

## Using an Arduino-based low-cost DAQ in science teacher training

David Rihtaršič

University of Ljubljana  
Ljubljana, Slovenia

**ABSTRACT:** The rapid development of Arduino open-source hardware platform-based projects has been reported for STEM education. However, it is rare to see this kind of very low-cost data acquisition (DAQ) system in science education, where it might replace expensive commercial devices. These modular, constructed DAQs can be highly customisable to meet teacher needs. In a pilot project, such devices were introduced to university students learning to become elementary school science teachers. The potential for such devices to replace currently used commercial DAQs was examined, as well as the attitude of the students to this equipment. Focus was on the Arduino-based platform, which can operate in two different modes as a standalone data-logger device or as a DAQ connected to a computer with full data visualisation. All items of equipment developed were Arduino *do it yourself* (DIY) devices published on the GitHub portal, where they are freely available with support and examples.

### INTRODUCTION

It is in the nature of science education that theoretical concepts are supported by experiments in front of students. This approach is widely used in the whole area of science, technology, engineering and mathematics (STEM) education. The purpose of experiments is to enrich the teaching process and to verify/confirm the underlying principles using the experimental data. The teacher often displays the measured data as charts to better visualise the measured physical quantities. Visualisation helps students to observe the experiment in more detail and contributes to an understanding of the subject matter. Also, the visualisation of measured data is essential for quantities that cannot be directly detected by humans, such as electrical current, voltage, humidity, temperature, force, acceleration and velocity.

Moreover, with the integration of inquiry-based learning (IBL) into education in the past decade, it is often the students themselves who conduct the experiments and collect, analyse and interpret the scientific data [1]. In such experiments, some kind of data acquisition (DAQ) system is generally used to measure and, to some extent, analyse the data. There are well-established devices used in education from the commercial company Vernier. These DAQ devices are easy to use, the data are well presented and the whole system is well suited for educational purposes. However, these devices are rather expensive; for example, costing from \$US100 for a DAQ device and \$30 to \$100 for a single temperature probe. Therefore, the affordability of these devices can be questioned; it can have an important impact on their use in education. Though many schools can be equipped with several such DAQ devices, others lack this type of equipment [2]; especially noticeable with the greater prevalence of IBL.

On the other hand, in STEM education, there has been a remarkable development of open-source hardware called Arduino. Hernando Barragán's Master's thesis project called *Wiring* in 2003 later developed into the Arduino project [3]. The Arduino platform has greatly contributed to technology education. Though Barragán's aim was to create simple, low-cost tools for creating digital projects by non-engineers, the project has expanded beyond that. The Arduino boards are now widely known and variations are well established as hobby electronics, as well as in education. Very good learning results are reported from a very early stage of learning in elementary school [4], in primary school [5], also in secondary school [6], and even at university level [7]. Mostly, these devices are used in STEM education, especially regarding electronics, computer science and robotics.

However, despite the popularity of the Arduino devices in the context of programmable electronics, it is rare to find those devices as DAQs in support of STEM education. It is plausible that this kind of equipment is not used in laboratories where high accuracy is required, since the Arduino devices are not designed for this; in general, they are equipped with (only) 10-bit analogue to digital converters and no accurate voltage reference. Nonetheless, the Arduino modules have been used successfully as educational laboratory systems in some cases; for example, in electronics [8], chemistry [9] and physics [10]. However, these are rare examples and designed by researchers for specific cases.

What is missing is an open-source hardware educational laboratory system that could be used instead of expensive commercial DAQ devices, such as those from Vernier. To close this gap, the author has developed a low-cost, open-source hardware system and has several examples of its use. As in other countries, Slovenia recognises the important role of ICT in education, which was highly supported by the Slovenian Government in last year's national project, *ICT in Teacher Training Study Programmes University of Ljubljana (UL)* where this research took place.

Research questions explored in this study are as follows:

1. Are such *do it yourself* (DIY) devices appropriate for use by science teachers?
2. How does a self-developed direct manipulation learning environment enhance STEM learning?

## DEVELOPING A DAQ USING OPEN SOURCE HARDWARE

In the past, commercial equipment such as that from Vernier was used in education. Since 2004, the University has developed some of its own DAQ devices, such as CMC-S3, eProLab-SC1 [11] and INFIRO-Xplained [12]. But, noting the popularity and low prices of the Arduino boards, it was decided to develop a DAQ system using the boards. In the acquisition and presentation of data, DAQ devices can be divided into two groups:

- on-line devices;
- off-line devices.

