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Development of low-cost Arduino-based equipment's for analytical and educational applications †

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Abstract: Modern microcontroller Arduino platform is often used to create electronic devices with the ability to receive signals from various digital and analog sensors, further primary processing of information with transfer to a computer, as well as to control various devices. This versatility makes it possible to create low-cost equipment for analytical and educational applications on these platforms. As an example, this white paper describes the benefits of using Arduino microcontroller boards to create two powerful and inexpensive interfaces for computers and laboratory equipment for automating analytical chemistry laboratories. The first one is a device for carrying out coulometric titration in galvanostatic mode with potentiometric or amperometric indication of the titration end point. The instrument is used to determine the concentration of individual substances and the total antioxidant capacity of food systems. Another development is a device for determining the water activity of food systems with a capacitive sensor for determining relative humidity. Both measurement equipment uses Arduino One or Nano microcontrollers in combination with various controls for analog signal measurement, A/D conversion, and indication. The measured values are monitored in real time by transferring information to a personal computer via the USB port under the control of the developed software. The effective use of the developed devices is presented on the example of measurements of foodstuff samples with obtaining validated data.

Keywords: Arduino board; coulometric titration; water activity; foodstuff; low-cost equipment; laboratory automation

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1. Introduction

The implementation of information technologies in the educational process is an irreversible process and a necessary attribute of the educational environment of a modern university, complementing traditional forms of education. Their use in the classroom in the chemical laboratory allows students to start getting acquainted with the elements of automated process control and data collection, which is important for technological and engineering specialties. Many research and teaching labs use commercial USB devices to collect instrument signal data. However, the affordability of such instruments and their software, coupled with the need to have enough for teaching labs, create a barrier to this approach. One alternative approach to solving this problem is to independently develop inexpensive devices using microcontrollers on an Arduino-based board [1]

Arduino-like microcontrollers are increasingly being used in the classroom to teach skills, attitudes, and knowledge about technology [2]. Arduino as a tool for designing electronic devices or, in other words, an electronic designer that interacts more closely with the surrounding physical environment than standard personal computers and goes beyond the virtual. It is an open source "physical computing" [3] platform built on a simple printed circuit board with a modern software development environment. Thus, it becomes possible to use these boards to create electronic devices with the ability to receive signals from various digital and analog sensors and control various actuators. There are a number of advantages to this approach:

- Arduino-based device designs can work on their own or interact with software on a computer;
- the development price can be a variable component depending on the use of boards either assembled by the user independently or purchased as a set;
- he open-source software development environment is suitable for both novice and advanced users, and is available for free download;
- the benefits for teachers and students are low cost, cross-platform (the Arduino software runs on Windows, MacOS and Linux) and the ability to expand hardware capabilities through a variety of modules.

This study presents a partial experience of using two Arduino-based devices for electronic data acquisition in an educational chemical laboratory in the course of academic subjects devoted to food analysis methods. In this context, the Arduino platform is used for the development of electronic devices with the ability to receive signals from various digital and analog sensors, assembly and initial processing of information with subsequent processing by more complex computing devices, as well as control of devices in the process of performing laboratory educational projects.

2. Development of the Arduino-based devices for electronic data acquisition

2.1. General description

A general architecture of both developed devices based on Arduino board is presented in Figure 1.

