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Scientific Instrumentation Techniques using Open-Source Hardware Platforms like Arduino and Raspberry-Pi: A Review

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Abstract: *The field of scientific instrumentation is constantly evolving due to technological advancements, leading to the development of more sophisticated instruments capable of achieving highly accurate measurements. However, despite these advancements, there are situations where researchers require simple specific intelligent setups that may not be easily accessible by the existing high end instruments due to cost constraints or limited project budgets. In such cases, open-source hardware platforms like Arduino and Raspberry Pi present an attractive solution. These compact and versatile boards offer the capability to perform accurate measurements and carry out tasks that would otherwise require expensive specialized instruments. The open-source nature of Arduino and Raspberry Pi fosters collaboration and innovation within the scientific community. Researchers can tailor and customize the hardware and software to suit their specific experimental needs, enabling the development of low-cost yet effective scientific instruments.*
This review article aims to explore the potential applications of Arduino and Raspberry Pi in scientific instrumentation. It will discuss various ways in which these open-source platforms can be utilized to address research challenges, and it will showcase prominent works that have leveraged Arduino and Raspberry Pi to achieve significant scientific advancements. By presenting practical examples and use cases, this review seeks to inspire researchers to harness the capabilities of open-source hardware platforms to enhance scientific experimentation, especially in projects with limited financial resources. Ultimately, embracing these versatile boards can foster a more inclusive and accessible approach to scientific research, benefiting the scientific community as a whole

Keywords: Scientific instrumentation, Arduino, Raspberry Pi, Open-source instrumentation

I. INTRODUCTION

Scientific instrumentation refers to the tools, devices, and equipment used by scientists, researchers, and engineers to measure, observe, analyze, and collect data in various scientific fields. These instruments are essential for conducting experiments, making observations, and obtaining accurate and reliable data to advance scientific knowledge and understanding.
Scientific instrumentation spans a wide range of disciplines, including physics, chemistry, biology, geology, astronomy, environmental science, engineering, and more. Each field requires specialized instruments tailored to the specific parameters and phenomena being studied. Overall, the complexity and cost of scientific instruments can vary widely depending on factors such as technological sophistication, level of precision required, and the specific research needs. Researchers must carefully consider the balance between instrument complexity, performance, and cost to make informed decisions that align with their research objectives and available resources. Advances in technology, open-source options, and collaborative efforts can continue to play a vital role in making scientific instrumentation more accessible and affordable to the wider scientific community [1].

1.1 Open-source solutions for scientific instrumentation:

Open-source alternatives for scientific instrumentation refer to hardware and software solutions that are freely available, customizable, and accessible to researchers, scientists, and educators [1 – 3]. These alternatives offer the

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flexibility to modify, extend, and share the designs, making them valuable options for various scientific applications. Among them the popular open-source hardware platforms for scientific instrumentation are Arduino [4] and Raspberry Pi [5]. Arduino boards are widely used in scientific instrumentation due to their affordability, ease of use, and rich ecosystem of sensors and modules [6, 7]. Researchers can build custom data loggers [8], environmental monitoring systems [9], and control devices using Arduino. Raspberry Pi serves as a versatile single-board computer that can be used for data processing, control, and data storage [9]. It is commonly employed in high-performance computing [10], automation [11], and remote monitoring applications [12].

1.2 Arduino:

Arduino was developed in 2005 by a team of programmers, artists, and designers in Italy, aiming to create an affordable and user-friendly platform for electronics projects [4]. It gained widespread popularity due to its simplicity and versatility, making it accessible to both beginners and advanced users. Arduino has a strong and active community, with numerous online resources, forums, and project examples available for users to learn and collaborate [13].