Both modes are commonly used in STEM education, which is reason to support both.

### On-line DAQ System

An on-line DAQ system would be preferred, if it could be attached to a stationary experiment and the measured data observed on a PC screen. In this situation, the computer provides all the instructions for the DAQ and controls the sampling rate. Some support can be found in Arduino for such systems [13], but these systems have two main disadvantages:

- slow serial communication on which the sampling rate depends;
- pre-defined functions provided by the firmware.

To address these problems, the communication should be as short as possible since this takes a significant amount of time. In this regard, the communication was designed in packets of two bytes, where the first four bits is the instruction and the last 12 bits the data. With only 16 possible instructions the firmware was designed to support general register control rather than supporting several single-purpose functions. This not only shortens the communication, but also makes the application more versatile. Now the user can compose functions on the PC side with no need to update the firmware. In the current version of firmware, 12 out of 16 possible functions are used, which are specified in Table 1.

Table 1: Set of 12 instructions for general register control.

Instruction name	Code	Description
PROCES_RESET	0x00	Reset function - also returns the firmware version number.
READ_REGISTER	0x10	Reads the register value from the address specified in the data byte.
SET_REGISTER	0x20	Sets the register value of address specified in the data byte. The data must be sent before using this function.
SET_REGISTER_BIT	0x30	Sets only the specified bit in the register with address specified in the data byte.
CLR_REGISTER_BIT	0x40	Clears the specified bit in the register with the address specified in data byte.
READ_REGISTER_BIT	0x50	Reads the specified bit in the register with the address specified in data byte.
WAIT_UNTIL_BIT_IS_SET	0x60	The execution of other instructions in the memory buffer is on hold until the bit is 1.
WAIT_UNTIL_BIT_IS_CLEARED	0x70	The execution of other instructions in the memory buffer is on hold until the bit is 0.
READ_16_BIT_REGISTER_INCR_ADDR	0x80	Function returns the values from two neighbouring registers incrementing the address for the second one.
READ_16_BIT_REGISTER_DECR_ADDR	0x90	Function returns the values from two neighbouring registers with a decision determining the address for the second one.
REPEAT_CMD_BUFFER	0xA0	Repeat last x numbers of the instructions where x is specified in the data byte.
SET_DATA	0xB0	Sets data to be written into register.

To reach even faster sampling rates, firmware was designed for Arduino that supports loop functions. The memory buffer in Arduino is designed to hold up to 256 instructions and the execution of those can include loops. In this mode, the PC can receive a stream of data without interruption. This approach significantly increased the sampling rate to about 6 kiloSamples/sec (kS/s) for one analogue channel with 10-bit resolution.

A Microsoft Excel program (with Visual Basic macros) was used to display the direct acquisition data from the Arduino DAQ. An example of using the DAQ system with Microsoft Excel is shown in Figure 1.

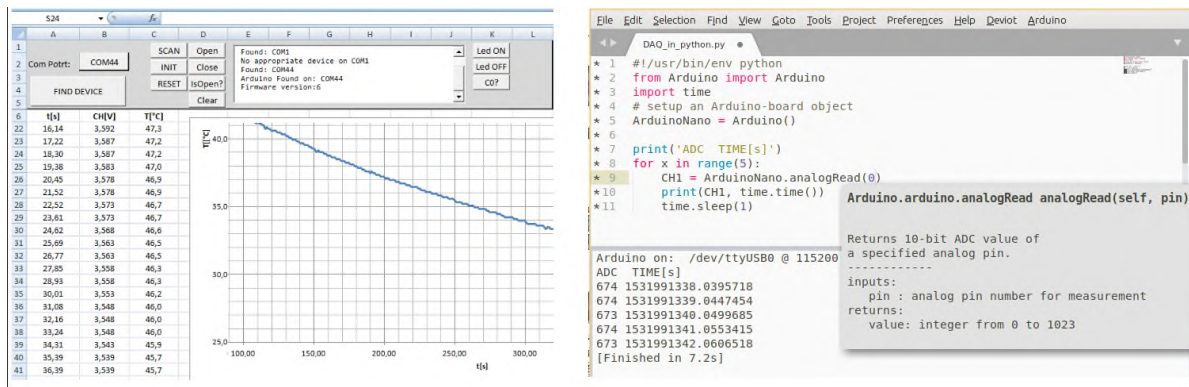


Figure 1: Using Arduino DAQ with MS Excel; Python programming language.

