



HAL
open science

Open source laboratory sample rotator mixer and shaker

Karankumar C Dhankani, Joshua Pearce

► To cite this version:

Karankumar C Dhankani, Joshua Pearce. Open source laboratory sample rotator mixer and shaker. HardwareX, 2017, 1, pp.1-12. <10.1016/j.ohx.2016.07.001>. <hal-02113463>

HAL Id: hal-02113463

<https://hal.science/hal-02113463v1>

Submitted on 28 Apr 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License



Open source laboratory sample rotator mixer and shaker



Karankumar C. Dhankani^a, Joshua M. Pearce^{b,c,*}

^a Department of Mechanical Engineering–Engineering Mechanics, Michigan Technological University, Houghton, MI, USA

^b Department of Materials Science & Engineering, Michigan Technological University, Houghton, MI, USA

^c Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI, USA

ARTICLE INFO

Article history:

Received 20 May 2016

Received in revised form 20 July 2016

Accepted 20 July 2016

Keywords:

Open source hardware

Open hardware

Shaker

Mixer

Rotator mixer

Lab mixer

ABSTRACT

An open-source 3-D printable laboratory sample rotator mixer is developed here in two variants that allow users to opt for the level of functionality, cost saving and associated complexity needed in their laboratories. First, a laboratory sample rotator is designed and demonstrated that can be used for tumbling as well as gentle mixing of samples in a variety of tube sizes by mixing them horizontally, vertically, or any position in between. Changing the mixing angle is fast and convenient and requires no tools. This device is battery powered and can be easily transported to operate in various locations in a lab including desktops, benches, clean hoods, chemical hoods, cold rooms, glove boxes, incubators or biological hoods. Second, an on-board Arduino-based microcontroller is incorporated that adds the functionality of a laboratory sample shaker. These devices can be customized both mechanically and functionally as the user can simply select the operation mode on the switch or alter the code to perform custom experiments. The open source laboratory sample rotator mixer can be built by non-specialists for under US\$30 and adding shaking functionality can be done for under \$20 more. Thus, these open source devices are technically superior to the proprietary commercial equipment available on the market while saving over 90% of the costs.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The success of free and open source development of software is now well established and this method of development outside of purely software has grown most rapidly in electronics such as with the Arduino microcontroller [1]. The open-source Arduino is already established for use in low-cost high-quality scientific and engineering equipment [2–7] including: an ambient sensor cloud system using OpenFS (open field server) for high-throughput phenotyping [8], electrophoresis [9], imaging [10,11], mass spectrometry [12,13], mechatronics [14], microscopy [15,16], oceanographic research [17], optics [5,6,18], sensors for open hardware [19], including for colorimetry [20], in-vivo optimal imaging [21], nephelometry [22], pressure monitoring [23], smart plugs [24], soil moisture [25], Skinner boxes [26], vision research [27] and developing a wireless sensor node to monitor poultry farms [28]. Arduinos are also an established technology for controls [29], used as controllers on numerous challenging projects such as for aerial vehicles [30], robots [31,32] and microfluidics [33].

One of the most important control projects for scientists is the use of the Arduino for the open source 3-D printing community around the self-replicating rapid prototyper (RepRap) 3-D printer family [34–38]. The combination of free and open software and hardware design can be combined with RepRap 3-D printing for distributed digital fabrication of

* Corresponding author at: 1400 Townsend Drive, Houghton, MI 49931, USA.

E-mail address: pearce@mtu.edu (J.M. Pearce).

low-cost scientific equipment [3,6,39] including: automated sensing arrays [40], biotechnological and chemical labware [41–43], colorimeters [20], DNA nanotechnology lab tools [44], liquid autosamplers [45], mass spectroscopy equipment [46], compatible components for medical apparatuses [47], microfluid handlers [48] and wax printing of microfluidics [49], turbidimeters [22,50], optics and optical system components [5], and phasor measurement units [51]. In addition, the delta style RepRaps can be converted into a scientific tool itself by taking advantage of the mobile and stationary tool modes [52] including laboratory auto-stirring, measuring and probing, automated fluid handling, shaking and mixing [53] and 3-D automated microscopy [16].

In general digital replication with RepRap 3-D printers has reduced capital cost of scientific equipment by 90–99% from the cost of conventional equipment [3,6], which has created substantial value [54] resulting in hundreds and even thousands of percent return on investment for science funders [55].

To contribute to this trend, this paper presents the concept of a low-cost laboratory sample rotator mixer capable of combining the benefits from digital replication using a RepRap 3-D printer and controls logic from the Arduino-based microcontroller. The 3-D printable open-source laboratory sample rotator mixer is developed here in two variants, which allow users to opt for the level of functionality, cost saving and associated complexity required for their laboratories. First a simple laboratory sample rotator mixer is developed, which can be used for tumbling of samples in a variety of tube sizes by gently mixing them horizontally, vertically, or any position in between. This wireless battery-powered device can be easily transported to operate in various locations in a lab including desktops, benches, clean hoods, chemical hoods, cold rooms, glove boxes, incubators or biological hoods. Second, the mixer is enhanced with an on-board open source Arduino-based microcontroller to add the functionality of a shaker mixer. The user can select the operation mode with a switch. The cost saving of each of these variants was computed against commercially available products with similar functionality.

2. Materials and methods

The full bill of materials (BOM) is available with all the design files for both variants of the mixer in registered [56] and live format [57] (including links to components available online) and can be seen in Tables 1 and 2. All values in the BOMs are given in U.S. dollars. The BOM can be broken into two categories: (1) custom 3-D printable mechanical components and (2) off-the-shelf mechanical and electrical components. Tables 1a and 2a list of hardware that is to be 3-D printed on a RepRap or similar 3-D printer is shown. The custom parts of this sample rotator were designed using version 0.15 of FreeCAD – an

Table 1a
Open source laboratory sample rotator mixer 3-D printed components, mass and cost.

Printed component		Quantity	PLA mass (15% infill)	Cost of print (USD)
1. Small pillar	×	1	29 g	0.67
2. Central shaft	×	1	12 g	0.28
3. Rotisserie for test tubes	×	4	72 g	1.67
4. Big pillar	×	1	50 g	1.15
5. Motor cover	×	1	23 g	0.53
6. Battery cover	×	1	6 g	0.14

Table 1b
Open Source Laboratory Sample Rotator Mixer list of hardware to be purchased for assembly with the printed parts including component, quantity and cost.

