry be in field observation systems, wearable systems, or autonomous systems. Table 5 analyzes a few of these studies that focused on Arduino uses in field observation systems.

3.2.9. Energy

Innovations in energy have from times immemorial ushered in eureka moments in the world's calendar. From the time our ancestors first ignited light from rocks till when Thomas Edison's in lamp first beamed yellow lights on New York streets, energy in any and all forms has remained vital for human existence. Today, we almost solely depend on energy. We need electricity to power our gadgets and appliances and the industries that improve those gadgets as well as some of the foods we eat, clothes we hear, and need a big amount of hydrocarbon energy to remain functional. Not surprisingly, the cost of getting a unit of energy has blown over the roof and still rising. Everyday effort have been putting in to ensure energy efficiency and hence cost reduction. Arduino has proved useful to such efforts. [64] adopted the open-source hardware resources of Arduino in developing a low-cost alternative for scientific instrumentation and research. This not only made it cheaper for energy researchers to conduct researches but also provided an efficient platform to prototype the proposed system.

Considering how costly energy is to the global economy, it is surprising to find out that billions of energy calories are left to waste. Smart studies like [140] devised ways to harvest these wasted energy calories by building a smart multi-application harvester using Arduino. The system comprises a solar, thermal plate, and dynamo mechanical parts that were deployed in harvesting the energy while an Arduino was used as a microcontroller to reduce the power stored from the input.

Since energy harvesters exist, it would not be a bad idea to develop systems that measure their performance and possibly recommend if they need maintenance to increase efficiency.

Table 4
A concise review of Arduino applications for healthcare-centric wearable systems.

Reference	Author, year, title	Arduino Variant Used	Purpose of Wearable System	Methodology	Remarks
[66]	Majee, 2016, IoT Based Automation of Safety and Observation System Operations of Mines	Arduino Nano Arduino UNO	Observation of air quality	Designed, prototyped, and implemented a system that could observe mines to ensure safety.	While the system had roles to play in overall safety, data gathered helped decide when the quality of air was not good enough for the safety of miners.
[124]	Harshitha et al, 2018, ZigBee based intelligent helmet for Coal Miners Safety Purpose	Arduino UNO	Observation of air quality	Used Arduino UNO and intelligent systems and sensors to consider air density and temperature.	Air quality is dependent on air density and temperature. Equipping a helmet with systems that can detect the two and inform the wearer made it easier for people to know when the environment is not safe enough.
[125]	Roja and Srihari, 2018, IoT based smart helmet for air quality used for the mining industry	Arduino UNO	Observation of air quality, Helmet wearing status	Used IoT technologies to prototype on Arduino a system which when implanted in so-called smart helmets could detect air quality.	Innovations of the internet of things (IoT) has made a lot of things possible. The system built relied heavily on IoT to facilitate communication between the wearer and the smart helmet system.
[126]	Bhuttoa et al, 2016, Development of a wearable safety device for coal miners	Arduino Nano	Observation of air quality, Collision detection	Built a system that could make health safety suggestions by observing the environment	The wearable system alerts wearers to the presence of obstacles. Useful in fast-paced environments.
[127]	Noorin and Suma, 2018, IoT based wearable device using WSN technology for miners	Arduino Nano	Observation of air quality, Collision detection Helmet wearing status	Implemented and prototyped a wireless system network device that could observe air quality while detecting obstacles and providing other useful tips.	The system made use of sensors that detect temperature vibrations and humidity for effectiveness.
[33]	Priyadarsini et al, 2018, LabVIEW Based Real-Time Observation System for Coal Mine Worker	Arduino UNO	Heart rate observation	Used Arduino Uno to develop, prototype, and implement a system for observing heart rate	ECG AD8232, a sensor for detecting heartbeat rate was used in building the system.
[128]	Dudwadkar et al, 2016, Wireless Mine Surveillance with Data Logging	Arduino Uno, Arduino Mega	Observation of air quality and Heart rate observation	Implemented an Arduino-based robotic system that surveys its environment and logins in the data in a database from which the gathered data could be extracted for decision making.	Infrared light reflection and refraction were studied in detecting changes in heartbeat rate with several other technologies deployed in studying such factors as humidity and temperature all of which were used by the system to make reports.
[129]	Oliveira et al, 2014, Tactile interface for navigation in underground mines	Arduino Mega	Navigation and Heart rate observation	Built a system that could help in navigation in places that are not well-lit while checking the wearers' heart rate	The system built was effective in navigating the environment it was deployed to.
[88]	Alam et al, 2015, Design of an intelligent helmet for mine workers	Arduino Mega	Observation of air quality, Heart rate observation	Designed and prototyped a	This system was effectively simulated. Remains to be seen if it could be built for real-life use.

(*continued on next page*)

That is where the Piezoelectric rainfall energy harvester performance measuring system based on advanced Arduino-based proposed [90] comes in.

In countries where energy theft is a problem, as is often the case in a host of developing nations, there is [91] a smart energy metering and power theft control system whose prototype was

Table 4 (*continued*).

Reference	Author, year, title	Arduino Variant Used	Purpose of Wearable System	Methodology	Remarks
[130]	Dewarkar et al, 2019, Smart Device for Security of Coal Mine Workers	Arduino Nano	Observation of air quality Position observation Pulse rate observation	Prototyped on Arduino Nano and implemented a security system that took notice of an environment's air, the wearer's position, and pulse rate to offer suggestions.	The system observes certain key factors that are necessary for the safety of the wearers and provides useful information offering advice when the environment suddenly changes and requires proactive action.
[123].	Sanjay, 2019, Smart Helmet Using ZigBee	Arduino Nano	Observation of Air quality, detection of destructive event, observation of pulse rate	Implemented a smart helmet that was based on Arduino-compliant technologies and intended to observe parameters which when properly studied could serve as a preventive measure against adverse health effects.	The system was successfully built and deployed for the observation of air quality, detection of destructive events, observation of pulse rate, and in such other functions as would ensure the safety of the wearer.

Note: It has to be noted that health is important in any domain. That explains why the systems for the health of miners could suffice for consideration under systems for health.

designed with Arduino and which was eventually implemented with an Automated Smart Metering GSM. [93] also developed a system, based on Arduino, that measured power and energy. While [92] built a similar system, a smart energy meter, also using Arduino and GSM Automated Smart Metering. There is the ever-constant need to optimize energy cost and ensure the value derived from a unit of energy equals or even exceeds the cost. That was in the mind of [141] when they developed an Arduino Based IoT Metering System that is used for on-demand energy scrutiny.

With hydrocarbons contributing to atmospheric pollution, global warming, and climate change, environmental activists had since the beginning of the millennium been calling for a radical decision concerning the world's energy sources. Dire consequences and imminent catastrophe were predicted to await the world by both scientists and activists if alternative energy sources did not immediately replace the hydrocarbons. It took time, but eventually most agreed that solar was perhaps the best of the available alternatives. This is chiefly because solar, being a direct product of sunlight, is readily available anywhere in the world. Harnessing it also is not as risky as manufacturing nuclear energy in nuclear reactors. The compounds used in producing nuclear energy have on several occasions exploded in the warehouses where they were kept, killing several. Solar was also found to be cheaper to produce. Depending on sunlight means that 50% of the raw materials required have been paid for by God. Not surprisingly, solar panels and solar products in different forms started proliferating the energy market. With this solar proliferation also came studies and applications to optimize solar production and consumption. Interestingly, some of these solutions were prototyped with Arduino. [65] developed a new temperature data acquisition device for solar energy uses. The system was prototyped with Arduino and took advantage of Arduino's capability to work effectively with sensors to build a flexible system that can be used to gather data on and for solar installations in the remotest of places anywhere in the world. scholars like [142] felt there is a need to measure solar energy, they were right and so went ahead to develop a system to measure Solar using the Arduino computing platform.