The Python programming language is widely used in ICT, and hence was used for this development. With this option the user can implement Arduino DAQ functionality for a broad variety of applications. The functions are simply named as in Arduino IDE (integrated development environment). An example of a measured 3.3 V reference voltage with function description and data output is shown on the right-hand side of Figure 1.

### Off-line DAQ System

Another scenario is for the acquisition of data about some phenomena where permanent connection to PC is not an option. In that case, data-loggers can be used to store the data on SD cards or the data can be sent to other devices. Following are three different examples:

- data-logger and saving data on SD card;
- devices with LCD display of data;
- serial data output (wired or wireless).

Since the code runs on the Arduino side, all the examples are written in Arduino IDE, which is freely available on the GitHub portal [14]. Figure 2 shows an example where raw ADC (analogue to digital converter) values are sent to a PC serial terminal (left); then, the data were imported into a spreadsheet program for curve fitting (middle), and finally, the true temperature data were sent to a PC terminal for visualisation (right) [15].

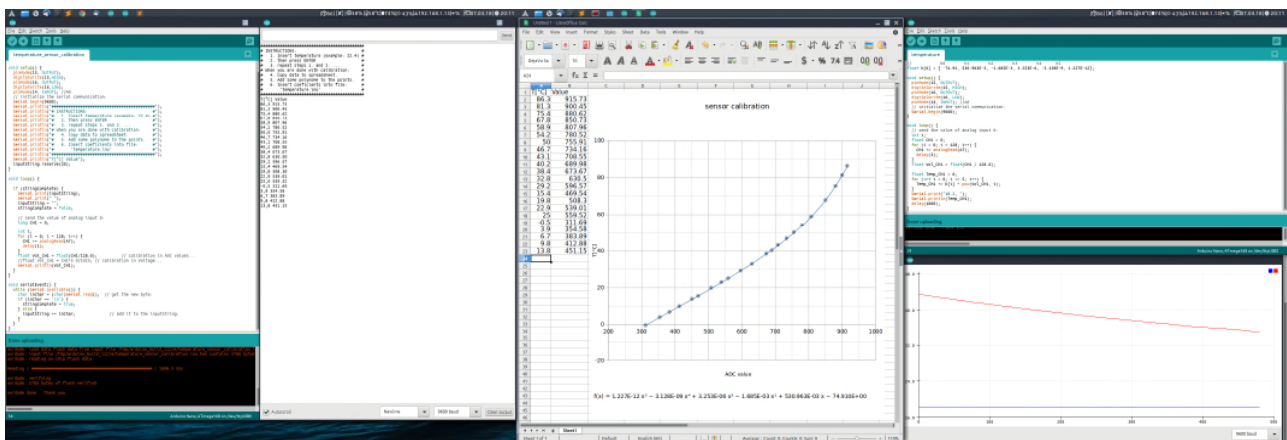


Figure 2: Example of off-line DAQ.

### COURSE IMPLEMENTATION

The equipment and prepared examples were incorporated into the university course for elementary school science teachers called *Computers in Physics Classrooms*. There are 15 contact hours of laboratory work available. The aim of

the subject is to introduce ICT usage into teaching physics and to make students more confident with the hardware and dedicated software. A more detailed set of activities is presented in Table 2, but in general the course can be divided into two parts:

- formal introduction to DAQ systems, guided exercises and examples;
- students design their own DAQ project.

Table 2: Overview of the course content.

Duration (hours)	Title	Addressed content
1	Basics of DAQ systems	Sampling frequency, sample resolution/accuracy, digital vs analogue data, timing, data streaming, auto ranging.
1	Introduction to Arduino UNO	Pin-out, programming, basic circuits, I/O limitations, 10-bit ADC, timers.
2	Designing a sensor	Voltage dividers, resistance-type sensors, volt, amplifiers, filters.
3	Exercise 1: Temperature sensor	NTC resistor, ADC values, serial output.
2	Exercise 2: Data analysis	Importing data to MS Excel, data statistics, chart output, regression, polynomial fitting, calibration curve.
2	Exercise 3: Stand-alone DAQ	LCD output, SD card data logger.
5	Student project	Designing Arduino DAQ, acquisition, analyses and interpretation of data, data measurements.