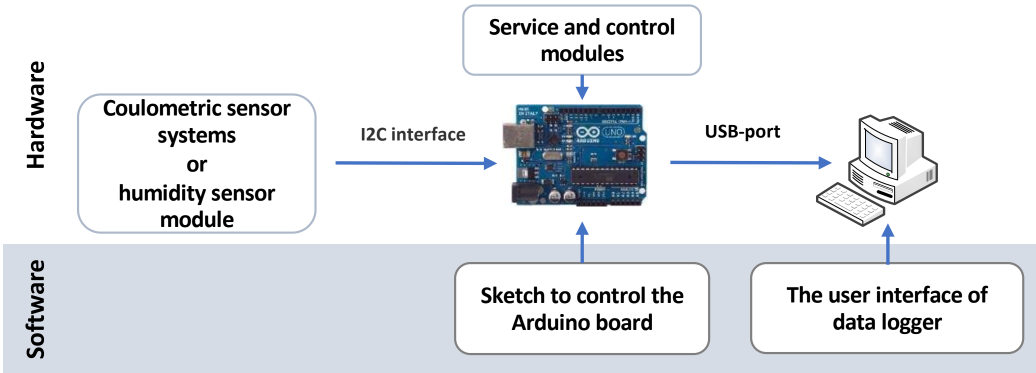
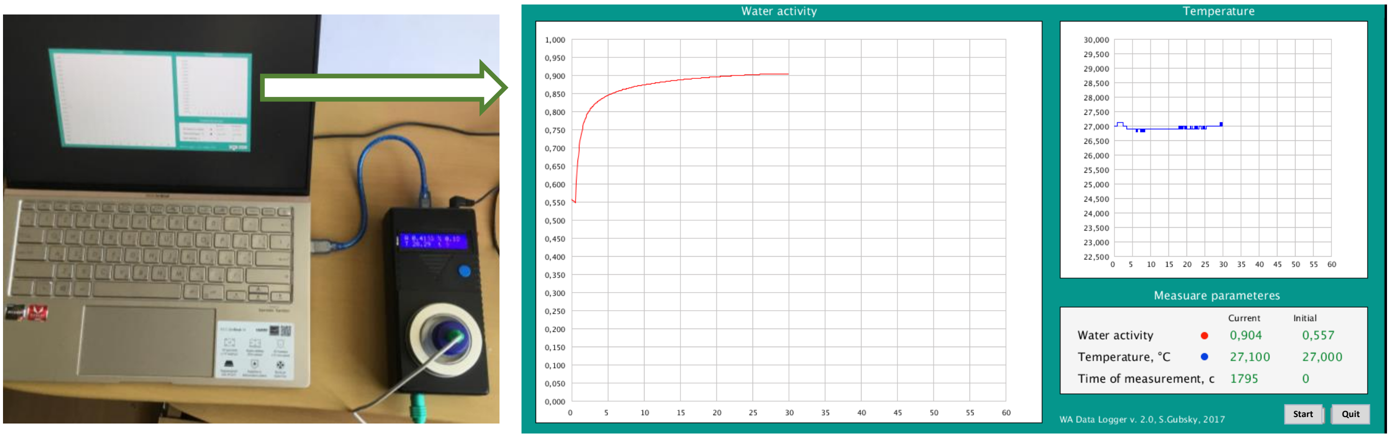


Figure 1. A general Arduino-based circuit for electronic data acquisition devices.

The devices use the modular principle of building hardware using commercial or self-built modules, the description of which will be given below. With the help of modules, the analog signal received from the sensors is converted into digital and transmitted via the USB-port to the computer. These processes are controlled by a software sketch. The data is received and processed in a continuous process of data exchange between the board and the computer data logger. The user interface of the latter, written in Processing as open-source software, allows you to control the operation of the devices.

2.3. Device for water activity determination

One of the most important chemical components of any food system is water, which affects their chemical, physical, and microbiological stability. An important parameter for monitoring the specified stabilities in food systems is water activity.



(**a**) (**b**)

Figure 2. An Arduino-based water activity data acquisition device of foodstuff: (**a**) Photograph of a device connected to a computer; (**b**) Screenshot of the user interface for monitoring the change in water activity and temperature over.

This parameter, within the framework of the thermodynamic concept, is related to the partial specific Gibbs free energy of the system, which is required in the study of the necessity of the system being in equilibrium at a given temperature. When this equilibrium is reached, the activity of water within a satisfactory approximation is equal to the relative humidity of the air around the sample in the hermetic measuring chamber. This allows for measurements to use relative humidity sensors that change electrical resistance or capacitance. The advantages of capacitive sensors are simple design and low-cost implementation. The latter technology was the basis for the development of a device for determining the water activity of food systems (Figure 2a).

This device was used in laboratory studies to determine the water activity of food systems and the influence of various factors such as formulation ingredients, packaging, and storage conditions. Such knowledge is important for future technologists of food production.

