The use of open-source hardware and software in low-cost geotechnical sensors: a strain-gauge logger and a tilt-test machine

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ABSTRACT: The laboratory equipment is commonly expensive, making its acquisition difficult for laboratories and universities with low budgets. This problem could be solved with the use of open source software and hardware. Last decade, different initiatives were born that promulgate the use of these technologies for the design and construction of low-cost devices. Two of these initiatives, Arduino project and Raspberry Pi project, could be used for the design of sensors, loggers, and machines useful for a rock mechanics laboratory. Two examples of these technologies are a very low-cost strain-gauge logger and a control mechanism for a tilt test machine. These two devices have been designed, manufactured, and tested. Their performance satisfies the needs of a rock mechanics laboratory, proving the utility of these open source initiatives for this purpose.

1 INTRODUCTION

Sensors used in geotechnics are, in most cases, very expensive. This can be a problem for some researchers and technicians, especially in developing countries, small companies, and educational centres. The development of simple and inexpensive sensors may be a great opportunity for every researcher, and it may allow improving testing methods in both laboratory and in-situ rock mechanics.

Since the beginning of the 21st century, different companies and research groups have started projects for developing open-source hardware, initially for educational purposes. Today, some of these projects have created numerous devices that allow people without much knowledge in electronics to design and build complex electronic devices. The most widespread platforms are Arduino and Raspberry Pi, both with an active community of users who share and discuss their projects through the internet.

The capabilities of commercial sensors are almost impossible to reproduce in "handmade" sensors. However, the requirements are much lower in most projects. To use Arduino and related technologies, only a basic knowledge in electronics is required to fabricate a simple sensor for a given project. The low cost of these kind of sensors, together with their somewhat quick and easy manufacturing, make them ideal for research projects.

Here we present the prototype of a strain-gauge data logger with a simple design based on Arduino, as an example of what can be done with these open-source technologies. Figure 1 shows a photo of the first prototype. We also present the control unit of a tilt-test machine based on Raspberry Pi microprocessor and Python programming.

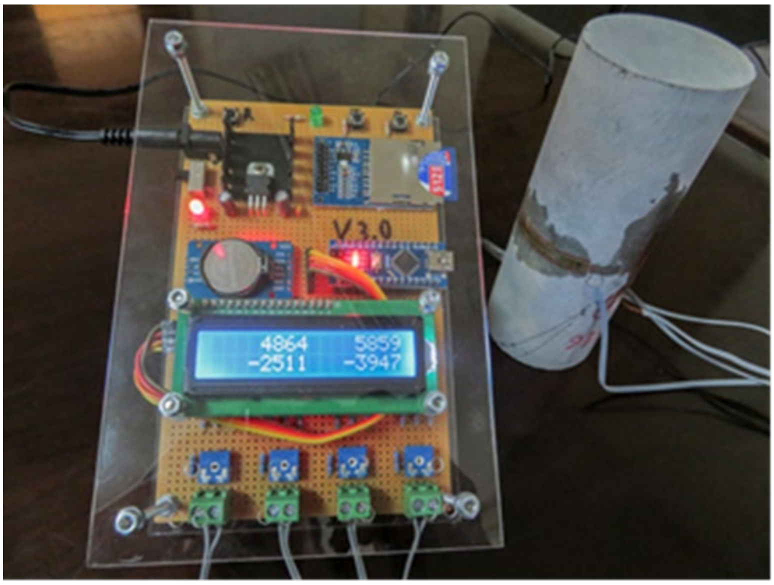

Figure 1. Strain-gauge data logger based on Arduino prototype.

2 STRAIN-GAUGE DATA LOGGER

2.1 *General description*

Part of the "Arduino philosophy" is the use of preassembled boards that contain all the electronic components needed for the use of a certain sensor, actuator, logger, etc. The use of preassembled boards simplifies the design and fabrication of electronic devices. People with a basic knowledge in Electronics may be able to design and make many different electronic devices in an easy, quick, inexpensive, and safe way. The device presented here uses this kind of boards for signal conditioning and amplification, data visualization, data record, etc.

The electronic components are soldered onto a prototyping circuit board. All the components are protected by two PVC plates.

The design can be divided into three main elements: the Wheatstone bridge and signal conditioner, the microprocessor, and the data record and display. Figure 2 shows the basic circuit diagram of the prototype.