In the first 10 hours of laboratory work the students are introduced to the basics of DAQ systems. This part of the course is guided by a teacher explaining the relevant content supported by examples of acquisition and the basics of data analysis.

The second part of the course is more IBL-orientated, with each pair of students dedicated to a selected measurement experiment. The experiments were from physics for which students designed software and hardware support with data visualisation. The experiments deal with average velocity, acceleration, acceleration under gravity, harmonic oscillation, angular velocity and projectile motion.

## RESEARCH METHODOLOGY

Commercial DAQ equipment is rather expensive. But using these devices in STEM education is essential, especially with IBL. Therefore, it was interesting to investigate the potential of DAQ devices designed using open source hardware as a DIY project. The experimental research measured students' attitude towards this kind of equipment and their ability of using and contributing to open source content. A six-level (0 - 5) Likert scale questionnaire was devised, where students agree/disagree on their use, learning and contribution to open source content and on solving specific tasks. The questionnaire consisted of 27 items grouped into six general areas:

- Using/contributing to open source content (Number of items, N = 4);
- STEM learning with the help of ICT (N = 3);
- Problems during the DIY project (N = 10);
- Plug and play (PnP) cons and pros (N = 2);
- Plug and play (PnP) device contribution to students' STEM knowledge (N = 4);
- DIY devices contribution to students' STEM knowledge (N = 4).

Students (N = 19) were tested three times during the research. First, they were tested before the activities, which served as a baseline. Second, they were tested after the introduction to DAQ systems and guided exercises, to measure the gains from these activities. Finally, they were tested after they finished their DAQ project, which provided a measure of the impact of IBL.

For data analysis, Python 3.6.6 was used with imported libraries for statistical analysis viz. *pandas 0.23.1* for data handling and reporting the mean scores and standard deviations; *statsmodels 0.9.0* for multiple regression analysis and ANOVA; *SciPy 1.1.0* for calculating *t*-test statistics, and Levene's test for homogeneity of variance. The statistical significance was selected at a probability level of  $p > 0.05$ . The size effect was calculated using the eta squared ( $\eta^2$ ) test.

## RESULTS AND CONCLUSIONS

Students would not have had much prior experience with DIY projects and using open source content. This was confirmed by the small average score (mean, M = 0.68; standard deviation, SD = 0.54) of using and contributing to open source content before the pilot research, i.e. the baseline scores. During the course the students' attitude changed towards using and contributing to open source content. Students became aware of open learning possibilities and were

able to make a contribution. The course had a great measured impact on the students. Significant differences were found for the three measurements before course, after the guided section and after the DAQ project, with  $F(2,45) = 7.18$ ,  $p = 0.003$  and  $\eta^2 = 0.22$ .

In the pilot research, attention was paid to where the students had problems during the course or if they lacked knowledge, equipment, instructions or experience. These data can help to prepare content in the future. The mean scores of the four most important issues are presented in Table 3 sorted in descending order after students have finished their DAQ project.

Table 3: Important issues in DIY projects.

Issue	M (before course)	M (after guided session)	M (after DAQ project)
Step-by-step instructions	3.05	3.00	3.62
Electrical schematics	3.63	3.81	3.54
Solving the problem eminently	3.58	3.31	3.39
Listed possible issues	3.05	3.00	3.00
Check for errors after each step	2.21	2.56	2.85

The results were regarded as satisfactory since all students managed to successfully design their own DAQ system. They all prepared full documentation including how to assemble the DAQ system, and supporting documentation of examples and data presentation. Figure 3 shows an example of a DAQ system for measuring oscillations with data visualisation. The snapshot of a video presenting the experiment is shown on the left of Figure 3. The upper right of Figure 3 shows the position of the mass; electronic schematics with the general setup of the experiment are shown at the bottom right of Figure 3.

