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Open-source Mobile Water Quality Testing Platform

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Abstract
The developing world remains plagued by lack of access to safe drinking water. Although, many low-cost methods have been developed to treat contaminated water, low-cost methods for water-quality testing are necessary to determine if these appropriate technologies are needed, effective, and reliable. This paper provides a methodology for the design, development, and technical validation of a low-cost open-source water testing platform. A case study is presented where the platform is developed to provide both the colorimetry for BOD/COD and nephalometry to measure turbidity using method ISO 7027. This approach resulted in equipment that is as accurate, but costs between 7.5 and 15 times less than current commercially-available tools. It is concluded that open-source hardware development is a promising solution for the equipment necessary to perform water quality measurements in both developed and developing regions.

Keywords: open-source hardware; nephalometry; water testing; turbidity; COD; BOD

Introduction

Water quality is a major problem in the developing world as roughly 780 million people are still without safe drinking water (Unicef, 2012). Every year about 760,000 children die from diarrhea (WHO, 2013) - largely caused by a lack of clean drinking water and sanitation (Unicef, 2012; Esrey et al, 1991; Cairncross et al., 2010). There are many low-cost methods to provide safe drinking water from known biological and chemical contaminants (Hashmi & Pearce, 2011; Mahmood et al., 2011; Grau, 1996; Brownell et al., 2008; Newton & Wilson, 2008; Brown & Sobsey, 2010; Simonis & Basson, 2013; Khan, Yamamoto & Ahmed, 2002; Mustafa et al., 2013; Buamah, Asare & Salifu, 2013). For example, solar water disinfection (SODIS) has been proven in both bench and field scale trials to significantly reduce microbial content in contaminated water, and associated incidence of diarrhea in users, and techniques have been developed to make SODIS usable in most places in the world (Centre for Disease Control 2008; Meierhofer 2006; Conroy et al., 1996; 1999; 2001; Graf et al., 2010; Rose et al. 2006; Dawney and Pearce, 2012; Dawney et al., 2013). While these simple water treatment methods have demonstrated efficacy, there has been little development of simple and inexpensive water quality assessment instrumentation. This sort of instrumentation is required to know whether or not such methods are 1) needed, 2) effective, and 3) reliable (e.g. in the case of filter blinding). Most importantly they must have a minimal cost in order to be deployed in the field in developing regions.

One promising method to obtain both high-quality scientific tools while radically reducing costs is to use an open-source hardware approach (Pearce, 2012;2013). Due to the tremendous success of free and open source software development (Deek and McHugh, 2007), the concept of open source has spread to areas of both appropriate technology for sustainable development (OSAT) (Buitenhuis, et al., 2010; Stokstad, 2011) and other hardware (Acosta, 2009) such as 3-D printers (Sells, et al., 2009; Jones, et al., 2011; Wittbrodt, et al., 2013), which in turn can be used to fabricate open-source scientific tools (Pearce, 2012;2013; Zhang, 2013). This approach was used recently to combine the open-source Arduino electronics prototyping platform and the RepRap 3-D printer to make an open-source colorimeter, which could be used for water testing using the COD method (Anzalone, et al., 2013). This open-source hardware approach is expanded here to create a platform which could be used for a collection of water tests.

This paper provides a methodology for the design, development, and technical validation of an open-source (OS) water testing platform. A case study is presented where the platform is developed to provide both the colorimetry for BOD/COD and nephalometry to measure turbidity using method ISO 7027 (ISO, 1999). This approach is evaluated for its potential to reduce the cost of equipment to perform these measurements of water quality and the results are discussed to provide conclusions about the future of water testing in developing regions.

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Methods

Design Methodology

The schematic for the built open-source water testing platform was designed to do perform colorimetric COD/BOD and nepheleomatry is shown in Figure 1.