With the increasing need for renewable energy and indeed a spike in the number of households using renewable energy sources, it becomes imperative to have systems that analyze and ensure optimal maintenance of operation status [143]. [144] proposed such a system. They developed a LoRa based renewable energy observation system with an open IoT platform. LoRa, a low-power WAN protocol (achieving a distance of 15-20km), has pins that can be connected on the Arduino Uno board. Table 6 analyzes a few of these studies that focused on Arduino uses in energy and energy management.

3.2.10. Defense

Defense of human lives and properties gulp a big chunk of national budgets in all countries of the world. This goes to tell how much we value our safety and the safety of our properties. Today, systems such as drones and missiles rely heavily on telecommunication technologies to function properly. Software is also gaining wide use in the development of sophisticated defense gadgets. Several of these gadgets require to be prototyped before they are finally deployed to the field. Arduino provides the best platform for this. And indeed, many have. Automatic Enemy Detecting Defense Robots that use Face Detection Techniques are prototyped with Arduino in [94]. Arduino Uno, like other variants of Arduino boards, provides a cost-effective approach to developing dense systems. This was the argument of [95] while showing the development of a small unarmed robot for defense and security. In collaboration with android phones, Arduino can be used to build systems that are useful in the war-field. [96] built an Arduino controlled war field spy robot that made use of night vision wireless camera and android application. When installed on an android phone, soldiers can use the system developed to spy in their enemy's camp at night and gather relevant information.

But defense extends beyond the military. Individual safety is as important as territorial integrity and is why nations also invest in ensuring safety for their citizens. Nations want to see as few air crashes as possible, as few accidents as possible, as few thefts as possible, etc. while governments owe their citizens these functions, some level of responsibility ultimately rests on the shoulders of the citizens themselves. Developers have stepped in with devices to assist individuals in staying as safe as possible. [145] developed a vehicle tracking system that got information from real-time google maps was based on Arduino

Table 5
Summary of Arduino uses for field observation devices in the mining industry.

Reference	Author, year, title	Type of Arduino Board Used	Mine type	Purpose of Field Observation System	Methodology	Remarks
[132]	Anitha and Seshagiri, 2019, Implementation of Wireless Sensor in Coal Mine Safety System using ZigBee.	Arduino UNO	underground	observation of environmental changes	Implemented a wireless sensor network system that used Arduino technologies to observe air quality in underground mines.	The Zigbee technology works perfectly with Arduino in solving problems and did not fail here.
[133]	Kugan et al. 2019, Coal Mine Observation and Alert System With Data Acquisition	Arduino Mega	underground	observation of environmental changes	Implementation of a system with the capacity to acquire data and process the same in alerting the user to dangers.	The system built is capable of informing the wearer if the air in an environment is not good enough and should therefore exit the place.
[134]	Bhagat, 2016, Wireless Surveillance and Safety System for Mine Workers Using ZigBee	Arduino UNO	underground	observation of air quality	Implemented and prototyped with Arduino a system for the safety of wearers	The system monitors the environment and makes deductions from its observations. These observations are then relayed to the user for decision making.
[135]	Ünsal et al, 2016, Power management for Wireless Sensor Networks in underground mining	Arduino UNO	underground	observation of environmental factors	Implemented a system that managed power in WSNs used in a mining site.	Wireless sensor networks in mining sites require power to function. Without a good system for managing power usage, wastage frequently occurs. This system mitigates against such wastage.
[97]	Shah et al. 2019, IoT enabled worker safety system	Arduino Mega	polluted area	observation of atmospheric variations	Implemented and prototyped on Arduino Mega, a system that ensured mineworkers' safety by observing the air.	The system could study if the environment is polluted or not and made available on a liquid crystal display (LCD) attached to it.
[136]	Rajalakshmi and Vidhya, 2019, Toxic Environment Observation Using Sensors Based on Arduino	Arduino UNO	polluted area	observation of air quality	Implemented on Arduino a system that observed environments with sensors, deciphered if they were toxic or not, and communicated results to the user interface attached.	The system was built in the knowledge that temperature and odor were important factors in the toxicity of any place. By studying the two and comparing it with existing data, the system could know if an environment is polluted.
[137]	Sudila et al, 2017, A IoT Proactive Disaster Management System for Mines	Arduino UNO, Mega	underground	surveillance of environmental changes	Implemented a system that managed disastrous events in mines and limited casualties and damages.	Sensors and IoT technologies were deployed in the system which noticed when environments had taken an unusual outlook and alerted concerned professionals.
[138]	Durán et al. 2019, Wireless Smell System for Hazardous Gases Detection	Arduino UNO	underground	observation of changes in atmospheric odor	Implemented a system that detected the smell of an environment and provided the same for decision making.	Activated by a vacuum pump, this system perceives the smell of the air in an environment and quickly raises an alarm if some hazardous smells had been released to the environment. This promptly saves lives.

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on the computing platform. In the United States, gun violence remains a huge threat to public safety and worst of all these occur unmitigated even in classrooms that should normally be free from such. [146] designed and prototyped a moveable classroom attendance system based on Arduino and biometric data that makes it possible to know everyone in a class and to easily identify who could constitute a possible threat.

Workers in certain hazardous occupations are always fearing for their lives. Colleagues have either died on the job or got

Table 5 (*continued*).

Reference	Author, year, title	Type of Arduino Board Used	Mine type	Purpose of Field Observation System	Methodology	Remarks
[75]	Jo and Khan 2017, An Event Reporting And Early-Warning Safety System Based On The Internet of Things For Underground Coal Mines: A Case Study	Arduino UNO	underground	observation of air quality	Developed, prototyped with Arduino, and implemented a system that could report occurring events and raised alarm if any event that portends danger suddenly occurs.	The system is helpful in several cases. Examples include when there is a fire outbreak and when a pipe begins to leak.
[105]	(Mondal et al, 2015), Quantitative Recognition of Flammable And Toxic Gases With Artificial Neural Network Using Metal Oxide Gas Sensors In Embedded Platform	Arduino Due	underground	observation of air quality, detection of harmful gases	Implementation of fire and toxic gas recognition system using Arduino sensors.	An artificial neural network was used in classifying gases and using that to know which is harmful and which is not. That way it is easy for the system to report when it detects a harmful gas.
[76]	Rodriguez-Diaz et al, 2019, Benchmark For Analysis, Modeling, and Control of Ventilation Systems In Small-scale mine	Arduino Mega	underground	observation of air quality	Studied, theorized, and then implemented a ventilation system using Arduino and its sensors	Provided a comprehensive framework that can work anywhere.
[139]	Adjiski et al, 2019, Methodology for Evaluation of The Evacuation Time In Case of Fire In Underground Mines	Arduino Nano	underground	observation of air quality	theorized a model and then implemented a system for quickly evacuating people and properties from fire scenes.	Showed how by studying the air in a place, fire outbreak can be detected and victims evacuated before the situation blows out of proportion
[77]	Adjiski et al, 2019, System for prediction of carboxyhemoglobin levels as an indicator for on-time installation of self-contained self-rescuers in case of fire in underground mines	Arduino Nano	underground	observation of air quality	Implemented a system for predicting carboxyhemoglobin levels as a means to ensure safety and quick response to fire outbreaks in mines.	Carboxyhemoglobin is toxic to the human body. If carbon is inhaled and the same binds with the hemoglobin it could result in a lot of health problems for the victim. If one quickly knows when his carboxyhemoglobin level begins to rise, he could perhaps know that something has gone wrong in the environment and could thus save himself and others.

seriously injured. [97] stepped in to solve this problem by developing an IoT enabled worker safety system that was prototyped with Arduino and that could detect the quality of air in a work environment.