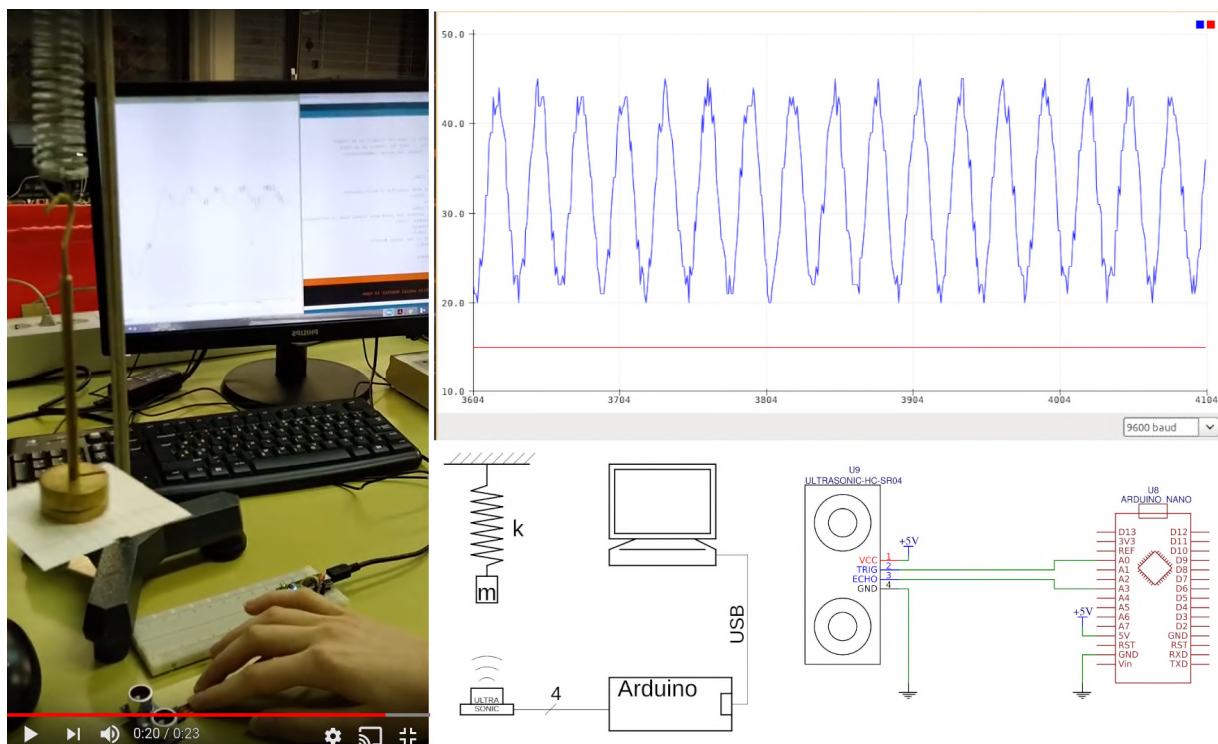


Figure 3: Student DAQ project of oscillation movement.

During the pilot research another interesting phenomenon was noticed. Students' opinions on whether the use of DIY or PnP equipment contributes more to STEM knowledge showed no preference at the beginning of the course ( $M_{DIY} = 2.789$ ,  $SD_{DIY} = 1.653$  and  $M_{PnP} = 2.35$ ,  $SD_{PnP} = 1.687$ ), since there are no significant differences ( $F(1,36) = 0.66$ ,  $p = 0.42$ ) in results. However, at the end the students' opinions had changed. Then, students believed that using DIY devices contribute to the STEM knowledge more ( $M_{DIY} = 3.676$ ,  $SD_{DIY} = 1.322$ ) than using commercial devices ( $M_{PnP} = 2.359$ ,  $SD_{PnP} = 1.853$ ). The result is significant with  $F(1,24) = 4.353$ ,  $p = 0.048$  and a medium impact factor of  $\eta^2 = 0.15$ .

The students pointed out that though they would gain their own knowledge in the STEM field using DIY devices, they intend to use commercial DAQ systems in their professional work as a teacher, regardless of the higher price. This confirms a finding that the experiences of pre-service teachers can boost their knowledge of direct manipulation learning environments. and how they can be used in teaching [16]. Moreover, the results presented here provide evidence that theory-driven technology practice [17]:

- enriches subject matter;
- promotes reflective learning;
- informs conversations and thinking;
- engages students in learning.

Future studies will be focused on how creativity, driven through technology, may be sustained in a classroom, where a direct manipulation environment might scaffold learning and creativity. This has been argued for in the context of low intensive technology-based learning environments [17].

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