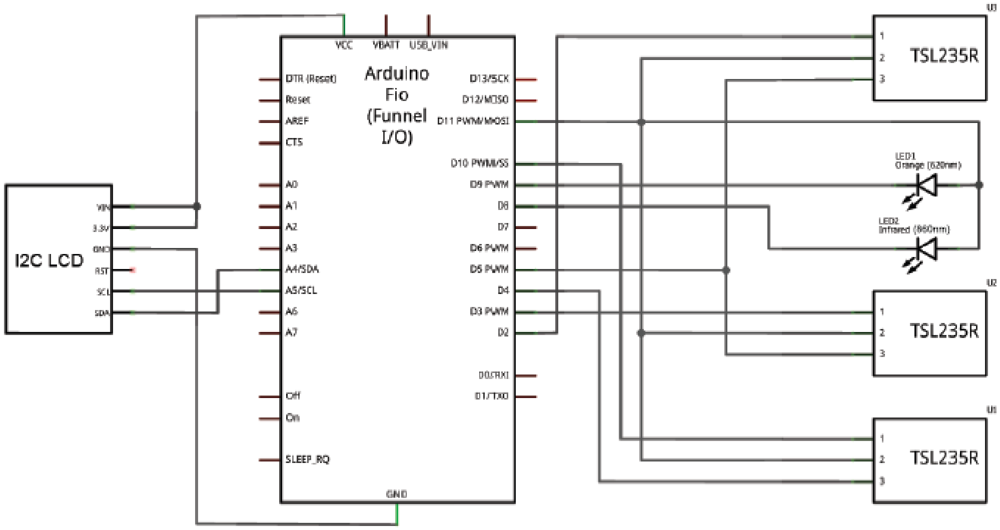

Figure 1. The schematic of the open-source mobile water quality testing platform.

The open-source water testing platform case design was wholly completed in OpenSCAD 2013.06.09, a freely available, open-source, script-based solid modeling software. The assembled case with electronics is shown in Figure 2 and the design of the case body is shown schematically in the inset. The case was printed with a RepRap 3-D printer with black polylactic acid (PLA) media so as to minimize stray light inside the detection area.

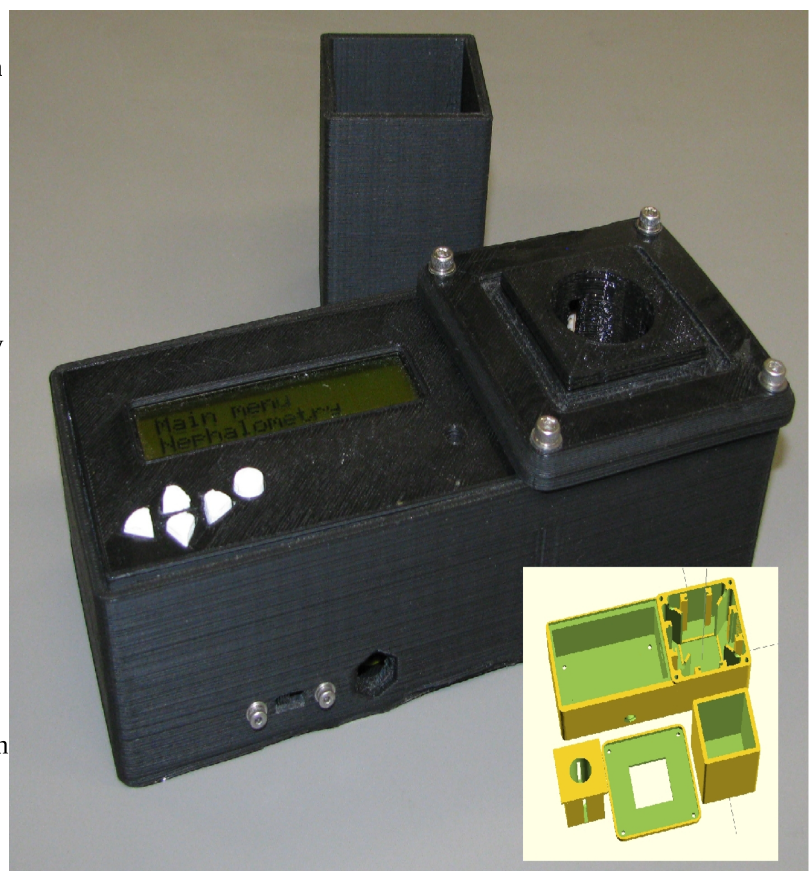

Figure 2. The open-source water testing platform with the assembled case with electronics and an inset schematic of case design in OpenSCAD.

The electronics are based upon the open-source Arduino prototyping platform, which is designed to use “shields” or customized electronic boards that can be pressed into place and that typically come with software libraries so as to facilitate integration of board features into the custom code developed by the end user. As can be seen in Figure 1, multiple LEDs and light intensity sensors are connected directly to the Arduino's digital inputs and outputs. The microcontroller contains flash memory to store a program for performing the measurement and providing a user interface using a shield containing a character LCD screen and navigation/control buttons.