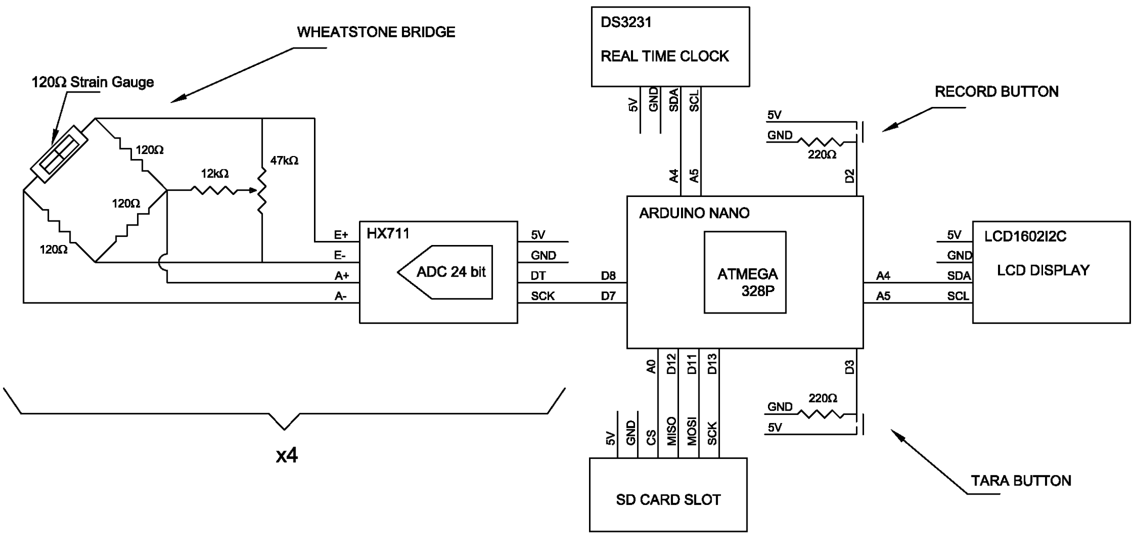

Figure 2. Simplified circuit diagram of the data-logger prototype.

2.1.1 *Signal conditioning and amplification*

The strain gauges are connected to a classic Wheatstone bridge circuit in a quarter-bridge configuration. The bridge is directly connected to a HX711 module for the amplification and conversion of the signal to digital. This board could amplify the signal up to 120 times and has a 24-bit analog-to-digital converter (ADC).

2.1.2 *Microcontroller board*

Arduino is an open-source electronics platform based on easy-to-use hardware and software created by an international team in 2005. This project, born in Italy, has produced several microcontrollers and software codes that allow the development of any kind of electronic devices for many different purposes, and for educational, domestic, and professional use. Arduino has a very active community all around the world that shares designs and advice. It is already used by many researches and technicians in Rock Mechanics (e.g. Hernandez-Uribe et al. 2017), as well as in many other science fields (e.g. D'Ausio 2012; Fuentes et al. 2014; Lockridge et al. 2016; Schubert et al. 2013).

The plans of the Arduino boards are published under a Creative Commons license, permitting other hardware designers than the Arduino Company to manufacture and sell these boards. This fact makes it easy to get boards for low prices.

This prototype uses an Arduino Nano board (Figure 3). Arduino Nano is a small, complete, and non-expensive board based on an ATmega328 microcontroller. This microcontroller has a clock speed of 16 MHz and 32 kB of memory and 2 kB of SRAM. It allows up to eight analog inputs and 22 digital input-outputs. The operating voltage of the board is 5V DC and can be powered directly by a Mini-B USB cable.

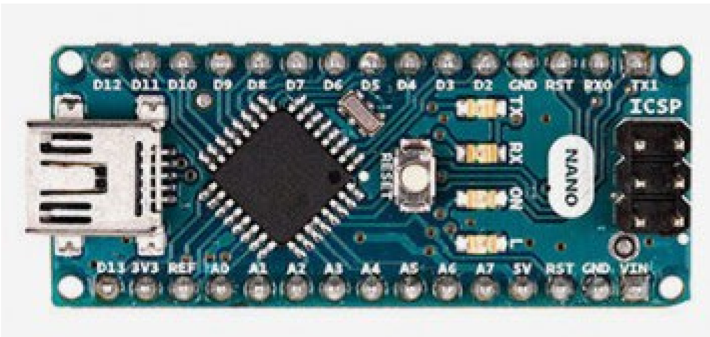

Figure 3. Arduino Nano board (www.arduino.cc).