[75] built an Arduino prototyped event reporting and early-warning security system based on IoT for underground coal mines while [137] came through with an IoT Proactive Disaster Management System for Mines that was also prototyped with Arduino. [138] described and also built a Wireless Smell System for Hazardous Gases Detection that is relevant in many workplaces especially those that deal with chemicals. [147] has a theory on how to increase the safety of people in dangerous locations. This was eventually modeled and simulated with the aid of an Arduino platform. Table 7 analyzes a couple of these studies that focused on Arduino uses in defense.

3.2.11. Education

Arduino has found many uses in education. This no doubt comes in different shades and forms always geared towards educating the target audience. Education can help develop Arduino and Arduino can also be beneficial to education, either helping to educate people or being used to build systems that can be used to make education easier, more accessible, and more fun. [98] showed how the Arduino platform is connected to the education process. They believed that the massive growth and expanding development of the relatively new fields of electronics and informatics requires that the educational curriculum are changed to reflect the new trends in the technology industry. They argued that the disruption of electronic and hardware solutions supplies with the availability of more sophisticated and better solutions made possible by Arduino based technologies should be matched in vigor by systematic including Arduino in the education process. Such systematic inclusion could mean adding an Arduino topic to the topics covered by High School Computer Science or even integrated science.

If educationists realize that open-source hardware, including those offered by Arduino, are growing ever influential in controls education [68] then a concerted effort should be made to introduce them to kids early enough. [60] contended that since control education generally profoundly and almost unchangeable depends on simulation suites and virtual laboratories, Raspberry Pi and Arduino boards could be adopted to offer control education students a more physical, more realistic outlook of the experiments so that they enjoy physical feedback that clearly shows

Table 6
Summary of Arduino uses in energy and energy management.

Reference	Author, year, title	Type of Arduino Board Used	Energy type	Purpose of Energy System	Methodology	Remarks
[144]	Chang-Sic et al, 2018, LoRa based renewable energy monitoring system with an open IoT platform.	Arduino Mega	Renewable Energy	Energy monitoring	Developed, prototyped with Arduino, and implemented a system for monitoring renewable energy.	The system monitors the quantity of energy generated from renewable energy sources such as solar energy, wind, and nuclear energy. It aims to know the quantity that is effectively utilized
[92]	Chaudhari et al, 2017, Smart energy meter using Arduino and GSM	Arduino UNO	Electricity	Smart metering	Implemented a smart energy metering system that tapped from Arduino technologies and Global System for Mobile Communication (GSM)	The system that made energy metering fair to all involved parties — buyers or sellers.
[142]	Jumaat and Othman, 2018, Solar Energy Measurement Using Arduino.	Arduino UNO, Mega	Solar Energy	Energy measurement	Developed, prototyped, and implemented a system that measured the quantity of solar energy used.	The system aimed to achieve solar energy efficiency, reduce wastage, and find how best excess solar energy could be moved to those that need it most or stored in accumulators for future uses.
[141]	Okafor et al, 2017, Development of Arduino Based IoT Metering System for On-Demand Energy Monitoring.	Arduino UNO	Electricity, solar energy, fuel	Energy metering and monitoring	Developed an Internet of Things (IoT) system that monitored the metering of on-demand energy	The system is efficient for solar energy, electricity, and even hydrocarbon energies such as petrol and diesel.
[140]	Rizman et al, 2018, Smart multi-application energy harvester using Arduino	Arduino UNO	Solar energy, wind energy	Energy harvesting	Implemented a system that facilitated energy harvesting from energy-dependent devices.	In most cases, excess energy is wasted by several devices. This system taps this energy that could have been wasted and makes them useful.
[90]	Acciari et al, 2017, Piezoelectric rainfall energy harvester performance by an advanced Arduino-based measuring system.	Arduino Due	Rainfall energy	Determination of energy harvester performance	Developed a system prototyped with Arduino whose goal is to measure the performance of Piezoelectric rainfall energy harvester	Ceramic materials and crystals when subjected to mechanical pressure produce electric energy which can be harvested for energy solutions. An efficient harvest achieves a better result than an inefficient one. The system uses an established benchmark to decide if a harvester is efficient enough.
7 [93]	Srividyadevi et al, 2013, Measurement of Power and Energy Using Arduino.	Arduino Mega	Electricity, solar energy	Power measurement, energy measurement	Implemented an Arduino-prototyped system for the measurement of power and energy	The developed system measures the total power generated by an electricity generating plant or the total sum of solar energy produced by a solar panel.
[91]	Visalatchi and Sandeep, 2017, Smart Energy Metering and Power Theft Control Using Arduino and GSM Automated Smart Metering	Arduino Nano	Solar energy, electricity	Smart energy metering, power theft control	Developed and implemented a smart energy metering system which when deployed could reduce power theft	Energy buyers a times want to manipulate the system and shortchange the sellers and producers. The system stops them on their track and effectively stops f\them from stealing the power while ensuring that they are charged only a fair price by the energy company.

Table 7
Summary of Arduino uses in defense.

Reference	Author, year, title	Type of Arduino Board Used	Defense type	Purpose of defense System	Methodology	Remarks
[148]	Mumtaz et al, 2018, An Automatic System for Controlling Streetlights and Monitoring Objects Using Arduino	Arduino Nano	Car and human Safety	Controlling streetlights and monitoring vehicles and pedestrians	Implementation of a system for controlling streetlights using solar rays together with the detection of an object's movement and position	The system makes it easier to control traffic and reduce accidents.
[149]	Ghoghre et al, 2017, Radar System using Arduino	Arduino Mega	National security	Detecting missiles, traffic control, advanced warfare	Design and implementation of a system that uses microwaves to determine military and paramilitary object's range, altitude, speed, and direction.	The radar system built can be deployed in air-defense, air traffic control, antimissile systems, and aircraft anti-collision systems. All of which are important for defense.
[150]	Alghamdi, 2017, Autonomous: PC Controlled Robot Using Arduino Uno	Arduino Uno	Rescue and Emergencies	Robotic arms for controlling weapons and machinery	Implemented an autonomous robot that could carry out specified activities	These robots can replace humans in high-risk operations such as when rescuing people from a blast zone.
[151]	Hoque et al, 2017, Arduino based battlefield assistive robot.	Arduino Mega	Battlefield defense	Military robots	Implemented and designed, an Arduino-prototyped system that made use of night vision monitoring and other technologies to equip robots to fight in battlefields.	Robots are deployed to reduce casualties while presenting a formidable force than opponents.
[152]	Pavithra et al, 2018, Design and Implementation of a Rescue System for the Safety of Women by using Arduino Controller	Arduino Uno	Human assistance, personal defense	Safety of women	Design and implementation of a wearable band that captures images and videos and sends to the wearer informing them of dangers around so they take precautions early on.	Sensors are used here to analyze wearers' physiological signals such as pulse rate and body vibration. If the wearer has a cause to fear, the system can advise them to leave the environment or make an SOS call.
[153]	Mohamad et al, 2016, Design and implementation of a real-time tracking system based on Arduino Intel Galileo	Arduino Intel Galileo	Vehicle and gadgets tracking	Tracking system	Design and implantation of a vehicle tracking and monitoring system that uses GSM, GPS, and GPSR in finding a vehicle's location coordinates and processes the data so that a missing vehicle can easily be located.	Vehicle theft is a common occurrence in most parts of the world. The system provides real-time tracking of a missing vehicle. This makes it easier to not only find the vehicle but to also arrest the criminals behind its missing.
[154]	Aphiratsakun et al, 2018, Defense System Modelling	Arduino Uno	National security	Defense system	Created a model system to detect and track the motion of objects and publish the objects' real-time location.	The system is useful in building automatic snipers and killer lasers which use the location found to know how to easily eliminate a target.