Component		Quantity	Total cost
1. Bearing Details: This is the widely available roller skates bearing: O.D. = 21 mm and I.D. = 8 mm	×	1	USD 1.45
2. Battery Details: 9 V alkaline widely available (bought in pack of 8)	×	1	USD 2.05
3. Rocker switch Details: This can be purchased from Amazon or similar	×	1	USD 0.45
4. Geared motor 60 rpm 12 V DC Details: This can be purchased from Amazon or similar	×	1	USD 12.98
5. Battery clip Details: This can be purchased from Amazon or similar	×	1	USD 0.24
6. Rubber sheet (printed version cost) Details: This is sandwiched between the Rotisseries to grip the test tubes. Multiple options available on Amazon or similar	×	2	USD 3.12
7. O-rings Details: 9/16" outer diameter × 5/16" inner diameter × 1/8" wall or 14 mm × 8 mm × 3 mm	×	4	USD 2.04
8. 5/16" (or M8) screw 195 mm long	×	2	USD 2.80
9. 5/16" (or M8) nuts	×	6	USD 0.60

Total equipment cost: USD 30.17 (including battery).

Table 2a

Open source laboratory sample rotator mixer and shaker 3-D printed components, mass and cost.

Printed component		Quantity	PLA mass (15% infill)	Cost of print (USD)
1. Small pillar	×	1	29 g	0.67
2. Central shaft	×	1	12 g	0.28
3. Rotisserie for test tubes	×	4	72 g	1.67
4. Big pillar	×	1	58 g	1.33
5. Motor and microcont. cover	×	1	38 g	0.87
6. Electronics tray	×	1	5 g	0.12

Table 2b

Open source laboratory sample rotator mixer and shaker list of hardware to be purchased for assembly with the printed parts including component, quantity and cost.

Component		Quantity	Total cost
1. Bearing Details: This is the widely available roller skates bearing: O.D. = 21 mm and I.D. = 8 mm	×	1	USD 1.45
2. Rocker switch Details: This can be purchased from Amazon or similar	×	1	USD 0.45
3. Geared motor 60 rpm 12 V DC Details: This can be purchased from Amazon or similar	×	1	USD 12.98
4. Rubber sheet (printed version cost) Details: This is sandwiched between the Rotisseries to grip the test tubes. Multiple options available on Amazon or similar	×	2	USD 3.12
5. O-rings Details: 9/16" Outer diameter × 5/16" inner diameter × 1/8" Wall or 14 mm × 8 mm × 3 mm	×	4	USD 2.04
6. 5/16" (or M8) screw 195 mm long	×	2	USD 2.80
7. 5/16" (or M8) nuts	×	6	USD 0.60
8. Adafruit Pro Trinket 5 V microcontroller Details: This can be purchased either from Amazon or Adafruit or similar	×	1	USD 9.95
9. Motor driver controller L298N Details: This is the most commonly available type and can be purchased from Amazon or similar	x	1	USD 3.05
10. 12 V DC supply adaptor Details: 12 V supply is provided using an adapter that can be purchased from Amazon or similar	×	1	USD 6.98
11. 5.5 mm Jack Connector Socket Details: Can be purchased from Amazon or similar	×	1	USD 1.03

Total equipment cost: USD 49.39 (including power supply adapter).

open source parametric 3-D CAD modeler [58] and can be customized for various applications (e.g. test tube sizes). The custom parts are 3-D printed in polylactic acid (PLA) or similar hard thermoplastic on any open-source RepRap 3-D printer [59]. The 3-D printable design files for the sample rotator can also be downloaded from the NIH 3D Print Exchange based on the 1) rotator [60] and combination rotator/shaker [61]. Off-the-shelf hardware and electrical equipment is also needed such as the motor, switch, battery, nuts and bolts, o-rings, and others have been listed in the separate BOM for both variants (Tables 1b and 2b). Fig. 1 shows the partially disassembled laboratory sample rotator mixer where all of the main components are visible.

The microcontroller used for the combination rotator/mixer is the Adafruit Pro Trinket due to its smaller proportions, low cost and ease of availability. The microcontroller is employed to work with a commonly available motor driver integrated circuit to drive the motor. Example code is provided in Appendix A, which can be used to drive the 60 rpm motor in the equipment to work as a sample shaker mixer when running on a 12 V supply.

The major custom 3-D printed parts include:

1. One small pillar (shown in Fig. 2), which is a structural part that houses a ball bearing and two 8 mm nuts to hold the spacing threaded rod.
2. A central shaft (Fig. 3), which runs from the bearing on the small pillar (Fig. 2) to the motor in the big pillar on the other end of the device (Fig. 4). This shaft has two arms at the middle that hold test tube rotisseries after setting of the O-rings in the grooves as shown in Fig. 3. This enables rotation of rotisseries to obtain different mixing angles about these arms but also offers resistance so they remain in place at a set angle after being positioned manually.
3. Next, test-tube rotisseries can be customized to variable sizes and numbers of test tube, containers, cuvettes etc. Two types of rotisserie designs are shown in Fig. 4. In addition, the user can easily modify the design in FreeCAD to suit their experimental requirements. Each fully assembled system would have four of these parts and would be bolted together in pairs of two to sandwich rubber sheet with holes, which are required to grip and hold the test tubes during mixing. When

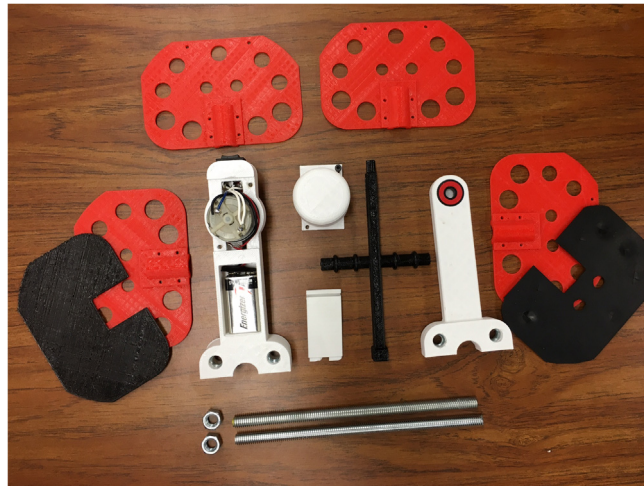


Fig. 1. Partially disassembled laboratory sample rotator mixer showing components.