2.1.3 *Data recording and visualization*

The data are recorded in a SD card memory. The characteristics of the microcontroller give a maximum capacity of 512 MB for the SD card. This amount of memory is more than enough for a long-time test log. The real-time visualization of the data is made through an LCD panel with 2 lines of 16 characters LCD1602i2C. The screen is self-illuminated, allowing the use of the logger in low-light conditions.

2.1.4 *Other sub-circuits*

The prototype is completed with other sub-circuits:

A 5V voltage regulator, based on L7805CV chip, which allow the use of any adapter power supply or batteries from 9 to 14V DC.

The design also includes two buttons for the starting of the recording and a tare button, as well as two LEDs for functional indications.

2.2 *Software*

The microcontroller was programmed in Arduino code. This code is a simplified version of C/C++ code (C/C++ is also supported). The coding could be easily made using the Arduino IDE: this tool allows an easy and direct uploading of the program to the microcontroller. The code is released under the GNU General Public License. The control of the boards used is easy programmed through a large number of libraries shared in the internet by the fabricator and the users following the open-source philosophy of the Arduino project.

The code used in the project we present here is available in the web hosting service GitHub: https://github.com/mauromuniz/Rock_Mechanics

2.3 *Technical Specifications*

Table 1 shows the main technical specifications of the design.

Table 1. Prototype data logger specifications.

Microcontroller board	Arduino Nano
Microcontroller	ATMega328P
ADC type	HX711
ADC Resolution	24 bits
Channels	4
Maximum strain	$5.9 \cdot 10^{-2}$ m/m
Sensitivity	$3.5 \cdot 10^{-9}$ m/m
Resolution	10^{-6} m/m
Memory	SD card
Max memory	512 MB
Max sampling rate	0.5 sec^{-1}
Weight	270 g
Size	170 x 110 x 55 mm
Power supply	9 - 14V DC

2.4 *Costs*

The main objective of this project was to design a low-cost logger, so we tried to reduce the costs as far as possible.

The micro controller board used was a Toogoo® Nano V3.0 with a cost lower than four euros. The HX711 and the SD boards can be bought for less than two euros each. The real time clock DS3131 can be buy for less than one euro. All the other electronic components do not have a cost higher than a few cents. The total price of the prototype was lower than €30 (US$34). This price includes the delivery costs. The cost of this prototype is much lower than the cost of the data logger present in most of the rock mechanic labs.

2.5 *Weak points*

During the assembling and testing of the prototype we detected some weaknesses on it.

First, we have noticed a low sampling rate. Our device cannot record more than two samples per second. This may be due to the microcontroller programming and it could be improved modifying the code. However, this sampling rate is high enough for rock mechanic pseudo-static tests such as uniaxial compression test.

Another issue we have detected is some drift of the data during the first minutes after the logger is switched on. This is due to the heating of the electronic component. After 5 to 10 minutes the readings stabilise, so we recommend turning on the device at less 15 minutes before the test.

2.6 *VALIDATION TEST*

To validate the prototype, we carried out a uniaxial compression (UCS) test while measuring the deformation of the rock specimen with eight strain gauges—four vertical and four horizontal—.

Four of the gauges were measured through the prototype and four through a signal conditioner SV111 designed by the company SERVOSIS for the control of the loading machines of the CEDEX rock mechanics laboratory. After the test, we compared the average strain of the vertical gauges and the horizontal gauges of both loggers. The results are shown in Figure 4.

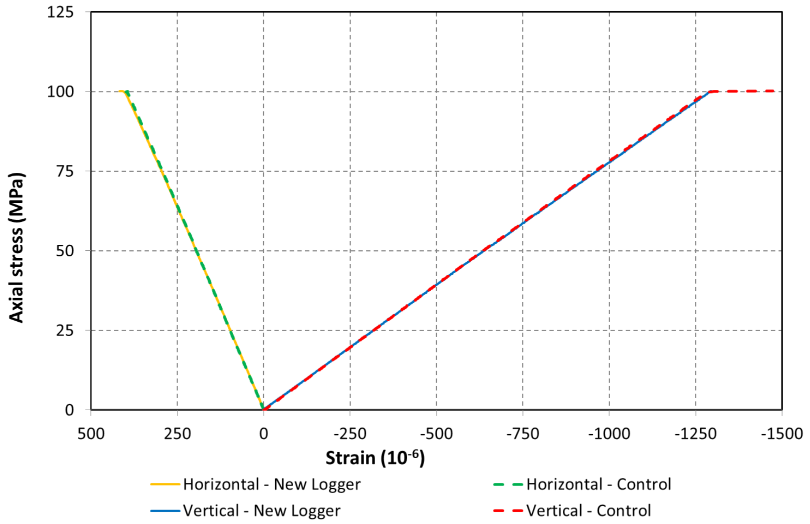

Figure 4. Strain results of the validation test.