the impact of control algorithms and the workings involved in the interaction between the experiment's parameters. To that end, [69] proposed inexpensive open-source hardware in control education and adopted Arduino-feedback as a case study.

Indeed, this has become an Arduino age and likely technology has thought the world over and over again, Arduino is perhaps a forerunner to something else, something better, more sophisticated, and more efficient. Understanding Arduino perfectly could place us in a better position to fully utilize similar but better systems of the future. It was on that note that [155] conducted a review of embedded systems education, arrived at lessons certain lessons he hoped key industry players should have learned, and made predictions on future directions of Arduino and similar systems.

[100] concluded that so many are missing the boat, left technologically behind because they have failed to see that engineering education needs Arduino, Raspberry Pi, and other small prototyping boards. This failure has resulted in requisite attention not being paid to these devices. Integrating them into the course flow, however, would yield positive results for all.

[99] developed and showed the practical use of an Arduino Based Education program for high school students in South Korea. Table 8 analyzes some selected studies that focused on Arduino uses in education.

3.2.12. Internet of Things (IoT)

The internet of things is a relatively new phenomenon that has transformed and promises to bring even further transformation

Table 8
Summary of Arduino uses in education.

Reference	Author, year, title	Type of Arduino Board Used	Education type	Purpose of System	Methodology	Remarks
[156]	Vital et al, 2018, Educational Humanoid Robot Using a Sensoring Fusion.	Arduino UNO	Higher Education	Using Arduino for final year engineering projects	A description of the use of the NAO robot for engineering projects was followed by the integration of the robot with Arduino sensors that made it easy to make analysis, obtain information, and do projects.	Such a system makes learning easier for students.
[157]	Ishikawa and Maruta, 2010, Rapid prototyping for control education using Arduino and open-source technologies.	Arduino UNO	Control education	Simplification of learning and research	Prototyped on Arduino and Implemented a small-sized investigational device that facilitated control education.	Because Arduino systems are cheap and easy-to-use, they hold enormous advantages over traditional learning techniques which does not place much emphasis on practicality as it does on theory.
[158]	Sohn, 2014, Design and Evaluation of Computer Programming Education Strategy Using Arduino.	Arduino UNO	Computer Programming Education	An environment for making software and hardware learning easier.	It developed a teaching and learning model that borrowed heavily from Arduino-based programming education.	The model presented makes learning coding easier.
[159]	Cheng et al 2016, Establishing the connection between control theory education and application: An Arduino based rapid control prototyping approach.	Arduino Due	Control education	Offers an alternative to existing control education approaches.	The introduction of digital simulation and hardware-in-loop simulation into the teaching profession is aimed at using these Arduino-based rapid control prototyping approaches to diminish the gap between classroom theory and real-life application.	Digital simulation makes learning easier and hardware-in-loop simulation makes it easier to see a practical implementation of whatever is taught in the classroom.
[160]	Zieris et al 2015, Using Arduino-Based Experiments to Integrate Computer Science Education and Natural Science.	Arduino Mega	Computer Science Education and Natural Science	Integration of computer science with natural science	A student-programmed microcontroller is used to perform and evaluate measurements such as that of humidity and pressure, mass and density, etc.	Students do not have to depend on industry built calculators if they can build theirs. This way they are trained to be skilled in software and hardware engineering while proffering solutions to problems.
[161]	Chou, 2018, Skill development and knowledge acquisition cultivated by maker education: Evidence from Arduino-based educational robotics.	Arduino Nano	Skill development and knowledge acquisition	Facilitation of skill development and knowledge acquisition	A study group of high school students was divided into two, one group learning Arduino-based robotics and the likes while others learned tailoring and bead making. The first group was found to have become proficient in engineering while the last was not.	Arduino, if introduced to young people early enough, has the power to increase their problem-solving capabilities, reasoning capacity, and likelihood to find a career in engineering and acquire high paying skills.

to the interconnectivity of devices. IoT aims to use the internet in connecting all computing devices in typical everyday use so that such devices can share data and communicate amongst themselves without any form of human-to-human interaction. Arduino has found varied uses in building IoT systems. Several such systems were discussed and described by various studies, describing in great detail how the Arduino computing platform played an enormous in the final IoT product released to the public. These IoT products are used in several fields and domains. [83] described a system built for the observation of soil moisture using IoT enabled Arduino sensors which were used in conjunction with neural networks. The aim of the system, which is relevant in the agricultural domain, is to improve soil management for rural, subsistent farmers and to also predict seasonal rainfall that could help them in planning future harvest. In healthcare, [85] conducted a survey on the building of an IoT and Arduino system for observing a patient's health. In energy use and management [144] built an IoT system for observing renewable energy that used Arduino based LoRa technology. In that same energy domain [141] simplified energy metering by building a fair, on-demand energy observation and metering system that tapped from both IoT technology and the inexhaustible capabilities of the Arduino computing platform. The mining industry also has IoT systems that were prototyped in Arduino and used to somewhat make life easier for the miners. [127] used wireless sensor network technologies on the Arduino library to build an IoT based wearable device that could observe air quality while detecting obstacles and providing some other useful tips. While [125] used IoT technologies to prototype on Arduino a system which when implanted in smart helmets could detect air quality. A similar IoT system in [97] is also instrumental in ensuring worker safety by observing the air ion a particular environment. [137] implemented a system for disaster management that heavily relied on IoT in noticing when environments had taken an unusual outlook and quickly alerted concerned professionals so proactive measures could be taken to avert disaster. Certain IoT systems like [81] are also built on Arduino for home automation, connecting all home devices including kitchen utensils and TVs, Siri, and vacuum cleaners. Table 9 analyzes some selected studies that focused on Arduino uses in education.