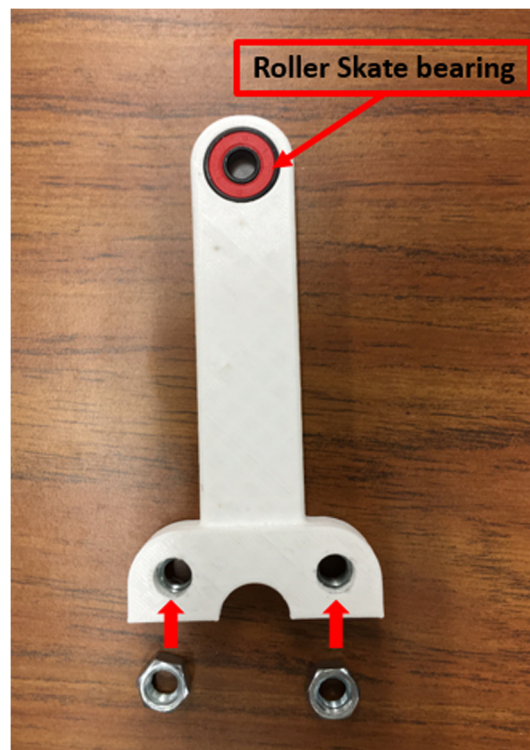


Fig. 2. Small pillar assembled with bearing and 8 mm nuts.

using a rubber sheet an “X” or star pattern must be cut in each test-tube hole with a sharp knife to enable samples to be loaded and gripped appropriately. For this type of design the hard plastic holes must be slightly larger than the test-tubes. It should be noted that if the user has access to a 3-D printer that can print in elastomers such as NinjaFlex this rubber sheet can be replaced with 3-D printed tube holders, which can entirely replace the rotisserie designs shown in Fig. 4 or be used as a substitute for the rubber sheets.

4. The large pillar (shown in Fig. 5 for the mixer variant) includes mounting holes for the DC motor, slot for the switch (top), slot for a 9 V alkaline battery and internal channel for wires. The part also includes nut traps for two 3 mm nuts to bolt the motor cover (another separately 3-D printed piece) and for two 8 mm nuts to hold the two spacing threaded rods that constrain the two pillars at a fixed distance.
5. The snap fit 9 V alkaline battery cover (Fig. 5) is required only for the mixer variant of the rotator.

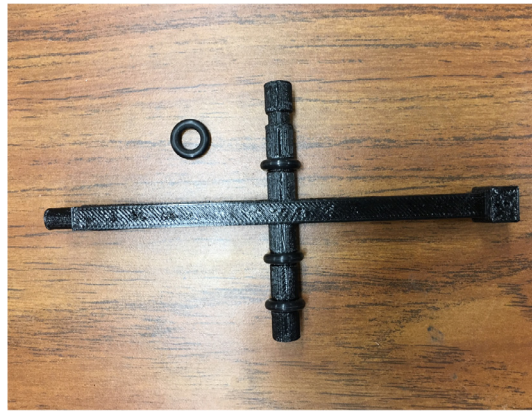


Fig. 3. Central shaft with o-rings.

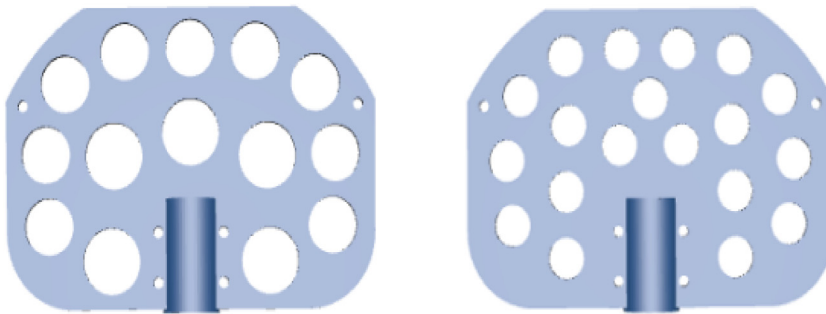


Fig. 4. Two rotisserie designs to hold the most common test tube sizes ranging from 0.5 ml to 10 ml.

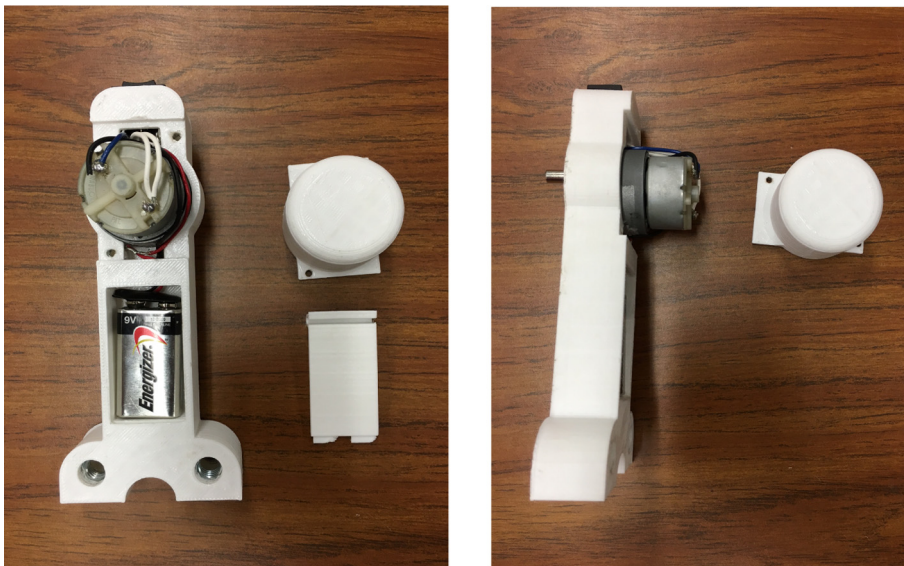


Fig. 5. Large pillar for sample mixer variant from the back (left) and side view (right). The snap fit battery cover is shown disassembled (left) and installed (right). The motor cover is in the upper right of both images is for the mixer variant.

6. The motor cover is used for covering the part of the motor that extends out of the large pillar (Fig. 5). This part gets bolted on to the large pillar and is only opened for maintenance.

While most of the parts in the two variants of this equipment are common, the large pillar uses a more complex design for the shaker/mixer combination variant. The large pillar from the second variant includes housing for the microcontroller and motor driver chip and this makes the large pillar design shown in Fig. 6 slightly bulkier than the mixer variant (Fig. 5).