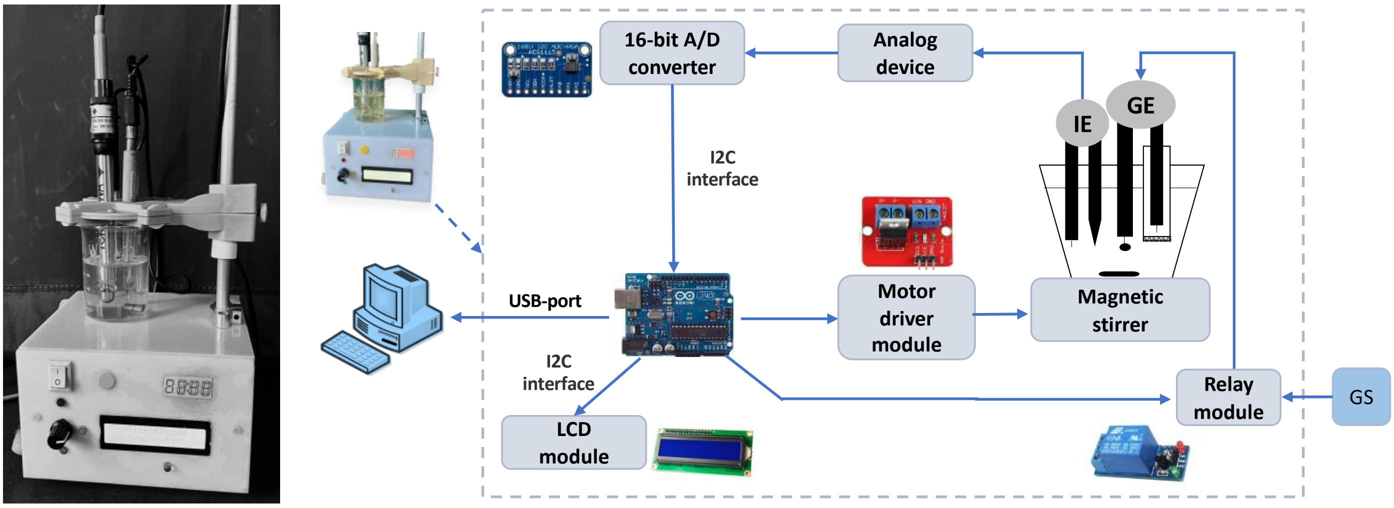
The device utilizes an Arduino Nano board [1] and module SHT31-D (Adafruit Industries, New York) connected via a I2C interface to or control and data acquisition (Figure 1). The SHT31 temperature sensor and characteristics (Sensirion AG, Stäfa, Switzerland) has a high relative accuracy of ±2% and an accuracy of ±0.3°C, which is sufficient for most educational tasks.

During use, the Arduino plugs into a standard USB port on any computer to provide power and data collection capabilities (Figure 2a). The data logger software used to control this device and monitor the change in water activity and temperature over time until the moment of equilibrium. The user-friendly interface of the software shows two separate graphs of water activity and temperature values (Figure 2b). Experimental data are duplicated in digital form both on the LCD display of the instrument and on the computer screen. In addition, the data is output as a tab-delimited text file and can be easily displayed and analyzed in any spreadsheet or graphing program.

The instrument was validated at the measurement temperature using a series of standards, which were saturated salt standards [4].

2.2. Device for constant-current coulometric titration

The coulometric method of chemical analysis is an absolute method based on the Coulomb law, which is distinguished by its simple implementation and high accuracy of experimental data. Therefore, it is quite often included in the course of quantitative analysis for pedagogical purposes [5].



(**a**) (**b**)

Figure 3. An Arduino-based water activity data acquisition device of foodstuff: (**a**) Photograph of the device; (**b**) A general Arduino-based circuit for constant-current coulometric titration equipment with potentiometric indication of the titration end point.

There are two types of coulometric techniques [6], one of which, namely current-constant coulometric titration, has been realized by the development of the Arduino-based devices for electronic data acquisition (Figure 3a). A glass chemical beaker with a capacity of 50 ml is used as a coulometric cell (Figure 3b)). Two pairs of electrodes generating (GE) and indicator (IE) are immersed in it. The generating electrodes are a platinum electrode with an area of about 2 sq cm, placed in the main beaker, and a wire platinum electrode, located in a separate 5 ml glass chamber with a glass membrane. The indicator electrodes are platinum redox and silver-chloride electrodes. A glass chemical beaker with a capacity of 50 ml is used as a coulometric cell. Two pairs of electrodes generating (GE) and indicator (IE) are immersed in it. The generating electrodes are a platinum electrode with an area of about 2 sq cm, placed in the main beaker, and a wire platinum electrode, located in a separate 5 ml glass chamber with a glass membrane. Indicator electrodes are platinum redox and silver chloride electrodes. The analytical signal from the indicator electrodes is fed to a portable lab pH/ion meter with an analog output, or to a built-in own module with an operational amplifier.