We calculated the Young's modulus (E_i) and the Poisson's ratio (ν) with the strains of the two groups of four gauges. The differences between the two loggers are close to cero (Table 2). These results validate the prototype for, at least, the use in laboratory rock mechanics tests in pseudo-static conditions.

Table 2. Comparison between prototype and SV-111.

	E_i (GPa)	Poisson ratio (ν)
Prototype	77.25	0.314
SV-111	77.62	0.308
Difference (%)	0.48	1.80

3 TILT-TEST MACHINE CONTROL UNIT: FIRST STEPS ON THE DEVELOPMENT

The tilt test is commonly used in rock mechanics laboratories and rock engineering projects as a straightforward, sufficiently reliable and affordable technique for estimating the basic friction angle of planar rock surfaces. In addition, the procedure for obtaining this parameter through the tilt test has been recently published in the format of an ISRM Suggested Method (Alejano et al. 2018). Based on a former study, which aimed at assessing the influence of the tilting rate of the testing platform on tilt-test results (Pérez-Rey et al. 2016), we modified the original tilting machine in our rock mechanics laboratory. Years later, with the arrival of single-board computers (SBC), it was decided to improve the system. On the one hand, basic operations (like start, stop and selection of tilting rate) were implemented in a Python program, allowing the remote control of the tilting platform through the SBC, via the RS232 standard with a serial port.

3.1 *The original tilt-test machine*

The original tilting platform for tilt tests available at 'John P. Harrison' rock mechanics laboratory (University of Vigo) was designed in 2011 and consisted of a metal frame with a mobile platform, which is connected to an endless screw (Figure 5). The movement of the machine is carried out through a gearbox connected to an asynchronous motor, controlled, in turn, by a

Siemens Synamics G110 frequency inverter. Originally, this machine only allowed testing at constant tilting rates of about 24 °/min (corresponding to an AC utility frequency of 50 Hz). The control has two switches, one for lifting the platform and the other one for lowering it, which originally required a constant touch while running the test. The machine is complemented by two safety limit switches to automatically stop the machine either when the starting position or an inclination of about 50° are reached.

Figure 5 Original tilt-test machine in the 'John P. Harrison' rock mechanics laboratory of the University of Vigo (Photo courtesy of Javier González).

The main advantage of this tilt-test machine with respect to typically commercialized hand-operated ones, is the possibility of keeping an almost constant lifting velocity during the entire test. This significantly reduces the vibrations, which represent an undesired effect that may mask results, as recently studied by Alejano et al. (2017). Different tilt test series encompassing more than 1000 results were successfully carried out in our laboratory with this machine (Alejano et al. 2012; González et al. 2014; Pérez-Rey et al. 2015).

3.2 *First upgrade of the tilt-test machine*

Different laboratories performed tests at different velocities ranging from 2 to 25°/minute, depending on their own experience, technical capabilities or available equipment. Aiming to cover tilt testing velocities reported in the literature, which are 2.5°/min (USBR 2009), 8°/min (Bruce et al. 1989), 23°/min (Ruiz & Li 2014) or 24°/min (Alejano et al. 2012), the original control system of the presented tilt-test machine was modified, by connecting a variable resistor to the frequency inverter, allowing to perform tests from almost 0.5 to 25 °/min. Moreover, the original control was replaced by one with three switches, in such a way that this new device allows lifting, stopping and lowering the platform with just a touch. This has also improved the test comfort for the operator. As a result of this upgrade, it was possible to experimentally evaluate the effect of tilting rate on tilt-test results with reasonable success (Pérez-Rey et al. 2016).

3.3 *Last update of the tilt-test machine*

Taking into account the evolution of electronics and software and, particularly, high-level programming (such as Python), it seemed appropriate to try to improve, by using these technologies, the performance of tests with this tilt-test machine. The first thing that was proposed was the possibility of registering the vibrations during the test—which nowadays can be carried out by using an inexpensive (less than four American dollar) but sufficiently accurate Inertial Measurement Unit (IMU)—, as well as the automatic stoppage of the machine at the exact moment of sliding of the upper tilt-test specimen. A break-beam infrared sensor will carry out this task.