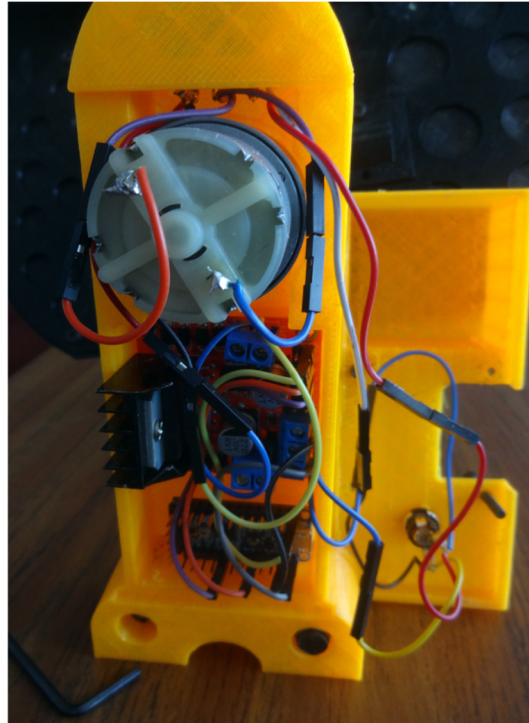


Fig. 6. Inside of large pillar of shaker showing wiring.

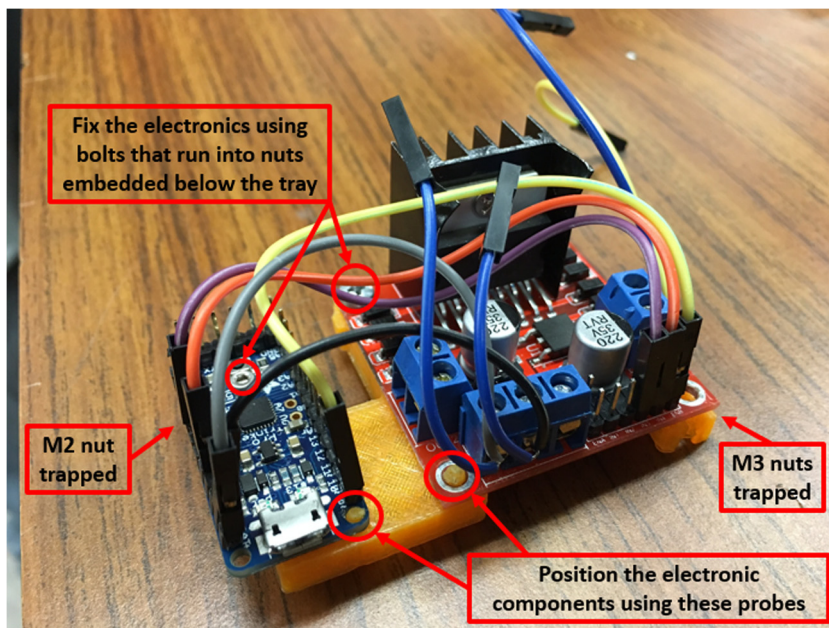


Fig. 7. Assembled electronics tray for mixer/shaker variant with microcontroller and motor driver mounted and soldered.

7. The microcontroller cover is required only for the mixer/shaker variant of the rotator and is used to protect the microcontroller and motor driver from the outside environment. This part also covers the motor and a separate motor cover is not needed. This is also bolted onto the large pillar (Fig. 6) and should only be opened for maintenance activities.

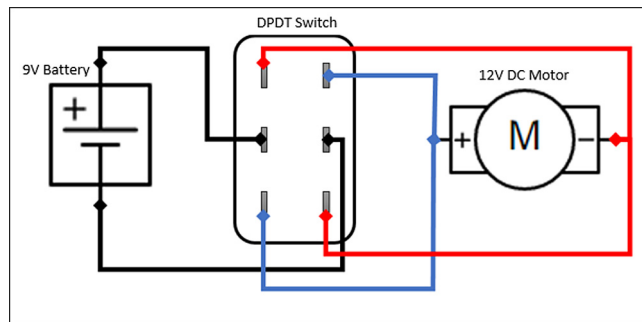


Fig. 8. Circuit diagram for mixer variant.

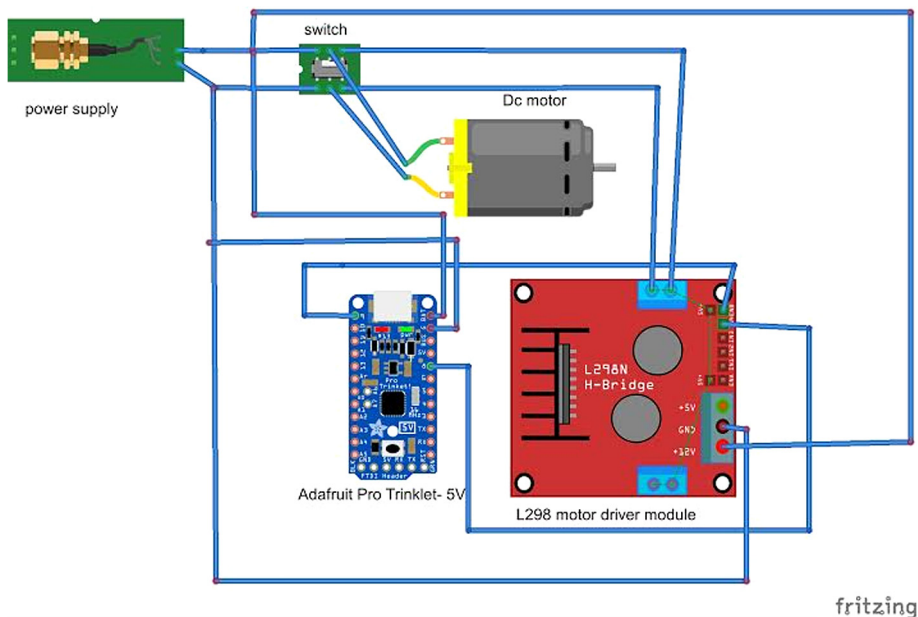


Fig. 9. Visual circuit diagram for the mixer/shaker combination variant.

8. The electronics tray is required only for the second mixer/shaker variant of the rotator and is used to hold the microcontroller (left side of Fig. 7) and motor driver integrated circuit (right side of Fig. 7) in place while soldering and fixing to the slot in the large pillar (Fig. 6). The tray also has nut traps on the bottom for M3 and M2 nuts. The Adafruit Pro Trinket requires a M2 nut and the motor driver requires three M3 nuts. These nuts on the motor driver are also used to hold the microcontroller cover by using long M3 screws. Plastic pillar probes are provided to assist in properly positioning the primary electronic parts.

The soldering for the simple mixer is straight forward and shown in Fig. 8 and the slightly more complex mixer/shaker system is shown in Fig. 9.

The more detailed diagram with pin configurations is shown in Fig. 10 for the mixer/shaker combination variant.

This system uses a switch to enable users to choose the direction of tumbling in the mixer variant and in the mixer/shaking combination it is used to choose between rotator mixer and shaking modes (Fig. 11).

The assembly procedures for the open source mixer are explained in a dedicated video (Video 1).