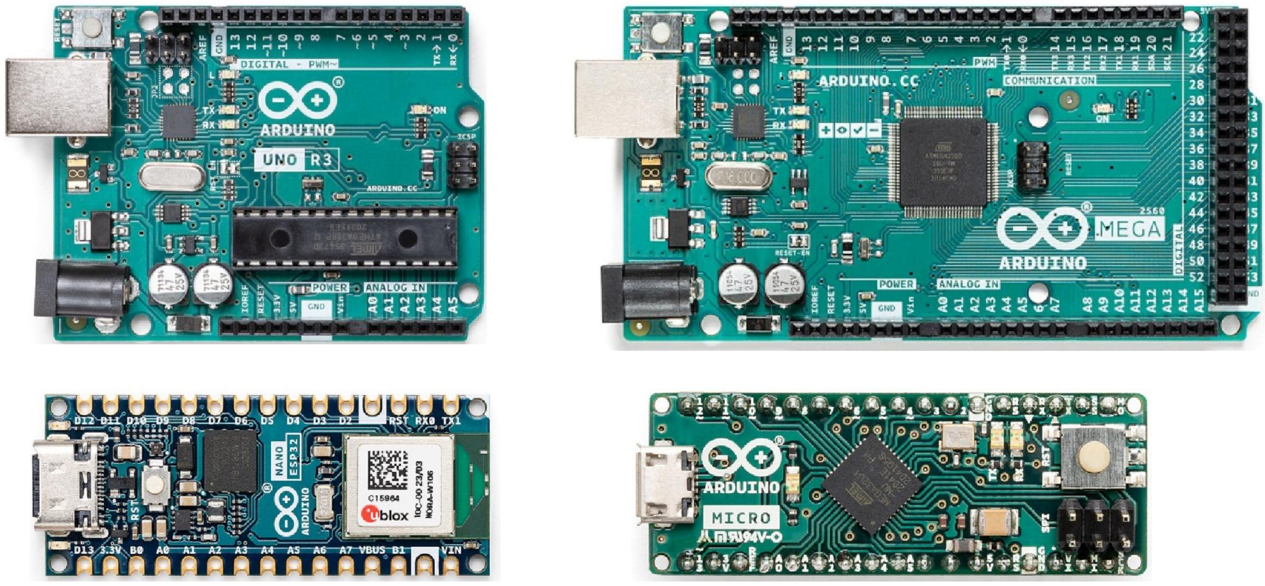

Figure 1: Arduino Uno R3, Nano, Mega and Micro boards (Source Arduiono.cc [4])

The Arduino platform has found applications in various fields, including education, home automation, robotics, environmental monitoring, art installations, and scientific instrumentation. It has become a powerful tool for prototyping and developing projects that involve data acquisition, control systems, automation, and interactivity.

A. Technical Specifications:

- Microcontroller: Various models use different microcontrollers, such as ATmega328P [14], ATmega2560 [15], SAMD21 [16] for traditional boards, u-blox® NORA-W106 (ESP32-S3) [17] and STM32H747XI dual Cortex®-M7+M4 32bit low power Arm® MCU [18] for latest Wifi enabled boards.
- Clock Speed: Typically from 16 MHz to 480MHz for latest boards.
- Digital I/O Pins: Varies depending on the model but typically includes multiple digital I/O pins, analog input pins, and pulse-width modulation (PWM) pins.
- Analog Input Pins: Typically 6 or more analog input pins, allowing measurement of analog signals.
- Communication: Supports serial communication through USB and UART, and some models offer I2C, SPI, and wireless communication options like WiFi, Bluetooth etc.
- Operating Voltage: Most boards operate at 5V, but some models support from 3.3V to 18 V.

There are several types of Arduino boards, each with its unique features and capabilities. Here are some of the common Arduino boards available:

- Arduino Uno: Arduino Uno [19] is one of the most popular and widely used Arduino boards. It is based on the ATmega328P microcontroller and has 14 digital input/output pins, 6 analog input pins, and various other features.
- Arduino Nano [20]: A compact version of the Arduino Uno, featuring the same ATmega328P microcontroller but in a smaller form factor. It is popular for projects with space constraints.
- Arduino Nano ESP32 [21]: An advanced version of Nano board with ESP32 wifi connector for IoT enabled projects.
- Arduino Mega [22]: This board is based on the ATmega2560 microcontroller, offering significantly more digital and analog pins compared to the Uno. It is ideal for projects that require a large number of I/O connections.
- Arduino GIGA R1 WiFi [23]: Is an advanced version with WiFi enabled module in Mega foot print. It is designed for ambitious makers who can develop instruments which can be read and controlled over internet.
- Arduino Leonardo: This board is built around the ATmega32U4 microcontroller and has native USB capabilities, making it easier to create projects that require USB communication.
- Arduino Due: Featuring a more powerful 32-bit ARM Cortex-M3 processor, the Arduino Due offers improved performance and more memory. It is suitable for more advanced applications and high-speed data processing.
- Arduino Mini: Similar to the Arduino Nano, the Arduino Mini is a compact board designed for projects with limited space. It is available in 5V and 3.3V versions.
- Arduino Pro: The Arduino Pro series includes various boards like Arduino Pro Mini and Arduino Pro Micro, designed for advanced users and for embedding into projects with specific form factors.
- Arduino Zero: Based on the SAMD21 microcontroller, the Arduino Zero is a 32-bit board with improved performance and features, suitable for advanced projects.
- Arduino MKR Series: The MKR series includes boards like Arduino MKR1000, MKR WiFi 1010, and MKR GSM 1400, designed for IoT applications with built-in connectivity features.

