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Fabrication of an Economical Arduino-Based Uniaxial Tensile Tester

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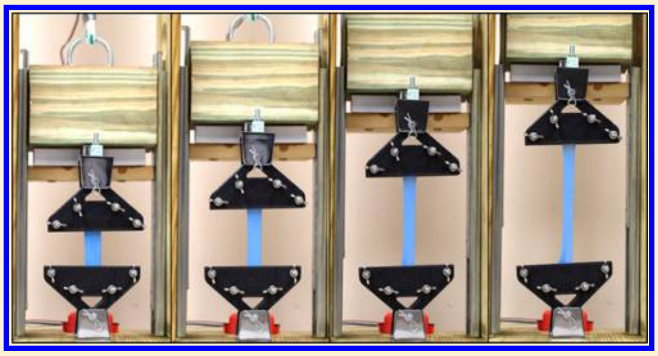
Supporting Information



ABSTRACT: The mechanical properties of soft materials are critically important for a wide range of applications ranging from packaging to biomedical purposes. We have constructed a simple mechanical testing apparatus using off-the-shelf materials and open-source software for a total cost of less than $100. The device consists of a wooden frame supporting a central loading apparatus attached via drawer slides. To perform a mechanical test, a sample is secured within two custom-made 3D-printed clamps affixed to brackets on the base of the frame and the load cell. The extension force is applied by the user pulling on a rope, moving the central loading apparatus up (thereby stretching the sample) while recording the force (measured by a load cell) and the displacement (measured by an ultrasonic sensor). The load cell and ultrasonic sensor are linked to an Arduino microcontroller connected to a laptop through a USB port for data acquisition and analysis. This instrument was easy to assemble and enabled students to better grasp the meaning of tensile testing while promoting experimentation with electronics, computer programming, and mechanical design. Because of its low cost and ease of use, this Arduino-based uniaxial tensile tester can be an ideal device to introduce the concepts of mechanical properties, among other concepts, to students in numerous fields.

KEYWORDS: *Second-Year Undergraduate, Upper-Division Undergraduate, Interdisciplinary/Multidisciplinary, Computer-Based Learning, Hands-On Learning/Manipulatives, Instrumental Methods, Laboratory Computing/Interfacing, Laboratory Equipment/Apparatus, Materials Science*

INTRODUCTION

The mechanical properties of a material relate to how it responds to mechanical stress. These properties are critical in determining a material's suitability for potential applications. Uniaxial tensile testing is the most common procedure used to measure these mechanical properties, which include the Young's modulus, yield strength, and ultimate tensile strength, among others. Commercial tensile testers are highly accurate, but their cost and size make them impractical for hands-on-learning in a classroom setting.[1] Furthermore, they often require costly proprietary software to operate with restrictive software licensing agreements. Recently, open-source electronics have been used to build hardware/software systems that are yet not commercially available or otherwise too expensive.[2] Among them, the popular Arduino microcontroller has already proven effective in controlling scientific hardware for research purposes[3−7] while also serving as a practical platform for the training of students.[8,9] Previous educational applications of the Arduino platform include the fabrication of a photometer,[10] an automatic titrator,[11] a pH meter,[12] a gas sensor,[13] an electronic buret,[14] and a potentiostat.[15] Our objective was to develop an inexpensive and portable mechanical tester that could be used for both accurate measuring and educational purposes. Because of its flexibility, low cost, ease of use, and wide range of successful applications, we decided to use an Arduino microcontroller to develop our tester, combining it with simple off-the-shelf components.

MATERIALS AND METHODS

The mechanical tester consists of a wooden frame with a central loading apparatus attached via drawer slides to allow for uniaxial translation, provided by a rope and pulley system (via manual application of force to the rope by the user). The central loading apparatus consists of a wooden block with a rope attachment point on top with a mounting bracket for the load cell on the bottom. Sample holding clamps with symmetric interlocking teeth were designed and 3D-printed (the STL file is available in the Supporting Information). The clamps were attached to both the frame and the load cell via mounting brackets with clevis pins, as shown in Figure 1.