3. Results and discussion

3.1. Technical performance

Fig. 12 shows the fully constructed open source laboratory sample rotator mixer, which has a rotation rate of about 1.4 s/rotation, which was quantified over 100 rotations. Fig. 13 displays the open source laboratory sample rotator mixer/shaker combination device.

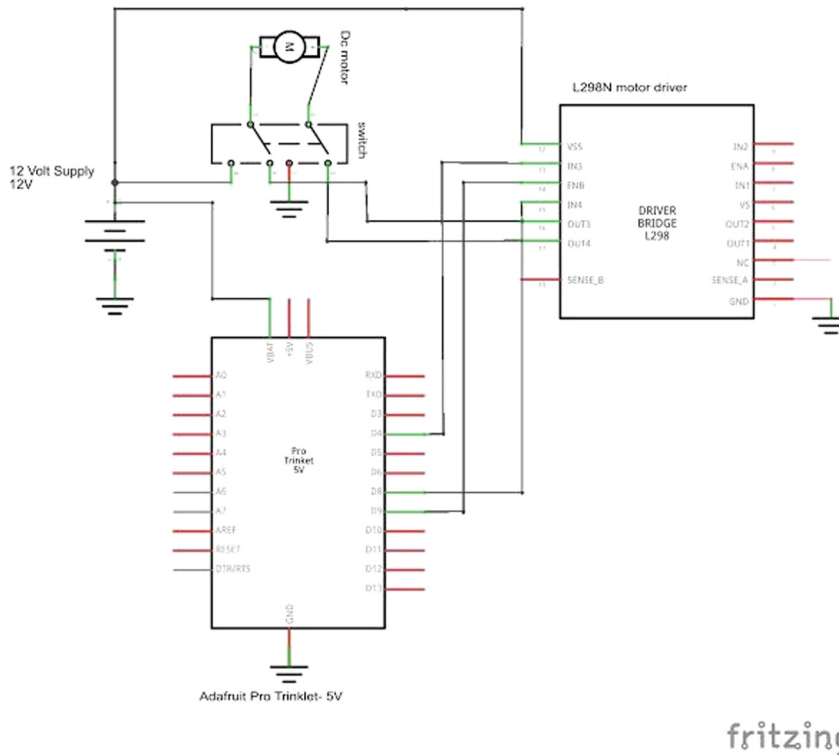


Fig. 10. Diagram of pin configurations of mixer/shaker combination variant.



Fig. 11. Rotator mixer on one switch pole and shaker on another switch pole and center off.

Both the open source laboratory sample rotator mixer and shaker function as designed as can be seen in [Video 2](#) and [Video 3](#), respectively. In [Video 2](#) the method to push a sample through the cut rubber sheet is demonstrated. The user simply pushes the vial or test tube through the hole and the rubber sheet holds it in place. As can be seen by comparing [Figs. 12](#) and [13](#) the latter combination device is considerably wider and the motor cover is bulkier due to on-board microcontroller and motor driver board. The functionality of this second device is far more flexible as the on-board microcontroller can be re-flashed using the USB slot in the large pillar to fulfill user requirements for a specific experiment. This was designed to avoid requiring the opening of the cover of the large pillar. This gives it the advantage of being a completely programmable scientific tool, which can be made to suit an individual scientist's needs. Sample code is provided in [Appendix A](#).

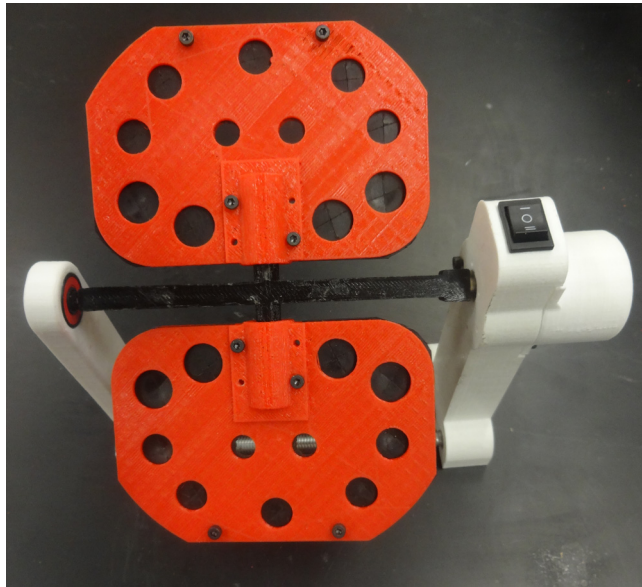


Fig. 12. Fully constructed battery-powered open source laboratory sample rotator mixer.

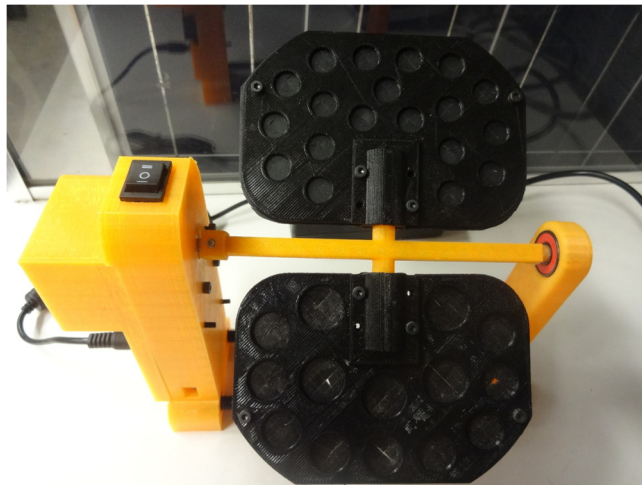


Fig. 13. The open source laboratory sample rotator mixer/shaker combination device.

3.2. Cost analysis

Basic cost analysis for both the variants of the sample rotator was performed for the hardware material costs in the U.S. as shown in BOM attached. The material costs of the battery-powered open source laboratory sample rotator mixer totaled US \$30.17 including the battery and under \$30 without it. The closest available commercial product, which has inferior adjustability, is available for US\$419.99 (+US\$20 shipping) [62]. Thus shipping costs for commercial products represent a significant fraction of an open source device. However, even ignoring shipping costs the simple variant of the open source laboratory sample rotator mixer provides US\$390 in savings representing a 92.8% discount for fabricating the device in lab. This savings is consistent with observations of other types of open source scientific hardware [6].