1.3 Raspberry Pi:

Raspberry Pi is a series of single-board computers developed in the United Kingdom by the Raspberry Pi Foundation [24]. These credit card-sized computers are designed to promote teaching of basic computer science in schools and in developing countries, as well as to facilitate DIY electronics projects for hobbyists and enthusiasts [25].

A. Technical Specifications

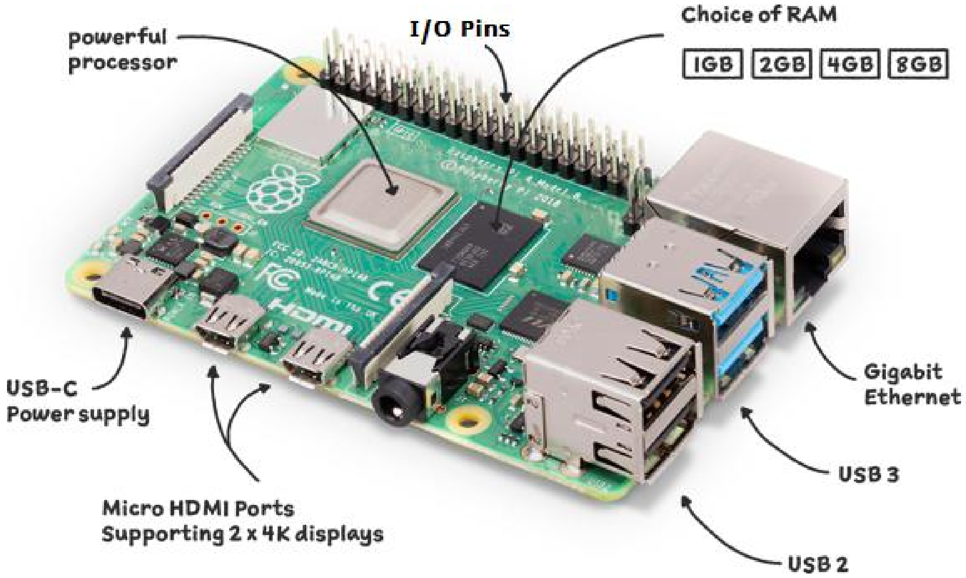

Figure 2: Raspberry Pi Model 4 B (Source Raspberry Pi portal [5])

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- Models: Raspberry Pi modules are available in different models like, Raspberry Pi 1, 3 and 4 with Models B, B+, A and A+, and Raspberry Pi Zero and Pico series [26] etc.
- Processor and RAM: Raspberry Pi models are powered by various processors, including ARM-based Broadcom SoCs (System-on-Chip). For instance, the Raspberry Pi 4 Model B, one of the latest models, features a Broadcom BCM2711 quad-core Cortex-A72 (ARMv8) 64-bit processor running at 1.5 GHz. RAM options for different models vary, with the Raspberry Pi 4 Model B offering options with 2GB, 4GB, or 8GB of LPDDR4 SDRAM [27].
- Storage: Raspberry Pi boards use microSD cards for storage. Users can install an operating system and store data on these cards. Some models also support USB booting, enabling the use of USB storage devices.
- GPIO Pins: Raspberry Pi boards feature GPIO (General Purpose Input/Output) pins that allow users to connect and control external devices, sensors, and other peripherals. The number of GPIO pins varies depending on the model.
- Connectivity: Most Raspberry Pi models come with built-in Wi-Fi and Bluetooth connectivity. They also have USB ports and HDMI output for connecting peripherals and displays. The Raspberry Pi 4 Model B introduced dual micro-HDMI ports to support dual displays.
- Operating System: Raspberry Pi supports various operating systems, with the official Raspberry Pi OS [28] (formerly known as Raspbian) being the most commonly used. However, other operating systems like Ubuntu, Fedora, and specialized distributions for specific purposes are available.
- Power Supply: Raspberry Pi boards can be powered using a micro-USB connector or USB Type-C connector, depending on the model. The power requirements vary depending on the board and peripherals being used.
- Form Factor: Raspberry Pi boards have a compact form factor, generally the size of a credit card, making them suitable for embedding into various projects.
- Expansion: Raspberry Pi supports expansion through add-on boards called HATs (Hardware Attached on Top), which connect directly to the GPIO pins, providing additional functionalities like sensors, motor controllers, and audio enhancements.
- Software Ecosystem: Raspberry Pi benefits from a thriving community that creates and shares projects, tutorials, and software. This active community support is instrumental in the versatility and adaptability of Raspberry Pi for a wide range of applications.