The device utilizes an Arduino Uno and commercial modules for control and data acquisition:

- an ADS1115 module (Adafruit Industries, New York, USA) as a high-precision 16-bit A/D converter at 860 samples per second over I2C interface, which provides higher resolution data acquisition than is possible only with the Arduino Uno.
- LCD display 1602 (HiLegto Technology Co., Shenzhen, China), based on the HD44780 controller, to display information about the progress of the titration in the form of an analytical signal-time;
- MOS module based on MOSFET transistor IRF520N (HiLegto Technology Co., Shenzhen, China) as a simple motor driver for PWM control of DC motor of magnetic stirrer;
- a single-channel 5V relay module with high/low level trigger (HiLegto Technology Co., Shenzhen, China) as a switch that turns on or off the supply from the potentiostat/galvanostat (GS) of a given constant current to the generating electrodes (GE).

During use, the Arduino is connected to a standard USB-port on any computer to supply power and enable data acquisition. The software allows you to display experimental data both on the LCD display of the instrument and on the computer screen, and save it as a tab-delimited text file.

3. The use of Arduino-based equipment's for analytical and educational applications

The operability of the coulometric titration equipment has been confirmed by the validation of various chemical analysis methods. Let us show this by the example of data on aqueous solutions of ascorbic acid (AA), which are used as a standard in the determination of this antioxidant in food systems. The content of AA was determined by titration with electrogenerated iodine at a constant current strength of 5 mA. The validation procedure included the following parameters: specificity, linearity range of the analytical method, detection and determination limits, accuracy, and repeatability. The dependence of the quantity of electricity on the AA amount in solution has a linear relationship with a high determination coefficient (Table 1).

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

Parameter	Magnitude	Regression equation Y=a+b·X	Magnitude
Linearity range, μg/g	49.2-1276	Slope, b	1.0966
Limit of detection, μg/g	16.2	Intercept, a	35.238
Limit of determination, μg/g	49.2	Determination coefficient	0.9993

The slope of the experimental linear regression equation equal to 1.0969 does not differ significantly from that calculated according to Faraday's law of 1.0956 ($p < 0.05$), which confirms the specificity of the method. The accuracy of the method is confirmed by the results obtained by the "taken-found" methods for five aqueous solutions of AA of various concentrations of the operating range. According to Table 2, the results were obtained at the level of RSD < 0.83%, which does not exceed 1%, which indicates the absence of a systematic error.

Table 2. Results of analysis of aqueous solutions of ascorbic acid.

Amount taken, μg/g	Amount found*, μg/g	Recovery ± RSD, %	Variation, %
124.0	124.2 ± 1.6	100.2 ± 0.8	+0.16
250.8	252.2 ± 2.1	100.5 ± 0.5	+0.44
482.5	483.0 ± 3.2	100.1 ± 0.4	+0.23
852.4	848.5 ± 3.3	99.5 ± 0.2	–0.46
1277	1280 ± 8.0	100.2 ± 0.4	+0.23

* Average as the result of 5 replicate measurements, $p < 0.05$.

The developed device was used both in educational laboratories and in scientific research of PhD students. Recent research is most characterized by the use of constant-current coulometric titration. This allowed us to obtain reliable data in two directions of research:

- to determine the content of individual compounds in the food matrix, for example, iodine in algae [7] or ascorbic acid in fruit jelly [8];
- determination of the total antioxidant capacity of food systems such as marshmallows and marmalade [9], candy caramel [10], grape seeds powder [11].

For most food systems, water activity values were obtained that are in good agreement within the accuracy of the sensor with research data from other authors obtained using more accurate and expensive instruments.

4. Conclusion

This report provides a description of two electronic devices for DC coulometric titration and determination of water activity as a tool for both educational and research laboratories in the chemical analysis of food systems. The proposed design is based on the use of a 16-bit data acquisition device based on an Arduino controller with open-source software. One of the important features of the development is its low price compared to commercial products and the lack of access to commercial software licenses. This design is an economical option for use in virtually any environment that requires time dependent signal processing. In addition, a number of obvious advantages in the organization of the educational process are achieved:

- shifting the focus of the student's attention to the essence of physical and chemical phenomena instead of routine work to obtain the results of the experiment;
- gaining experience with automated process control systems as an integral part of the modern industry;
- increasing the motivational component of the student in the cognitive cycle of task-realization-result;
- activation of the student's independent work on the formation of skills in the latest information and communication technologies with the possibility of their use in future professional activities.

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