In case of second version, the increased functionality of the open source laboratory sample rotator mixer/shaker combination device increases the cost to US\$49.39. Here, a simple economic comparison is more difficult as there are no commercially equivalent products with such flexibility in operation. However, the additional functionality of laboratory shaker mixer could save the cost of a basic laboratory shaker, which has a wide range in prices to over several thousand dollars. Taking a conservative mid-range estimate, an average stand-alone shaker mixer costs more than US\$400, which provides over US\$800 for the combination mixer shaker device or over 94% savings. However, it should be pointed out that these savings should be

kept in context as the cost of the equipment varies significantly depending on the country where this equipment is assembled. This is mainly due to a high variation in costs of the basic components such as the DC motor, 9 V battery, microcontroller, motor driver integrated circuit, switches, etc. For example, the DC motor used was available in the U.S. for US \$12.98 while an identical motor can be purchased in India for approximately US\$5.00.

On the other hand, in this economic comparison the labor costs to construct the open source mixers was ignored, while the commercially available mixers and shakers come assembled. Both of the devices can be easily constructed in an afternoon by any science or engineering undergraduate student (or even a competent high school or grade school student), indicating that the necessary labor costs to fabricate them is low and would not normally be quantified in a research lab.

3.3. Discussion and future work

The advantages of employing open source hardware along with 3-D printing for the fabrication of scientific hardware are not just limited to saving substantial amounts of capital resources [6,54,55]. First, this approach allows scientists to fix their equipment. In these designs the most likely components to fail after continued rough use such as the central shaft can be 3-D printed for ~\$0.28 and easily replaced. Similarly, the devices can be upgraded as members of the open source scientific community continue to expand the functionality of the designs.

Most importantly, the user now has the ability to customize the equipment. Some users looking for a basic laboratory mixer could opt for the lower cost, non-programmable version whereas others may decide to provide additional functionalities to their equipment by writing a unique code for the microcontroller or even adding more hardware or integrating it into a larger system. The advantage of having complete control of scientific equipment to modify this basic design to meet their individual unique requirements is substantial. For users experienced in working with Arduino microcontrollers, a potential upgrade could include adding a LCD display along with a touch pad to incorporate timer functions, motor speed variations and additional modes for the equipment that combine rotation and shaking. Sensors could also be added for example that would begin a mixing routine when a solution changed color or temperature to automate a biological or chemical process. In addition, sensors could be used to provide feedback to go through precise rotations for more complicated experiments and analytical testing. This level of control for laboratory mixing and shaking is relatively easily achievable from this platform. Hence, the system provides the convenience of a programmable device at a much lower cost than commercial proprietary systems. This is normally not possible in case of commercially available equipment, although there is a growing trend of commercially available open source hardware [63].

One area where further research is needed in open source scientific hardware in general and this project in particular is on the durability of the device. Both of the variants of the sample rotator have been used conventionally in the lab for months without any failures. Although broken 3-D printed components could be easily replaced, there are still considerable unknowns on the mechanical properties of 3-D printed components from RepRap 3-D printers. Early work has shown that the mechanical properties of ABS and PLA are comparable (and in some cases even better) than proprietary additive manufacturing systems [64] although a wide variation was seen in the mechanical properties of components printed under realistic and uncontrolled environmental conditions [64,65]. In addition, even the color of the filament has an impact on the mechanical properties [66]. In general these properties are inferior to the same material synthesized into a component by more conventional methods of mass manufacture. In this case the mechanical components were sized to be strong enough for the application, while also minimizing the size to reduce print time, material used and costs. RepRap printed components have also been shown to be more than adequate for many other laboratory uses [3,6,47,53,67]. However, more detailed mechanical testing of RepRap 3-D printed parts is necessary along with inexpensive rapid methods to determine mechanical properties for more challenging applications. Finally, formal durability tests would be useful for expanding the acceptance of distributed manufacturing of open source scientific hardware.

4. Conclusions

This article showed how to fabricate an open source laboratory sample rotator mixer and shaker system using RepRap 3-D printed custom parts and commonly available mechanical and electrical components. The systems performed to specification and have improved functionality compared to proprietary systems available commercially. The open source laboratory sample rotator mixer can be built by non-specialists for under US\$30 and adding shaking functionality can be done for under \$20 more. These devices can be customized both mechanically and functionally and the latter can be programmed. Thus these open source laboratory sample rotator mixer and shaker combination devices are both superior to and can save over 90% of the cost of proprietary commercial equipment.

Acknowledgement

The authors would like to acknowledge technical support from E. Bow Pearce.

Appendix A

Example microcontroller code for mixer/shaker combination device:

```

const int positive = 8;           //define and initialize a variable 'positive' with value 8
const int negative = 4;         //define and initialize a variable 'negative' with value 4

void setup() {                  //setup() function runs once at the start of the program
  // put your setup code here, to run once:
  pinMode(positive, OUTPUT);    //defines the mode of pin 8 as an Output pin
  pinMode(negative, OUTPUT);   //defines the mode of pin 4 as an Output pin
  pinMode(9, OUTPUT);          //defines the mode of pin 9 as an Output pin
}                               //end of setup() function

void loop() {                   //loop() function runs repeatedly after setup() is run once
  // put your main code here, to run repeatedly:
  digitalWrite(positive, HIGH); //sets pin 8 to a digital high output
  digitalWrite(negative, LOW);  //sets pin 4 to a digital low output
  analogWrite(9, 255);          //sets pin 9 to an analog high output (PWM always on)
  delay(200);                   //sets a delay of 200 milliseconds
  digitalWrite(positive, LOW);  //sets pin 8 to a digital low output
  digitalWrite(negative, HIGH); //sets pin 4 to a digital high output
  analogWrite(9, 255);          //sets pin 9 to an analog high output (PWM always on)
  delay(200);
}

```

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ohx.2016.07.001>.