A total of three discrete electronic components are required for the circuit (in addition to the Arduino and the shield); an additional two components are necessary for the colorimeter functionality, as shown schematically in Figure 1. The device’s firmware (https://github.com/mtu-most/colorimeter) provides an easy to navigate hierarchical menu system for selection of device functions. The firmware can be changed and rewritten to the device using the Arduino IDE, which is distributed as free and open source software from the Arduino website (http://www.arduino.cc/).

There are multiple standards for measuring turbidity (Ziegler, 2002). The USEPA method 180.1 (EPA, 1979) was the first standard promulgated, but it suffers from poor reproducibility (Ziegler, 2002; Hongve and Åkesson, 1998). A newer standard is maintained by ISO (ISO, 1999), which tries to avoid some of the problems of the EPA method. It requires an infrared photodiode instead of a tungsten lamp, which improves measurement of turbidity resulting from the presence of biological material, which may not be measured by the USEPA method. The ISO method was chosen for this design as it has demonstrated greater reproducibility, utilizes a low cost, long life and less energy intensive diode light source and has greater sensitivity when biological material is present in the sample.

The light intensity sensor used is a TAOS TSL235R light-to-frequency converter. This device produces a digital signal with a frequency proportional to the amount of light that it detects. The Arduino's internal counter units are connected to it, permitting measurements up to 8 MHz. Both of the Arduino's two counter input pins are connected to different sensors. During measurement, one sensor measures the intensity of the LED directly (reference intensity)and a second sensor measures either transmitted or diffuse reflected light. Measurement of the reference (LED intensity) and the transmitted/reflected light intensities are made simultaneously. The reference measurement is used to compensate for any changes in illumination intensity, which can occur due to fluctuations in supply voltage, temperature or aging of the diode.

Because this device is similar to the open-source colorimeter (Anzalone, et al., 2013), both can be combined into one device. To include colorimetric capability, only one additional LED and light intensity sensor are required, the cost of which is negligible.

Performance Measurement Methodology

The performance of the COD colorimeter was reported earlier (Anzalone, et al., 2013) and so was not investigated as part of this research.

Turbidity standards (Hach StablCal Turbidity Standards Calibration Kit) were used to calibrate both the OS nephalometer and a Hach 2100P portable turbidimeter, an instrument in the same category as the OS nephalometer. Formazin Turbidity Standard (4000NTU) was diluted with distilled water to produce samples having turbidities of 2, 4, 40, 100 and 200 NTU and each of these was analyzed in triplicate with the two instruments.

Results and Discussion

The results from calibration and a least squares fit are shown in Figure 3. Measurements from the two calibrated instruments are compared and are shown in Figure 4 with the line indicating perfect agreement between the two instruments.

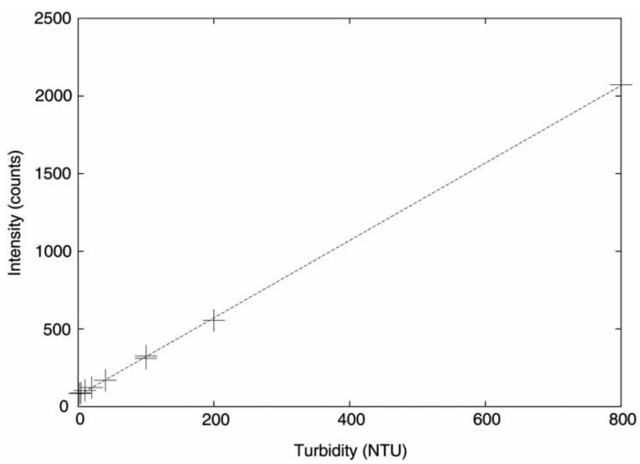

Figure 3. Calibration of the open-source nephalometer. The line shown is the result of the calibration.