In order to determine the mechanical properties of a sample, two parameters need to be recorded: the load applied to the sample and its extension. In order to measure the load, a 5 kg micro load cell (combined with an INA125P amplifier) was

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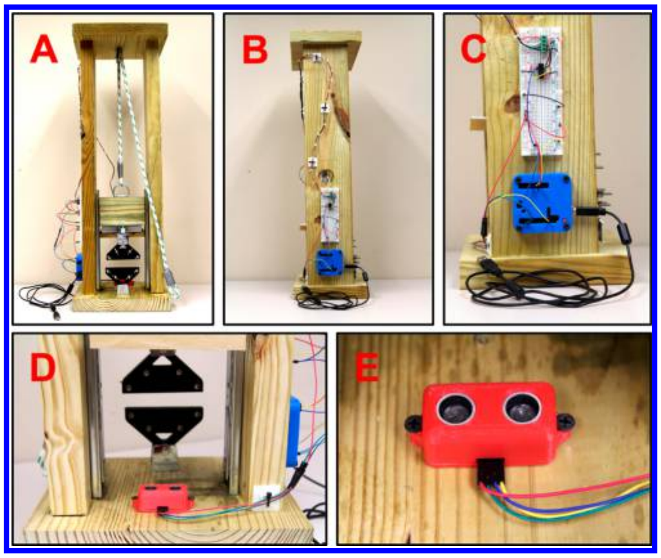

Figure 1. Several different views of the mechanical tester. The front view (A) shows the overall assembly of the tester, comprising a wooden frame, a rope-and-pulley system, a central loading apparatus with attached load cell, two sample clamps (black), and the electronics (left). The side views (B and C) reveal the circuitry, consisting of a breadboard (white), an Arduino Uno (in the blue case), and the USB interface for connection to a computer. The back views (D and E) reveal the placement and design of the ultrasonic proximity sensor (in the red case), with attached leads. More detail on the circuitry can be seen in Figure 2. More information on the materials is presented in the Supporting Information.

placed in series with the sample (prior to sample runs, the load cell circuit was calibrated via a linear two-point calibration spanning the sampling range). The extension was measured with an HC-SR04 ultrasonic sensor that measured the distance between the frame and the central loading apparatus to which the load cell (and upper sample clamp) were attached. This sensor works by emitting an ultrasonic pulse that reflects off the central loading apparatus and is subsequently read by the sensor; the time interval between the signal emission and detection is used to calculate the distance. Both sensors were connected to the Arduino Uno microcontroller, as shown in Figure 2.

The Arduino Uno was connected via a USB interface to a laptop running the Arduino Integrated Development Environment (IDE). Values were recorded every 100 ms during a sample run and subsequently exported to Microsoft Excel for processing.

RESULTS AND DISCUSSION

The total material cost to build this mechanical tester was under \$100 (the bill of materials is available in the Supporting Information). This apparatus is lightweight and compact, rendering it readily portable. The inexpensive, off-the-shelf load cell and ultrasonic sensor resulted in accurate and precise measurements. The resulting mechanical properties determined with our Arduino-based mechanical tester were comparable to those obtained with a commercial United SSTM-2 tensile tester, as shown in Figure 3 and Table 1.

A stress−strain curve represents the behavior of a material during mechanical testing. Stress is defined as the force applied divided by the area. For a tensile test, the relevant area is that perpendicular to the applied force (in this case the cross-sectional area). Strain describes the elongation with respect to