Advantage of using Arduino for prototyping in the reviewed domains

[162–165] identified some of the advantages of using Arduino as follows:

1. Low cost and inexpensive platform: Arduino boards are relatively economical especially when compared to other microcontroller platforms such as Raspberry Pi and Nanode. Most people buy Arduino components and assemble everything at home, DIY standard. The cheapest kind of the Arduino module that can be assembled at home costs below $50.
2. Cross-platform: Arduino IDE can run on most operating systems including Macintosh OSX, Windows, and Linux. This is unlike most other microcontroller platforms that run only on Windows
3. Energy-efficient — Arduino requires little energy. It functions with the lowest of voltage, saving costs for the user.
4. Fast prototyping process: it does not take long for a system to be fully prototyped with Arduino. In alternatives computing platforms, it takes longer in most cases to prototype the same type of device that would take very little time with Arduino.
5. Simple, clear programming environment — The Arduino IDE is the platform's programming environment. It is loved because of its ease-of-use and because it mastering it does not require much practice even for beginners. It is not oversimplified, however, they are advanced tools that help professionals perform more difficult functions. Being that the Arduino IDE was built on certain features of the Processing programming environment, working with it is quite easy for those who already know the Processing language and makes the work easier for teachers teaching to students that had already been taught programming in Processing.
6. Open source and extensible software — The Arduino IDE and accompanying software are completely open-source. This makes it easier for experienced programmers to add extensions and modifications that will make the platform better. The Arduino programming language also borrows extensively from C++ and can be extended from the C++ library. The technical details of the language are also mirrored from the AVR C programming language. It, therefore, accepts AVR-C codes as though they were written in the Arduino IDE.
7. Open source and extensible hardware — it is not only Arduino's software that is open source. The hardware which is based on Atmel's ATMEGA8 and ATMEGA168 microcontrollers are also open source and has their modules published under a Creative Commons license. By being open-source, experienced circuit designers can make their version of the module, extending it, or improve on it. Inexperienced users can even manage to build the breadboard version of the module. Doing this most often helps them better understand how the module works while also saving money.
8. Introduced more innovative techniques: when Arduino came into the microcontroller platform, some other platforms already exist but by introducing innovative techniques such as high processing speed Arduino was able to quickly become the dominant platform and the one most preferred by professionals.
9. Easy to Interface: Arduino is easy to interface. Extendable Pins where external modules such as USB can be attached to exist making it easier to transfer resources. Available also is a wide array of APIs or Application Program Interface.
10. A wide array of sensors: Arduino comes with some many sensors that make it a good choice for prototyping systems that involve some type of imaging
11. Huge community: Arduino has a huge community of users and enthusiasts alike. If you have any issues, some individuals will be glad to assist you. The fact that Arduino is a highly portable platform that requires little effort and zero or limited experience to use means that many flocks to it and eventually land in the developer community to provide help to newbies or learn themselves.
12. Suited for the Amateur: Arduino is simplified for the beginner and gives little head to students. Most functions and capabilities can be mastered by watching videos online or asking the question on the online Arduino community.

Challenges of using Arduino for prototyping in the reviewed domains

1. Complex structure
2. Its ease of use makes users lazier and uninterested in learning more difficult, even if better, platforms.
3. Accessibility: Arduino is still manufactured in only a few parts of the world and not in all. This makes it hard for those in countries where it is not manufactured to buy it. This sometimes leads to an increase in costs for people in such countries.
4. New findings take time before getting into the hands of the majority of users to be there professional or hobbyist. Because findings remain buried in the pages of journals not read beyond the contributing audience and key stakeholders in that field, it is usually difficult for new trends in Arduino to get to the wider public.
5. Lack of interest and/or support from governments. With government funding, more headway could be made in developing and propagating Arduino. Without this Arduino has been unable to fully go mainstream.

Limitations of using Arduino for prototyping in the reviewed domains

Limitations of using Arduino hardware and software to include the following:

1. Limited processing power: An Arduino's processing power is usually weaker than that of the microcontroller this limits how much it can process and how fast it processes the little one it can.
2. Small storage space and memory: Arduino's memory is most often very small and cannot store more than a few kilobytes. Assuming the user wishes to store something on the built system immediately after burning, the user would have to find a storage memory device. be built

Table 9
Summary of Arduino uses in education.

Refer-ence	Author, year, title	Type of Arduino Board Used	Domain	Purpose of Field Observation System	Methodology	Remarks
[83]	Athani et al, 2017, Soil moisture observation using IoT enabled Arduino sensors with neural networks for improving soil management for farmers and predict seasonal rainfall for planning future harvest in North Karnataka-India.	Arduino UNO	Agriculture	Soil moisture observation	Built an IoT system that was prototyped on the Arduino computing platform and designed to observe changes in soil moisture.	Soil moisture figures are important in making several farming decisions, hence the need for the system. The system when built proved useful for the targeted region.
[144]	Chang-Sic et al, 2018, LoRa based renewable energy monitoring system with an open IoT platform.	Arduino Mega	Renewable Energy	Energy monitoring	Developed, prototyped with Arduino, and implemented a system for monitoring renewable energy.	The system monitors the quantity of energy generated from renewable energy sources such as solar energy, wind, and nuclear energy. It aims to know the quantity that is effectively utilized
[85]	Karthik eta l, 2018, Survey on IoT & Arduino Based Patient Health Observation System	Arduino UNO, Arduino Mega	healthcare	Patient health observation	Conducted a practical survey for how an Arduino based IoT system can make patient health observation without a doctor's physical presence possible.	Found that Arduino could be used to build such an IoT system by observing existing systems and building a similar one.
[66]	Majee, 2016, IoT Based Automation of Safety and Observation System Operations of Mines	Arduino Nano Arduino UNO	Mining industry	Observation of air quality	Designed, prototyped, and implemented a system that could observe mines to ensure safety.	While the system had roles to play in overall safety, data gathered helped to decide when the quality of air was not good enough for the safety of miners.
[127]	Noorin and Suma, 2018, IoT based wearable device using WSN technology for miners	Arduino Nano	Mining Industry	Observation of air quality, Collision detection Helmet wearing status	Implemented and prototyped a wireless system network device that could observe air quality while detecting obstacles and providing other useful tips.	The system made use of sensors that detect temperature vibrations and humidity for effectiveness.
[141]	Okafor et al, 2017, Development of Arduino Based IoT Metering System for On-Demand Energy Monitoring.	Arduino UNO	Energy: Electricity, solar energy, fuel	Energy metering and monitoring	Developed an Internet of Things (IoT) system that monitored the metering of on-demand energy	The system is efficient for solar energy, electricity, and even hydrocarbon energies such as petrol and diesel.
[125]	Roja and Srihari, 2018, IoT based smart helmet for air quality used for the mining industry	Arduino UNO	Mining Industry	Observation of air quality, Helmet wearing status	Used IoT technologies to prototype on Arduino a system which when implanted in so-called smart helmets could detect air quality.	Innovations of the internet of things (IoT) has made a lot of things possible. The system built relied heavily on IoT to facilitate communication between the wearer and the smart helmet system.
[97]	Shah et al. 2019, IoT enabled worker safety system	Arduino Mega	mining industry	observation of atmospheric variations	Implemented and prototyped on Arduino Mega, a system that ensured mineworkers' safety by observing the air	The system could study if the environments were polluted or not and made available on a liquid crystal display (LCD) attached to it.
[81]	Zhenyu et al, 2013, Smart Home System Based on IPV6 and ZIGBEE Technology	Arduino UNO	Home Automation	Smart home system	Designed and built a smart home system that interconnected all the embedded devices in the home using IoT and thus facilitated communication between them.	The IoT system automated devices in the home and reduces what the homeowner had to do manually while also removing redundancy.
[137]	Sudila et al, 2017, A IoT Proactive Disaster Management System for Mines	Arduino UNO, Mega	underground	surveillance of environmental changes	Implemented a system that managed disastrous events in mines and limited casualties and damages.	Sensors and IoT technologies were deployed in the system which noticed when environments had taken an unusual outlook and alerted concerned professionals.