Prioritizing the use of low-cost technologies such as those described in this paper, it was first necessary, prior to read data from any sensor, to be capable of controlling the frequency inverter and, therefore, the start, stop and velocity of the motor through the operating system (Raspberry Pi-3b). For this, a detailed assessment of the operating interface in digital mode of the Siemens Sinamics G110 frequency inverter has been required. This interface is known as Universal Serial Interface Protocol (USS® protocol), and consists of an access technique according to the master-slave principle for communications via a serial bus. Essential features of the USS ® protocol are:

- Support of a multi-point-capable coupling (i.e. EIA RS232 or EIA RS485 hardware)
- Master-slave access technique
- Single master system
- Max. 32 nodes (max. 31 slaves)
- Simple, reliable telegram frames
- Ease of implementation
- Operation with either variable or fixed telegram lengths

A detailed description of the USS® protocol is provided by Siemens (1994) and has been omitted in this paper for the sake of briefness. In summary, the communication is made by sending and receiving telegrams from the master (in this case, the Raspberry Pi-3b) and the slave (frequency inverter Siemens Sinamics G110), with the following structure: Each telegram starts with the STX start character (= 02 hex), followed by the length specification (LGE) and the address byte (ADR). Then, the net characters follow, indicating the corresponding task assigned. The telegram is terminated by the BCC (block check character).

Taking advantage of the GNU *nano* text editor, included in the GNU *Raspbian* (Raspberry Pi-3b), a Python script that allowed to implement the telegram transfer, the telegram structure and data transfer through serial communication (RS232) to the Sinamics G110 was developed. The electronic assembly of the Raspberry pi and the frequency inverter is provided in Figure 7.

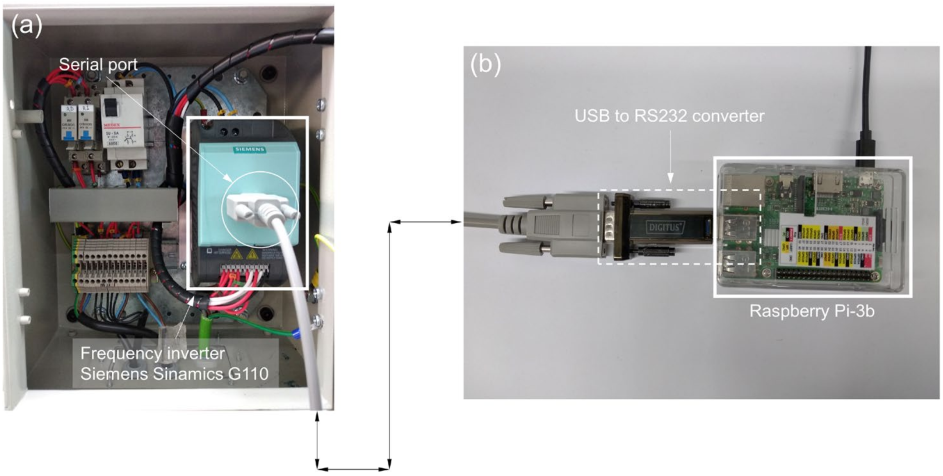

Figure 6 Electronic assembly between the slave (frequency inverter) (a) and the master (Raspberry Pi 3b) (b) via RS232 protocol.

The communication between the Raspberry Pi 3b and the frequency inverter has been established for starting, stopping, and frequency selection (tilting rate of the platform). These operations can be carried out via Secure Shell (SSH) protocol from any common computer equipped with a UNIX or LINUX-based operating system and connected to the internet.

4 CONCLUSIONS

We expose two examples of the possible use of open-source hardware and software for the design of low-cost laboratory equipment.

We present a low-cost strain-gauge data logger prototype, based on Arduino technology, which can be directly used in a rock mechanics lab. We also present an incipient project for the control of a tilt test machine based on Raspberry Pi technology. The validation tests have proved that the first equipment is valid for the desired use, although some development is still necessary for the second one, as well as the creation and upgrading of a user-friendly interface.

The advantages of this technology are: its low cost, its versatility, and its ease of ad hoc design and production. These technologies could also be useful for education and training purposes, allowing the students to learn the performance of sensor and data loggers, which enables an easy design of tests and experiments for the learning of rock mechanics and any other geotechnical subject.

All in all, open-source hardware and software could be a very useful tool for research centres and universities, mainly those with low budget, such as small research groups or those located in developing countries.

The creation of an online platform where rock mechanics practitioners could share its open source designs may be very rewarding, following the philosophy of Arduino and Raspberry Pi platform, where the members of the community could help each other and contribute to the spreading of these tools.

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