References

- [1] Arduino, <https://www.arduino.cc/>.
- [2] T. Baden, A.M. Chagas, G. Gage, T. Marzullo, L.L. Prieto-Godino, T. Euler, Open labware: 3-D printing your own lab equipment, *PLoS Biol.* 13 (3) (2015) e1002086.
- [3] J.M. Pearce, Building research equipment with free, open-source hardware, *Science* 337 (6100) (2012) 1303–1304.
- [4] D. Fisher, P. Gould, Open-source hardware is a low-cost alternative for scientific instrumentation and research, *Mod. Instrum.* 1 (2) (2012) 8–20.
- [5] C. Zhang, N.C. Anzalone, R.P. Faria, J.M. Pearce, Open-source 3D-printable optics equipment, *PLoS One* 8 (3) (2013), <http://dx.doi.org/10.1371/journal.pone.0059840> e59840.
- [6] J.M. Pearce, *Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs*, Elsevier, Amsterdam, 2014.
- [7] A. D'Ausilio, Arduino: a low-cost multipurpose lab equipment, *Behav. Res. Methods* 44 (2) (2012) 305–313.
- [8] M. Hirafuji, H. Yoichi, T. Kiura, K. Matsumoto, T. Fukatsu, K. Tanaka, T. Suzuki, Creating high-performance/low-cost ambient sensor cloud system using OpenFS (open field server) for high-throughput phenotyping, in: *SICE Annual Conference (SICE)*, IEEE, 2011, pp. 2090–2092.
- [9] J. Sáiz, I.J. Koenka, C. García-Ruiz, B. Müller, T. Chwalek, P.C. Hauser, Micro-injector for capillary electrophoresis, *Electrophoresis* 36 (16) (2015) 1941–1944.
- [10] P. Nikolaou, A.M. Coffey, L.L. Walkup, B.M. Gust, N. Whiting, H. Newton, S. Barcus, I. Muradyan, M. Dabaghyan, G.D. Moroz, M.S. Rosen, Near-unity nuclear polarization with an open-source ^{129}Xe hyperpolarizer for NMR and MRI, *Proc. Natl. Acad. Sci. U.S.A.* 110 (35) (2013) 14150–14155.
- [11] M.P. Walzik, V. Vollmar, T. Lachnit, H. Dietz, S. Haug, H. Bachmann, M. Fath, D. Aschenbrenner, S.A. Mofrad, O. Friedrich, D.F. Gilbert, A portable low-cost long-term live-cell imaging platform for biomedical research and education, *Biosens. Bioelectron.* 64 (2015) 639–649.
- [12] S.H. Chiu, P.L. Urban, Robotics-assisted mass spectrometry assay platform enabled by open-source electronics, *Biosens. Bioelectron.* 64 (2015) 260–268.
- [13] J.B. Hu, T.R. Chen, C.H. Chang, J.Y. Cheng, Y.C. Chen, P.L. Urban, A compact 3D-printed interface for coupling open digital microchips with Venturi easy ambient sonic-spray ionization mass spectrometry, *Analyst* 140 (5) (2015) 1495–1501.
- [14] J. Kentzer, B. Koch, M. Thiim, R.W. Jones, E. Villumsen, An open source hardware-based mechatronics project: the replicating rapid 3-D printer, in: *Mechatronics (ICOM)*, 2011 4th International Conference On, IEEE, 2011, pp. 1–8.
- [15] E.J. Gualda, T. Vale, P. Almada, J.A. Feijó, G.G. Martins, N. Moreno, OpenSpinMicroscopy: an open-source integrated microscopy platform, *Nat. Methods* 10 (7) (2013) 599–600.
- [16] B. Wijnen, E.E. Petersen, E.J. Hunt, J.M. Pearce, Free and open source automated 3-D microscope, *J. Microsc.* (2016), <http://dx.doi.org/10.1111/jmi.12433>, <http://onlinelibrary.wiley.com/doi/10.1111/jmi.12433/full>.
- [17] J. Busquets, J.V. Busquets, D. Tudela, F. Pérez, J. Busquets-Carbonell, A. Barberá, C. Rodríguez, A.J. García, J. Gilbert, Low-cost AUV based on Arduino open source microcontroller board for oceanographic research applications in a collaborative long term deployment missions and suitable for combining with an USV as autonomous automatic recharging platform, in: *Autonomous Underwater Vehicles (AUV)*, 2012 IEEE/OES, IEEE, 2012, pp. 1–10.
- [18] M. Gopalakrishnan, M. Gühr, A low-cost mirror mount control system for optics setups, *Am. J. Phys.* 83 (2) (2015) 186–190.