3. Requires efforts to accomplish tasks such as scheduling and database storage. This wastage of time is usually due to the low processing power and the small storage space.
4. Uses an advanced form of the 8-bit AVR ecosystem that is still below par when compared with their 32-bit offering.
5. Cannot handle the large complexities usually seen in very advanced projects.
6. Hardware limitations: kits are not suitable for courses that require expensive, high-performance hardware.

3.3. Alternatives to Arduino (RESEARCH QUESTION-3)

Several computing platforms exist in the market besides the Arduino platform. These platforms all have their specific features (See Table 10). For some, it is these features that may them stand out, while for others these features are a clog on the wheel of their wide acceptability as a good option for prototyping hardware and software.

3.3.1. Raspberry Pi

The Raspberry Pi consists of a series of small single-board computers developed to promote the teaching of basic computer science in High schools and developing countries [166]. Raspberry Pi is popular for its low cost and portability and is used in very advanced projects such as robotics, sensing, and weather observation. Raspberry Pi, however, does not have peripherals such as keyboards and mice.

Raspberry Pi supports the following operating systems Android, FreeBSD, Linux, NetBSD, OpenBSD, Plan 9, RISC OS, Windows 10 ARM 64, and Windows 10 IoT core [167].

3.3.1.1 Strength of Raspberry Pi

1. Low cost, affordable (∼35$)
2. Huge processing power in a compact board
3. Several interfaces (HDMI, multiple USB, Ethernet, onboard Wi-Fi and Bluetooth, many GPIOs, USB powered, etc.)
4. Supports Linux and Python (which makes it easy to build applications with)
5. Readily available examples with community support

3.3.1.2 Weaknesses of Raspberry Pi

1. Raspberry Pi boards are not always available for long. Products and projects developed with them cannot have a long life span because the boards themselves have a limited life span. This would prove too costly for many including developers and businesses who need to upgrade to newer and even more expensive embedded boards every few years. What is worse? There are times needed boards that may not even be available.

2. The Operating System (OS) runs on an SD Card

Raspberry Pi Board runs Linux on an SD card. The implication is that certain applications will pose a problem as this SD card connection may have issues with vibrations in the field. With no provision to ensure connections are intact while in operation, only unreliable workarounds such as double-sided tapes and glue become the designer's only hope. That is not even considering that a corrupted SD card would mean the end of your work

3. Absence of USB header connectors

Raspberry Pi boards do not have USB header connectors, making it impossible to connect modems, sensors, etc. The only alternative, in this case, becomes connecting peripherals via a USB cable which is usually counter-productive especially in industrial applications.

4. Absence of Real-time Clock with Battery Backup

The absence of a real-time clock in Raspberry Pi boards ensures that real-time events cannot be tracked. Although an external RTC circuit can be added to the board, it comes at additional cost, effort, and space.

5. Absence of LCD Interface: The Raspberry Pi board does not have a liquid crystal display interface. Hence, all display RGB signals come on the 40-pin header. If the designer needs to use a thin-film transistor (TFT) display, very few or no GPIOs will be available.

6. Absence of Onboard ADC: If a product needs an ADC (8/10/12bit resolution), the designer will need to add an external ADC chip via I2C/SPI. Again more cost.

7. Absence of EEPROM/FRAM/SPI Flash: For data logging applications, it is very important to have onboard EEPROM or FRAM or Flash any of which can be used data storage. Raspberry Pi does not, however, make provisions for any of them.

8. Limited Universal Asynchronous Receiver Transmitter (UARTs): Only one UART is available on the header and that does not allow eight signals. Usually, two or three UARTs are required for most of the requirements which leave a shortage of at least one UART.

9. A limited number of I/Os: Raspberry Pi has fewer input/output slots than required. 28 GPIOs are available on the header when commercial applications usually require more.

Due to points 4–9, a separate board might be required to meet up with these shortcomings.

10. Raspberry cannot handle External Power Supply

The lack of a reliable power supply connector means that commercial products that require additional power supply are not properly attended to. The use of a USB micro connector-based power supply further increases this unreliability and may jeopardize products.

This is because it cannot handle the reverse voltage, surge, and overload.

11. Poor thermal Management

The microprocessor on the Raspberry Pi produces heat which must be well managed else it may seriously affect the board's dependability. Yet the small, improperly fastened heatsink with glue that is currently used does a poor job of managing this heat. The solution is to custom design a heatsink with a good mounting hole and manufactures the same. What appears like a solution here is a call to spend more.

12. Restrictions on Form Factor Size

Form sides on Raspberry Pi are fixed, inflexible, and not designed to suit the designer's needs in terms of size and shape.

13. Abysmally limited professional development support

The online forums and community that Raspberry Pi operates perhaps discouraged them from offering highly needed professional dev support. Dedicated support, necessary in making certain decisions are hardly provided.

14. No provisions for scale

Raspberry Pi boards were not designed for commercial products ab initio that probably explains why the boards were designed for small projects and not large scale projects running into millions.

3.3.2. BeagleBone

The BeagleBoard [168] is the low-power open-source single-board computer invented by a dedicated group of engineers as a learning board that could be used in colleges and universities all over the world in teaching open-source hardware and software capabilities. As an open-source board, the public purchases it under the Creative Commons share-alike license. The board was designed with Cadence OrCAD for schematics and Cadence Allegro for PCB manufacturing; and adopted no simulation software. The Beaglebone is a version of BeagleBoard that was introduced in 2011 [169].

Strength of BeagleBone

1. Provides an environment for ultra-low-latency processing of audio and sensor data
2. low-cost
3. single-board computer.

Weakness

Shares moist of the weakness of Raspberry Pi.

3.3.3. Sharks Cove

Sharks Cove, developed by Microsoft and Intel, is a hardware development board that can be used to develop hardware and drivers for Windows OS.

Strength: efficient, purpose-driven, and low-cost.

Weakness: limited in scope

3.3.4. Waspmote

Waspmote is a Wireless Sensor Networks Open Source Platform that is focused on the implementation of low consumption modes to allow the sensor nodes ("motes") to maintain complete autonomy and while being powered by a powered offering a variable lifetime between 1 and 5 years. Waspmote is a specially adapted sensor device purposefully oriented to developers.

Strength: high availability, low-cost, efficient. [170]

Weakness: weak 4G signal.

3.4. Hardware components and software packages commonly used in Arduino (RESEARCH QUESTION-4)

Arduino has several hardware and software components that it needs in delivering its job. We look at each of these one after the other.

3.4.1. Hardware components

Several hardware components are necessary for Arduino prototyping. There contribute hugely to the success of the project being prototyped and have to be present before a particular project is completed. The type of components needed for one project may slightly differ from those needed for another project. Some of these hardware components include Sensors, connectors, accessories, controllers, and several other devices. Some of the major hardware components include:

3.4.1.1. Arduino controller. The Arduino board comes with several hardware components. These components have special purposes and functions they carry out on the board. The following are some of the most widely needed:

1. Power port.
   The power port provides a space to connect the Arduino power to the power supply
2. Microcontroller.
   Every Arduino board has an embedded microcontroller usually an ATMega
3. Analog input pins.
   Slots are made available for input pins. This could number anywhere from 54 in the Arduino Mega to 12 in the Arduino Uno board.
4. Digital pins.
   There are also digital pins on the board.
5. Reset switch.
   The reset switch helps to reset the board when necessary perhaps due to some discovered error or some other reason that prompted the designer to reset the whole process and start afresh.
6. Crystal oscillator.
   A crystal oscillator uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with precise. Every Arduino board has at least one crystal oscillator.
7. USB interface chip
   USB interface chips help connect the Arduino board to USB interfaces to enhance data communication and control between the Arduino board and the connected device.