Arduino and Raspberry Pi are two popular open-source hardware platforms that have revolutionized scientific instrumentation. Both platforms offer unique features and capabilities, making them valuable tools for researchers and scientists in various fields. Here's how Arduino and Raspberry Pi are utilized in scientific instrumentation:

1.4 Arduino as Scientific Instrumentation:

Arduino's rapid prototyping capabilities allow researchers to quickly build and test proof-of-concept setups before investing in larger and more complex systems. The following are the examples and case studies of scientific instrumentation of Arduino.

- Data Acquisition and Instrumentation: Arduino boards are commonly used to interface with sensors and collect data in scientific experiments. They can measure temperature, humidity, pressure, light, and other environmental parameters. Among them, Thirumalesh et al., [8] developed 8 MHz speed data acquisition system for a shock tube, in the study of shock wave impact effects on materials. In this research project an Arduino Mega board is utilized to acquire the shack wave movement data through number of shock sensors. Wickert et al., [29] designed and used Arduino-compatible data loggers for field research. Asua et al.,[30] effectively used in their research work 'High-precision displacement sensor based on resonant cavities through an electronic interface based on Arduino'. Sreeshma et al., [31] effectively used Arduino in their work 'Single thermal scan digital system for deep level transient spectroscopy'. Vajpyee et al., [32] worked on 'Design and development of nano pH sensor and interfacing with arduino'. Pérez et al., [33] presented their work on "Design and construction of a desktop AC susceptometer using an Arduino and a Bluetooth for serial interface". Iribarren et al., [34] demonstrated the successful usage of Arduino in their geographical data collection work 'Arduino data loggers: A helping hand in physical geography'. Mack et al., [35] obtained precision measurements in their research work 'Precision optical trapping via a programmable direct-digital-synthesis-based controller for acousto-optic deflectors'. Grinias et al., [36] developed an inexpensive, open-source USB Arduino data acquisition device for chemical instrumentation.

- Control Systems: Researchers use Arduino to create closed-loop control systems to regulate environmental conditions, such as temperature, in laboratory setups.Patel et al., [37] designed 'An experimental control system for electron spectrometers using Arduino and LabVIEW interfaces'. Ta Duc et al., [38] developed a system in Estimating modal parameters of structures using Arduino platform. Mucciaroni et al., [39] developed an efficient arduino-based control system for laser microfabrication of photonic platforms.
- Environmental Monitoring:Arduino-based systems are deployed for continuous environmental monitoring, including air quality, water quality, and soil conditions. Among them, Young et al., [40] developed an Arduino-based instrumentation to monitor greenhouse environmental conditions. Rodriguez-Vasquez et al., [41] worked on On-demand atmospheric secondary organic aerosol measurements with a mobile Arduino multisensor.
- Low-Cost Solutions:Arduino's affordability makes it an attractive choice for researchers with limited budgets. It offers low-cost alternatives to expensive commercial instruments. To list a few; Agudo, et al., [42] designed a low-cost real color picker based on Arduino for their project, Lockridge et al., [43] worked on Development of a low-cost arduino-based sonde for coastal applications. Ashwindran et al., [44] developed a Low-Cost Digital Torquemeter Coordinated by Arduino Board, Kriz et al., [45] developed a Low-Cost Arduino Based Laser Nephelometric Instrumentation for High Sensitivity determination of the Inflammatory Marker C-Reactive Protein (CRP).
- Automation: Arduino can automate repetitive tasks in scientific experiments, freeing researchers from manual interventions. Hnatiuk et al., [46] used Arduino boards in their work 'High-throughput and versatile design for multi-layer coating deposition using lab automation through Arduino-controlled devices'.

Arduino development platform effectively used in the curriculum to teach the usage of such advanced electronic devices for their scientific applications. To mention a few, Galadima et al., [47] presented their research paper on "Arduino as a learning tool", Kuan et al., [48] presented their curriculum implementation on "Development of a computer-assisted instrumentation curriculum for physics students: using LabVIEW and Arduino platform", Hadiati et al., [49] demonstrated the effect of laboratory work style and reasoning with Arduino to improve scientific attitude.

1.5 Raspberry Pi for Scientific Instrumentation:

The unique features of Raspberry Pi which are used for scientific instrumentation are as follows.