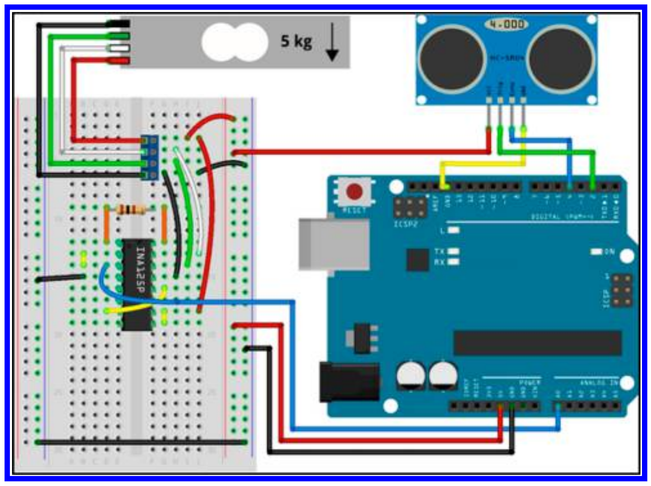

Figure 2. Wiring configuration for the 5 kg load cell (gray, top, silver bracket in Figure 1) and the ultrasonic proximity sensor (blue, top, depicted within the red enclosure in Figure 1) connected to the Arduino Uno microcontroller (blue, bottom-right, blue enclosure in Figure 1). A breadboard was used to connect these components with the addition of a 100 Ω resistor and an INA125P signal amplification chip. More information on the wiring is available in the Supporting Information. Created with Fritzing 0.9.3b.

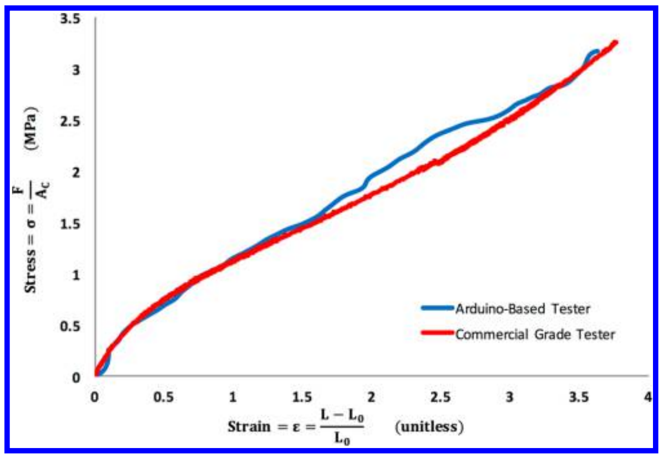

Figure 3. Side-by-side comparison of the Arduino-based tester developed herein (blue curve) and the commercial-grade tester (red curve; UNITED SSTM-2) for samples cut from a latex glove. Stress (on the ordinate axis) is the force F (as measured by the load cell) divided by the cross-sectional area A_c of the sample (calculated as the thickness of the sample times its width); strain (on the abscissa) is the amount of elongation with respect to the original length L_0 of the sample. From this graph, the ultimate tensile strength (UTS) is the maximum stress obtained prior to failure, and the Young's modulus is calculated by fitting a straight line to the initial part of the tensile curve (tangent modulus determined in the linear elastic region).

the initial length of the sample. The ultimate tensile strength represents the maximum stress that a material can withstand before breaking. The Young's modulus or elastic modulus of a material is defined as the slope of its stress−strain curve in the region of elastic deformation. Representative stress−strain curves for latex glove samples obtained from both the Arduino-based mechanical tester and the commercial uniaxial tensile tester (United Smart Table SSTM-2, Flint, MI) are provided in Figure 3 as a means of comparison between the two systems.

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Table 1. Mechanical Property Value Comparison for Tested Samples

Sample[a]	Thickness[b]	Young's Modulus[c]		Ultimate Tensile Strength[c]	
		Arduino	Commercial	Arduino	Commercial
Latex glove	110 μm	730 ± 10 kPa	740 ± 10 kPa	3.2 ± 0.1 MPa	3.3 ± 0.1 MPa
Nitrile glove	70 μm	2.3 ± 0.3 MPa	2.4 ± 0.2 MPa	4.4 ± 0.1 MPa	4.4 ± 0.1 MPa
Parafilm	130 μm	52 ± 5 MPa	57 ± 7 MPa	2.4 ± 0.2 MPa	2.4 ± 0.1 MPa
Biohazard bag	70 μm	133 ± 6 MPa	135 ± 5 MPa	11.8 ± 0.1 MPa	11.6 ± 0.1 MPa
Trash bag	40 μm	55 ± 4 MPa	52 ± 3 MPa	8.4 ± 0.1 MPa	8.2 ± 0.2 MPa
Gauze	300 μm	1.2 ± 0.1 MPa	1.4 ± 0.2 MPa	5.9 ± 0.3 MPa	6.1 ± 0.2 MPa