The Arduino Uno controller much like other variants of the Arduino board also contains, in addition to the above mentioned, net Wi-fi port, a Wi-fi socket, nRF24L01+ component interface, and an ATMega328. The board also has wireless ESP8266 wi-fi shield control provides an internet connection for the project.

3.4.1.2. Sensors. In a project that requires an intelligent operation for the systems being developed, sensors play a prominent role. In automating fans and lamps at home, for instance, temperature control and lamp control are coupled to the system. Sensors such as Light-dependent resistor (LDR) and Temperature sensor (LM35) are needed for the automatic control of lamps and fans [79]. The temperature sensor is used to detect ambient temperature. Popular sensors include the ultrasonic module used for non-contact detection and used when prototyping robotic systems. There is a soil hygrometer, a soil moisture sensor that generates a digital signal when the soil moisture in a particular place rises above certain levels. The hygrometer is useful in building many agricultural solutions on Arduino such as an automatic watering system. Digital Barometric pressure sensor measures the absolute pressure of the environment as well as the height of the robot or projectile. The photoresistor sensor module is used for light detection. A night security light system can be prototyped on Arduino using this sensor. To detect poisonous gases such as LPG, i- Butane, Propane, Alcohol, etc, the MQ-2 gas sensor is adopted. Sensors such as the rain sensor are used for weather observation while the ordinary light Flame sensor is used to detect the flame. PIR sensor is used to detect motion from humans, pets, and other animals, and the touch screen sensor plays a key role when designing a Touch dimmer circuit using Arduino.

Some of other Arduino Sensors include:

1. 5 V 2- Channel Relay module
2. Accelerometer Module
3. Breadboard Power Supply Module 3.3 V
4. DHT11 Temperature and Humidity sensor
5. Digital Barometric Pressure Sensor
6. Digital thermal sensor — Temperature sensor
7. HC- SR04 Ultrasonic Module
8. HC- SR501 Pyroelectric Infrared Sensor
9. Humidity and Rain Detection sensor
10. IR Infrared Flame Detection sensor
11. IR Infrared Obstacle Avoidance sensor
12. Microphone sensor
13. MQ-2 Gas sensor
14. Passive Buzzer Module
15. Photoresistor sensor
16. RF 433 MHz Transmitter/Receiver
17. Rotary Encoder Module
18. Soil Hygrometer Detection Module
19. Soil Moisture Sensor
20. Speed sensor Module
21. SW-420 Motion sensor

The role of Arduino sensors cannot be overemphasized in the development and implementation of many electronic projects.

Table 10
Summary of the Specifications of some selected embedded system computing platforms.

Platform/Features	Arduino	Beagle Bone	Raspberry Pi
Microcontroller chip	ATmega328	TI AM3359	Broadcom BCM2835 SoC full HD multimedia applications processor
Central Processing Unit.	Atmel AVR (8-Bit), ARM Cortex-M0+	1 GHz ARM Cortex-A8	700 MHz Low Power ARM1176JZ-F Applications Processor
GPU	Bismuth208/STMGPU	PowerVR SGX530	Dual Core VideoCore IV® Multimedia Co-Processor
USB 2.0	USB cable type A/B, female port A	USB 2.0 type A	Dual USB Connector
Operational Voltage	5 V	5 V	5 V
Input Voltage	Maximum of 12 V	5 V	5.1 V
Input Voltage (limits)	Maximum of 20 V	5 V	5 V
Digital I/O Pins	14 (6 of them provide PWM output)	2x 46 pin headers	13
Analog Input Pins	6	20	27
DC Current per I/O Pin	40 mA	1.2 A to 2 A	2 A
DC Current for 3.3 V Pin	50 mA	none	none
Video Output	VGA	micro HDMI	HDMI
Audio Output	MIDI	micro HDMI	3.5 mm jack, HDMI
Storage On the Board	SRAM	2GB 8-bit eMMC on-board ash versionmicroSD card 3.3 V Supported	SD, MMC, SDIO card slot
Flash Memory	32 KB (ATmega328) of which 0.5 KB used by bootloader	4 GB 8–bit eMMC on-board flash storage	32GB eMMC on-board flash memory
SRAM	2 KB (ATmega328)	512 MB DDR3 RAM	1 GB RAM
Electronic Erasable Programmable Read-Only Memory	1 KB (ATmega328)	32 KB	2 KB
Clock Speed	16 MHz	1 GHz	1.4 GHz
Ethernet	Arduino Ethernet (AVR + W5100)	Ethernet RJ45 Male Plug Terminal Block	onboard 10/100 Ethernet RJ45 jack
Operating System	Windows, Linux, and Mac OSX	Linux, Android, Cloud9 IDE on Node.js with BoneScript library, etc	Linux
Board Measurements	69 × 54 mm, 101.52 × 53.3 mm, etc	86.40 × 53.3 mm	86mm × 54 mm × 17 mm
Price	$20	$95 to $149	$75

Projects such as prototyping a Sun tracking system with Arduino requires using LDR. Other projects such as the Arduino rainwater alarm, Accelerometer-based gesture-controlled Robot with Arduino, IR sensor-based line follower, IR sensor-based motion-sensing alarm also require sensors. A door alarm cannot possibly be built without an ultrasonic sensor. The same ultrasonic sensor could also be used in prototyping distance measurement systems. PIR sensors are important for home appliances control. [171–173] and [174].

3.4.1.3. Connectors. Connectors such as DuPont connectors, USB connectors, and pin header connectors are used to connect Arduino boards to shields or USB cables and sensors to the board. Examples of Arduino connectors are:

1. USB A Male to B Male
2. USB Cable Extension
3. Phidgets 12-foot Sensor Cable
4. RobotGeek
5. Sensor Cable
6. Couplers
7. 2 Pin Dual-Female Jumper Wire

3.4.1.4. Shields. It is possible to extend the power, functionalities, and capabilities of Arduino boards beyond the manufacture's specifications. This can be done by plugging shields, some sort of boards, on top of the Arduino PCB. Most shields are easy to mount and ridiculously affordable. More than one shield can be connected to an Arduino board. When this occurs, that is when several shields are connected and then connected to the Arduino board, a "Big Mac" of Arduino modules is said to have been created. Arduino shields come with programming libraries that make it easier to implement the hardware features on the shield. Several types of shields exist. The most popular ones are:

1. LCD shields
2. LED matrix shields
3. Wifi shields
4. Bluetooth shields
5. Motor shields
6. Power supply shields
7. Geiger counter shields
8. I/O grove base shields

3.4.1.5. Power supply. The power supply is necessary to test the prototype and to get it up and running. There should be a reliable power source to which the board should be connected to while work is ongoing.