- Raspberry Pi-Based Telescope with Astrophotography Capabilities [50, 51]: In this case study, researchers designed a Raspberry Pi-powered telescope equipped with a high-resolution camera. The Raspberry Pi board controlled the telescope's movement and captured images of celestial objects. Additionally, the system performed real-time image processing and stacking to enhance image quality, making it a cost-effective solution for amateur astrophotography.
- Low-Cost Microscopy System with Raspberry Pi [52, 53]: Scientists developed a low-cost microscopy system using a Raspberry Pi camera module. The Raspberry Pi board controlled the camera and captured high-resolution images of microscopic samples. The system was used in educational settings and resource-limited environments, making microscopy accessible to a broader audience.
- Raspberry Pi Cluster for High-Performance Computing [54, 55]: In this case study, researchers created a Raspberry Pi cluster by interconnecting multiple Raspberry Pi boards. The cluster was employed for parallel processing in scientific simulations and data analysis. The low-cost and energy-efficient nature of Raspberry Pi clusters made them suitable for research institutions with budget constraints.
- Raspberry Pi-Based Environmental Data Logger [56, 57]: Scientists built an environmental data logger using Raspberry Pi to monitor various parameters in remote locations. The system integrated sensors for temperature, humidity, air quality, and GPS location. The Raspberry Pi board logged the data and periodically

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transmitted it to a cloud server, enabling researchers to collect and analyze environmental data over extended periods.

- Raspberry Pi-Powered DNA Sequencing and Analysis [58]: A group of researchers developed a DNA sequencing and analysis system using Raspberry Pi. The system controlled a DNA sequencer and performed real-time base calling and analysis of DNA sequences. The Raspberry Pi board processed the data and provided preliminary analysis results, reducing the need for expensive computational resources.
- Raspberry Pi-Controlled Hydroponics System [59, 60]: In this case study, scientists used Raspberry Pi to control a hydroponics system for plant growth experiments. The Raspberry Pi board managed the environmental conditions, such as nutrient levels, pH, and light cycles, to optimize plant growth. The system also collected data on plant health and growth rates for further analysis.
- Raspberry Pi-Based Seismograph for Earthquake Monitoring [61, 62]: Researchers developed a Raspberry Pi-powered seismograph system to detect and analyze seismic activity. The system utilized accelerometers to measure ground motion, and the Raspberry Pi board processed the data, recorded seismic events, and transmitted real-time data to a centralized server for seismic monitoring and analysis.
- Raspberry Pi-Controlled Drone for Environmental Sensing [63]: In this case study, scientists equipped a drone with Raspberry Pi to perform remote environmental sensing. The Raspberry Pi board integrated with various sensors, such as gas detectors and particulate matter sensors, to monitor air quality and environmental conditions in hard-to-reach or hazardous locations.
- Raspberry Pi-Powered Autonomous Underwater Vehicle (AUV) [64, 65]: In this case study, a team of scientists created an AUV using Raspberry Pi to explore and map underwater environments. The Raspberry Pi board controlled the AUV's movements, sensors, and data acquisition. The AUV collected data on water quality, marine life, and underwater topography for research and conservation purposes.
- Raspberry Pi-Based Smart Greenhouse System [66, 67]: Researchers developed a smart greenhouse using Raspberry Pi to optimize plant growth conditions. The system employed various sensors to monitor temperature, humidity, light, and soil moisture levels. The Raspberry Pi board controlled environmental parameters and automated irrigation and ventilation to create an ideal growing environment.
- Raspberry Pi-Controlled Spectroscopy System for Material Analysis [68]: Scientists designed a Raspberry Pi-based spectroscopy system for material analysis. The system utilized a spectrometer connected to the Raspberry Pi board to study light absorption and emission spectra of materials. The setup provided researchers with valuable insights into material properties and composition.
- Raspberry Pi-Powered Portable Laboratory for Field Research [69, 70]: In this case study, researchers developed a portable laboratory using Raspberry Pi for field research. The Raspberry Pi board integrated with various instruments, such as pH meters, conductivity sensors, and spectrometers, to perform on-site analysis and data collection, reducing the need for laboratory infrastructure.

1.6 Combined Use of Arduino and Raspberry Pi:

The combination of Arduino and Raspberry Pi offers researchers the best of both worlds. Arduino provides the flexibility for low-level sensor interfacing and real-time control, while Raspberry Pi brings computing power and connectivity for data processing, storage, and remote access. This synergy is particularly beneficial in scientific instrumentation where data collection, analysis, and control are all essential aspects of the research. To mention a few, Ferdoush et al., [71] designed Wireless sensor network system using Raspberry Pi and Arduino for environmental monitoring applications and Barik et al., [72] developed an IoT based temperature and humidity controlling setup using Arduino and Raspberry Pi.

In summary, both Arduino and Raspberry Pi have made significant contributions to scientific instrumentation. Their affordability, versatility, and ease of use have democratized access to scientific tools, enabling researchers to design, build, and customize sophisticated instruments for a wide range of scientific applications.

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