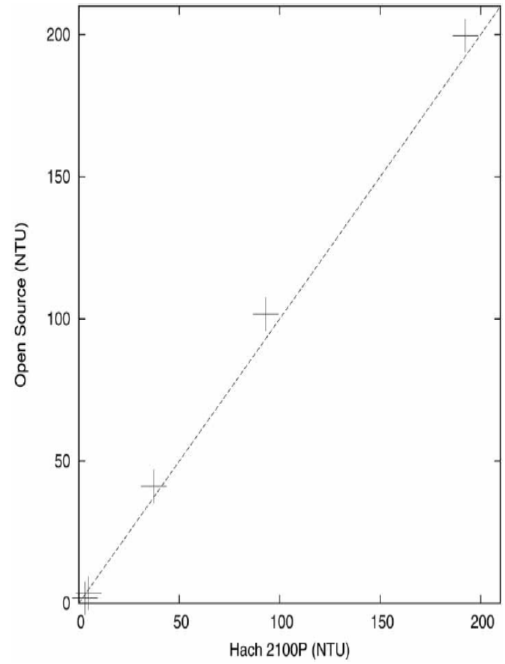

Figure 4. Comparison of the open-source nephalometer and the Hach 2100P. Points which have identical readings on both devices are on the line.

A device for measuring turbidity is presented, which in combination with other tests, is useful for determining whether water is safe for drinking. It has a direct application in determining the exposure times necessary for safe drinking water for those using the SODIS method or uv disinfection. This is especially a concern in developing countries, where people do not have money to buy the relatively expensive commercially-available nephalometers, which range in price from $600 to $1200, for equivalent quality to what is demonstrated here. The OS device performs as well as the commercial version it was compared to in this study, and for under $80.00, costs 7.5 to 15 times less. Low-cost and localized fabrication and maintenance of the device make it feasible for communities to do scientific measurements at both distributed and centralized water treatment facilities without depending on external support.

Limitations and Future Work

The drawbacks to an OSH approach to scientific tools are outlined in the *Open Source Lab* (Pearce, 2014) and found to be without merit, particularly concerning the lack of incentives for innovation. The one aspect of OSH that is very important for scientists is accuracy, which has been demonstrated for this particular device with the results of this study. For any other OSH for science a similar study is necessary.

It should be pointed out that BOD/COD and turbidity are not enough to ensure safe water alone. The device brings the price of a nephalometer down by an order of magnitude. With the simple addition more sensors, at minimal incremental cost, it replaces more devices designed to perform other water quality test methods, breaking the profit-by-specialization paradigm that drives commercial instrument development. In this way, a complete water testing lab may be built in pocket format in the future, containing not only turbidity and COD, but also pH, SDS, temperature, TDS, TSS, DO, ORP, UVT and BOD.

Because the hardware and software are all open-source, this is an ideal platform for adding more sensors or actuators to increase functionality. The software for controlling the new part can simply be added to the existing code base and it will work. This means any specialized measurement device can be built with relatively little effort. For instance, the device as tested does not contain the extra sensor for doing a ratio measurement shown to improve sensitivity by accounting for absorption (Hongve and Åkesson, 1998), but this sensor can easily be added because the software is open source; the user who is interested in this feature can implement it without help from an external manufacturer.

Because the design of the platform developed here is so flexible, many extensions are possible to make it more useful. For example, to allow the device to be used in places without access to a power grid, it can be adapted to function with a battery or it can be charged with a small solar photovoltaic cell or hand crank. To make it more flexible to use, it could be helpful to add wireless networking support, which would also reduce the cost as it would allow to remove the display and buttons and instead use the ubiquitous smart phone to control it. The phone could then be used to connect to several devices, and integrate several parts of an experiment, or do multiple separate experiments simultaneously. Using the power of 3-D printing the device could be configured as a phone attachment or could be used in conjunction with the open-source tricorder project (Pearce, 2014). Future work is also needed to test the platform in the field outside of controlled laboratory conditions. In addition, future work is needed to gauge the social acceptability of the device for any intended application, real world acceptance and if necessary marketing. To determine if the tests are effective, both field and clinical trials may also be useful. Because the software is open source, the communication protocol is automatically public as well. As an addition to that, it would be useful to design an open standard, which can be used by controlling computers to communicate with any such measurement device, without even knowing what type of measurement it is doing. Due to the low cost, this device, or a variation of it, would be very suitable for educational settings, which often function under severe budget constraints.

Conclusions

The results of this study have shown that a valuable device for testing water can be built using open-source hardware and software, for a fraction of the price of commercial options. Such a device not only matches the performance of commercial devices, but it is also expandable to enable other testing procedures at minimal additional cost. This method of developing and fabricating scientific testing equipment is valuable to all scientists, but may be particularly attractive to anyone in need of water-quality testing, but for financial reasons would not have access to the instrumentation necessary.

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