3.4.1.6. Other accessories. The following are also hardware accessories used while prototyping with Arduino:

1. Bluetooth and Wi-Fi technologies for connection
2. RF
3. Motor-drivers
4. Adapters
5. DIY kits
6. Motherboards
7. Arduino shield stacking headers
8. LCD Touch display

3.4.2. Software components of arduino

Different types of software are needed to make Arduino work. Before a particular project will be successfully prototyped in Arduino several software packages must have interacted and been adopted to believe the best possible product. The following are some of the most prominent software components of Arduino:

3.4.2.1. Arduino IDE. The Arduino IDE is the interactive development environment for writing Arduino codes which are then sent to the board. The IDE runs on Windows, Linux, and Mac OS it is written in Java and Processing and similar open-source software. The Arduino IDE is compatible with all the existing variants of Arduino boards. The functions and syntax are similar to C and C++ functions and syntaxes. To use the Arduino IDE, a developer first downloads it to a computer. The Arduino board is then connected to the computer through USB ports. The developer then writes the Arduino codes on the Ide right on the computer system. Once written, the codes are uploaded to the microcontroller which then executes the code, interacts with inputs, and also outputs like light, motors, and sensors. Prominent Arduino IDE or compatible alternatives include:

1. PlatformIO
2. Eclipse Arduino IDE
3. Programino IDE for Arduino
4. EmbedXcode
5. Kletchlab
6. Codebender
7. Visual Studio
8. Zeus IDE

3.4.2.2. C/c++ compiler (avr-g++) and fritzing compiler. Arduino uses a type of the C/C++ compilers called avr-g++ in compiling codes written on the Arduino IDE. What the avr-g++ does is to convert the codes written in high-level languages, C/C++, Java, Processing) to a language that is native to the machine being used. A fritzing compiler is also used sometimes.

3.4.2.3. Excel, LABVIEW and MATLAB. Microsoft Excel is used for Arduino data analysis, output processing and storage [175] allows Arduino users to import, view, and analyze live data from external devices like their Arduino microcontroller. With this tool, it is quite easy to making meaning of data gathered from sensors easy to get to, affordable, and user-friendly for a wide range of applications. Data Streamer reads values printed to a computer's serial port exactly how data is printed to the Arduino IDE Serial Monitor. Besides Excel's Data Streamer, similar add-ins also exist in LABVIEW [33] and MATLAB. All of these import data directly from Arduino and conduct real-time plotting and analysis on the data so extracted. Excel also a second add-in for Arduino data acquisition called PLX-DAQ. Analyzed data can be saved to CSV and made available for future use.

3.4.2.4. EEPROM. The electronic erasable programmable read-only memory can be used to store byte variables. The variables so stored can later be accessed for future use. EEPROM is permanent storage that is similar to how a computer system's hard drive works.

3.4.2.5. Virtual breadboard. A virtual breadboard is a circuit prototyping software in which hardware and software simulation gears are readily available. The goal of the virtual breadboard is to help amateur and professional circuit creators study, program, and test their ideas without spending anything in cash or time. Neither does the designer have to worry about the board getting damaged in the period of trial and error have usually seen while still trying to perfect skills or while learning. It is also good for distance learning [176] and a very effective virtual laboratory for the disabled [177]. The market is saturated with a plethora of simulator or virtual breadboard. Examples include:

1. Autodesk circuits
2. Autodesk Eagle
3. Electronify
4. Fritzing
5. Proteus
6. VBB4Arduino or Virtual Broadband for Arduino
7. Virtronics simulator for Arduino

Some of these virtual breadboards or simulators come with tutorials that can teach amateur Arduino enthusiasts a lot about Arduino.

3.4.2.6. Android apk. The android platform app is a prominent platform for developing smartphone applications using Arduino. There are numerous platforms for developing smartphone applications such as those running on Windows Mobile, Symbian, iOS, and Android. Platforms like Android studio are widely used.

4. Discussions

Software IDEs in existence before Arduino and similar computing platforms came to the scene usually had little or no compatibility with the existing hardware. Arduino came as an answer to the yearning of many developers, hobbyists, and professionals alike. This review has holistically studied the existing literature on Prototyping with Arduino, it is applications, advantages of using it over other alternatives, challenges, and limitations to its actualization of intended goals. The reviewed literature agrees on one thing: the application domains of Arduino are limitless. It is possible to build a personalized alarm system using an Arduino board. The alarm system is designed to get actuated every time a person or object appears in front of the sensor. The alarm can then be deactivated by the users by keying in a predefined keyword of their choice. All that is required in developing such an alarm system are an ultrasonic sensor, an LCD, a 4×4 keypad, and a buzzer. The sensor is to detect oncoming objects and activate the alarm immediately. The user then enters a keyword for disengaging the system.

More and more are being found each day and the different variants of Arduino boards become more powerful and sophisticated with more technological advancements. The reviewed literature also accepts that Arduino is not perfect. That explains why they call for more studies and more improvement. They also found it pertinent that it is introduced to kids earlier in their education studies so that they become professionals before they leave high school [99]. Arduino holds much promise for the future and deserves credit for the simplification of the prototyping of highly needed devices which have found wide use in systems designs, general application, hardware communication Healthcare, Education, energy, defense, agriculture, and the mining industry.

At present, Arduino has been able to serve its purpose. It has provided a low-cost, energy-efficient platform for academics, hobbyists, and professionals. That platform is responsible for the many products that Arduino has been used to prototype. The astonishing number of literature, published in journals or presented at conferences, confirm that Arduino has gained wide acceptability. On rare occasions do you come across studies that are critical of Arduino? None utterly dismisses it and few find any faults in it.

Yet, it is glaring that Arduino still has a long way to go. Its capabilities cannot as of yet cover very big projects. This is certainly disturbing in a world where devices are becoming more sophisticated and more powerful. The fact that it is easy to use does not help since people are made to feel comfortable in their mediocrity. Arduino may need to up its game to remain relevant and become the platform for not only the small projects but also the very complex ones. There is also the question of how accessible Arduino is to those who need it. How accessible, or even affordable, is it in developing countries? There are still issues with Arduino's limited processing power, small storage space, and hardware limitations.

In the future, Arduino will not only need to confront and defeat these limitations but will need to massively innovate to confront some of the challenges that currently besets it [155]. It is important to improve Arduino integration in teaching, for instance, to ensure more and more students remain interested in using Arduino. While it is true that Arduino is fast in its prototyping process [13], improving would go a long to save students' time to be used in other activities such as code maintenance, debugging, and documentation.

Several microcontrollers are in existence in the wider embedded system market but Arduino particularly adopts several. Most of the variants of Arduino boards available, and there are quite many, have separate microcontrollers. This makes it difficult for people to know which is better to use between the many in the market. Streamlining it all to just one or two will make it easier for people to know which to choose by reducing deficiencies and inefficiencies. Such a move would ultimately increase Arduino's popularity and acceptability.

Reviewing Arduino revealed how vast its application domains are. Only a few could be reviewed since they are so many. The literature on them was equally numerous. Thus, it was a cumbersome, tasking job reviewing the studies. A comprehensive review is almost impossible. The literature was inexhaustible and each of the literature had points that were relevant to our topic. In the end, we settled only on the most relevant after sifting through all the literature we came across.

More studies on Arduino, its applications, advantages, limitations, and challenges are going to be released in the nearest future. In the future, there will be improvements on the Arduino board and software. More applications will be prototyped with Arduino and even more, literature will be produced on it. In the future still, likely, there will be challenges associated with using Arduino for prototyping engineering projects, there may still be limitations to what it can achieve and if many innovations can be made in improving it, there will always be advantages of Arduino for prototyping solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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