[a]All samples were cut into 20 mm × 65 mm rectangles and clamped such that ~30 mm of sample was available for testing (i.e., between the clamps). As is evident, the Arduino-based tester values are in excellent agreement with those for the commercial-grade tester. Furthermore, the error in each value is quite low because of the commercial production (and regulation) of each of the materials tested. [b]The material thickness was measured with a digital caliper. [c]$n = 3$ for each; values are presented as mean ± standard deviation.

Several household and common laboratory items were used as samples for mechanical testing. Each sample was stretched until failure, and the resulting Young's modulus and ultimate tensile strength values are reported in Table 1. Samples were selected such that they would provide qualitative feedback for students during a sample run; this was accomplished by selecting samples with high strain rates at failure (so the student could witness a large degree of stretching) and fairly high, though obtainable, ultimate tensile strengths (so the student could feel the increasing force required to continue stretching the sample until failure). All of the samples tested were prepared with the same dimensions so that the geometry of the sample did not influence the result of the analysis.

Mechanical testing allowed us to illustrate the differences among mechanical behaviors. After some stress was applied to them, nitrile and latex gloves returned to their initial dimensions, thereby characterizing their deformation as elastic, reversible, and nonpermanent. For the trash and biohazard bags, however, permanent and irreversible plastic deformation was observed. The ability to characterize such deformations distinctly demonstrates the wide applicability of this device to a broad range of materials and thus a wide range of fields and disciplines.[1,16]

We believe that this mechanical tester is an ideal tool for project-based learning. We tested six different materials in order to determine the differences among them and validate the device. Many different samples could be tested by students, and their resulting values could be compared with reference values reported in this or other sources (of special interest could be the comparison of material properties with standard specifications such as ISO and ANSI). Students could also be asked to produce a composite material and try to match some target mechanical properties by altering its layers and composition. Having students replicate tests of the same type of sample could also be used as an introduction to some basic statistics concepts.

Furthermore, building this mechanical tester could be defined as a group project for upper-division undergraduate students. The Arduino IDE is downloadable for free online, and the Arduino programming language is simple and intuitive. Other resources are available to automate and visualize the process of data collection, such as the Excel spreadsheet PLX-DAQ.[17] Implementation of such open-source electronics in a curriculum has been shown to develop complementary skills for the students as well as to bring an extra element of interactive engagement with students.[18,19]

This mechanical tester could easily be modified for a variety of different tests. The 5 kg micro load cell could be replaced to adjust the reading range of the device (from 0.5 kg to 20+ kg) in order to better accommodate various samples. A stepper motor could be used instead of the rope and pulley mechanism, in order to provide a constant strain rate (though this would increase the cost of the device). Finally, this mechanical tester could also be modified for compression testing instead of stretching.

One final advantage of this device is that all of the parts and sensors used could easily be reused for other projects. The Arduino microcontroller has already been used for different applications as described earlier. It is possible to imagine that the same Arduino microcontroller could be used for several active-learning class activities throughout a semester.

■ CONCLUSION

We have described the fabrication of an easy-to-use uniaxial tensile tester for a total cost of less than $100. The simplicity and flexibility of the Arduino platform suggests that this is a practical, accurate system for hands-on demonstrations for the determination of the mechanical properties of several different materials. The experiments detailed herein, which can be applied to a wide variety of disciplines, were performed with household and common laboratory items as samples. These revealed the accuracy of the system (as compared with an industrial mechanical tester) and allowed for reliable determination of material properties. Though not intended as a replacement for truly quantitative experimentation, this device serves as an ideal platform for hands-on learning, as its construction and use encompasses several disciplines and it lends itself to numerous potential modifications for expansion to further applications.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.6b00639.

Bill of materials, STL file of the 3D-printed sample holding clamps with symmetric interlocking teeth, and Arduino code for the mechanical tester (ZIP)

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Notes

The authors declare no competing financial interest.

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