- [19] S. Trilles, A. Luján, Ó. Belmonte, R. Montoliu, J. Torres-Sospedra, J. Huerta, SEnviro: a sensorized platform proposal using open hardware and open standards, *Sensors* 15 (3) (2015) 5555–5582.
- [20] G.C. Anzalone, A.G. Glover, J.M. Pearce, Open-source colorimeter, *Sensors* 13 (4) (2013) 5338–5346.
- [21] R. Sun, M.B. Bouchard, E.M. Hillman, SPLASH: open source software for camera-based high-speed, multispectral in-vivo optical image acquisition, *Biomed. Opt. Express* 1 (2) (2010) 385–397.
- [22] B. Wijnen, G.C. Anzalone, J.M. Pearce, Open-source mobile water quality testing platform, *J. Water Sanit. Hyg. Dev.* 4 (3) (2014) 532–537.
- [23] L. Russell, A.L. Steele, R. Goubran, Low-cost, rapid prototyping of IMU and pressure monitoring system using an open source hardware design, in: *Instrumentation and Measurement Technology Conference (I2MTC), 2012 IEEE International, IEEE, 2012*, pp. 2695–2699.
- [24] A.H. Shajahan, A. Anand, Data acquisition and control using arduino-android platform: smart plug, in: *Energy Efficient Technologies for Sustainability (ICEETS), 2013 International Conference On, IEEE, 2013*, pp. 241–244.
- [25] R.S. Ferrarezi, S.K. Dove, M.W. van Iersel, An automated system for monitoring soil moisture and controlling irrigation using low-cost open-source microcontrollers, *HortTechnology* 25 (1) (2015) 110–118.
- [26] O. Píñeño, ArduiPod Box: a low-cost and open-source Skinner box using an iPod Touch and an Arduino microcontroller, *Behav. Res. Methods* 46 (1) (2014) 196–205.
- [27] P. Teikari, R.P. Najjar, H. Malkki, K. Knoblauch, D. Dumortier, C. Gronfier, H.M. Cooper, An inexpensive Arduino-based LED stimulator system for vision research, *J. Neurosci. Methods* 211 (2) (2012) 227–236.
- [28] K. Chelli, S. Chavhan, Development of wireless sensor node to monitor poultry farm, in: *Mobile Communication and Power Engineering*, Springer, Berlin, Heidelberg, 2013, pp. 27–32.
- [29] I.J. Koenka, J. Sáiz, P.C. Hauser, Instrumentino: an open-source modular Python framework for controlling Arduino based experimental instruments, *Comput. Phys. Commun.* 185 (10) (2014) 2724–2729.
- [30] H. Lim, J. Park, D. Lee, H.J. Kim, Build your own quadrotor: open-source projects on unmanned aerial vehicles, *IEEE Rob. Autom. Mag.* 19 (3) (2012) 33–45.
- [31] J. Gonzalez-Gomez, A. Valero-Gomez, A. Prieto-Moreno, M. Abderrahim, A new open source 3d-printable mobile robotic platform for education, in: *Advances in Autonomous Mini Robots*, Springer, Berlin, Heidelberg, 2012, pp. 49–62.
- [32] J.D. Warren, J. Adams, H. Molle, *Arduino for Robotics*, Apress, 2011, pp. 51–82.
- [33] R. Fobel, C. Fobel, A.R. Wheeler, DropBot: an open-source digital microfluidic control system with precise control of electrostatic driving force and instantaneous drop velocity measurement, *Appl. Phys. Lett.* 102 (19) (2013) 193513.
- [34] R. Jones, P. Haufe, E. Sells, Reprap – the self-replicating rapid prototyper, *Robotica* 29 (1) (2011) 177–191.
- [35] E. Sells, S. Bailard, Z. Smith, A. Bowyer, V. Olliver, The replicating rapid prototyper-maximizing customizability by breeding the means of production, *Handbook of Research in Mass Customization and Personalization*, vol. 1, World Scientific, New Jersey, 2010, pp. 568–580.
- [36] M. Woelfe, P. Olliaro, M.H. Todd, Open science is a research accelerator, *Nat. Chem.* 3 (10) (2011) 745–748.
- [37] A. Bowyer, 3D Printing and humanity's first imperfect replicator, in: *3D Print. Addit. Manuf.* 1 (1) (2014) 4–5.
- [38] G. Rundle, *A Revolution in the Making: 3D Printing, Robots and the Future*, Affirm Press, 2014.
- [39] J.M. Pearce, Laboratory equipment: cut costs with open-source hardware, *Nature* 505 (7485) (2014), 618–618.
- [40] J.N. Wittbrodt, U. Liebel, J. Gehrig, Generation of orientation tools for automated zebrafish screening assays using desktop 3D printing, *BMC Biotechnol.* 14 (1) (2014) 36.
- [41] T.H. Lücking, F. Sambale, S. Beutel, T. Scheper, 3D-printed individual labware in biosciences by rapid prototyping: in vitro biocompatibility and applications for eukaryotic cell cultures, *Eng. Life Sci.* 15 (1) (2014) 57–64.
- [42] B.C. Gross, J.L. Erkal, S.Y. Lockwood, C. Chen, D.M. Spence, Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences, *Anal. Chem.* 86 (7) (2014) 3240–3253.
- [43] C.-K. Su, S.-C. Hsia, Y.C. Sun, Three-dimensional printed sample load/inject valves enabling online monitoring of extracellular calcium and zinc ions in living rat brains, *Anal. Chim. Acta* 838 (2014) 58–63.
- [44] T.R. Damase, D. Stephens, A. Spencer, P.B. Allen, Open source and DIY hardware for DNA nanotechnology labs, *J. Biol. Methods* 2 (3) (2015) e24.
- [45] M.C. Carvalho, B.D. Eyre, A low cost, easy to build, portable, and universal autosampler for liquids, *Methods Oceanogr.* 8 (2013) 23–32.
- [46] M. Malonado-Torres, H.F. Lopez-Hernandez, P. Jimenez-Sandoval, R. Winkler, *J. Proteomics* 15 (1) (2014) 57–64.
- [47] K.-H. Hermann, C. Gärtner, D. Güllmar, M. Krämer, J.R. Reichenbach, 3D printing of MRI compatible components: why every MRI research group should have a low-budget 3D printer, *Med. Eng. Phys.* 36 (10) (2014) 1373–1380.
- [48] E.T. Da Costa, M.F. Mora, P.A. Willis, C.L. do Lago, H. Jiao, C.D. Garcia, Getting started with open-hardware: development and control of microfluidic devices, *Electrophoresis* 35 (16) (2014) 2370–2377.
- [49] J.M. Pearce, N.C. Anzalone, C.L. Heldt, Open-source wax RepRap 3-D printer for rapid prototyping paper-based microfluidics, *J. Lab. Autom.* 21 (4) (2016) 510–516.
- [50] C.D. Kelley, A. Krolick, L. Brunner, A. Burklund, D. Kahn, W.P. Ball, M. Weber-Shirk, An affordable open-source turbidimeter, *Sensors* 14 (4) (2014) 7142–7155.
- [51] D.M. Lavery, R.J. Best, P. Brogan, I. Al Khatib, L. Vanfretti, D.J. Morrow, The OpenPMU platform for open-source phasor measurements, *IEEE Trans. Instrum. Meas.* 62 (4) (2013) 701–709.
- [52] G.C. Anzalone, B. Wijnen, J.M. Pearce, Multi-material additive and subtractive prosumer digital fabrication with a free and open-source convertible delta RepRap 3-D printer, *Rapid Prototyping J.* 21 (5) (2015) 506–519.
- [53] C. Zhang, B. Wijnen, J.M. Pearce, Open-source 3-D platform for low-cost scientific instrument ecosystem, *J. Lab. Autom.* 21 (4) (2016) 517–525.
- [54] J.M. Pearce, Quantifying the value of open source hardware development, *Mod. Econ.* 06 (01) (2015) 1–11.
- [55] J.M. Pearce, Return on investment for open source scientific hardware development, *Sci. Public Policy* 43 (2) (2016) 192–195.
- [56] <https://osf.io/9c9q5/>.
- [57] <https://osf.io/q3nr5/>.
- [58] <http://www.freecadweb.org/>.
- [59] <http://reprap.org/>.
- [60] <http://3dprint.nih.gov/discover/3dpx-003287>.
- [61] <http://3dprint.nih.gov/discover/3dpx-003288>.
- [62] Amazon, Labnet H5600. <http://www.amazon.com/Labnet-H5600-Revolver-rotisserie-36-1-5/dp/B0048L0TTK>, (accessed 5.19.2016).
- [63] R. Arensman, Can Open-Sourcing Transform Electronics Hardware?, *Electronics* 360, 2016, <http://electronics360globalspec.com/article/6728/can-open-sourcing-transform-electronics-hardware> (accessed 5.20.2016).
- [64] B.M. Tymrak, M. Kreiger, J.M. Pearce, Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions, *Mater. Des.* 58 (2014) 242–246.
- [65] H.A. Habeeb, M.R. Alkahari, F.R. Ramli, R. Hasan, S. Maidin, S. Strength and porosity of additively manufactured PLA using a low cost 3D printing, in: *Proceedings of Mechanical Engineering Research Day 2016, 2016*, pp. 69–70.
- [66] B. Wittbrodt, J.M. Pearce, The effects of PLA color on material properties of 3-D printed components, *Addit. Manuf.* 8 (2015) 110–116.
- [67] A.P. Zwicker, J. Bloom, R. Albertson, S. Gershman, The suitability of 3D printed plastic parts for laboratory use, *Am. J. Phys.* 83 (3) (2015) 281–285.