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Open Source 3-D Printed Nutating Mixer

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Abstract: As the open source development of additive manufacturing has led to low-cost desktop three-dimensional (3-D) printing, a number of scientists throughout the world have begun to share digital designs of free and open source scientific hardware. Open source scientific hardware enables custom experimentation, laboratory control, rapid upgrading, transparent maintenance, and lower costs in general. To aid in this trend, this study describes the development, design, assembly, and operation of a 3-D printable open source desktop nutating mixer, which provides a fixed 20° platform tilt angle for a gentle three-dimensional (gyrating) agitation of chemical or biological samples (e.g., DNA or blood samples) without foam formation. The custom components for the nutating mixer are designed using open source FreeCAD software to enable customization. All of the non-readily available components can be fabricated with a low-cost RepRap 3-D printer using an open source software tool chain from common thermoplastics. All of the designs are open sourced and can be configured to add more functionality to the equipment in the future. It is relatively easy to assemble and is accessible to both the science education of younger students as well as state-of-the-art research laboratories. Overall, the open source nutating mixer can be fabricated with US$37 in parts, which is 1/10th of the cost of proprietary nutating mixers with similar capabilities. The open source nature of the device allow it to be easily repaired or upgraded with digital files, as well as to accommodate custom sample sizes and mixing velocities with minimal additional costs.

Keywords: mixing; nutating mixer; shaker; stirrer; open hardware; 3-D printing; scientific hardware; open source hardware; chemical mixing

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1. Introduction

Open source three-dimensional (3-D) printing developed from the self-replicating rapid prototype (RepRap) project [1–3], has widened the doors for innovation and excellence in varied domains [4]. Combining 3-D printing with off the shelf and easily available electrical mechanisms has provided cost effective opportunities to design and build customized scientific equipment [5,6]. This equipment ranges from an automatic feeder for animal experiments [7] and time-sorting pitfall traps for sampling arthropods [8], to electronics to provide big data like IoT meter devices for smart and energy-efficient buildings [9] and even entire smart cities [10]. Open hardware has also been developed for more conventional scientific tools in biology labs [11], optics labs [12], and even DNA nanotechnology labs, which can fabricate DNA-coated for up to 90% less than commercially offered tools [13]. This trend in cost savings from 90–99% is seen in a wide variety of open hardware tools for science and their outputs [5,6,11,12]. Moreover, the open source design platform has provided the opportunity for distributed manufacturing [14–18]—specifically to download the designs and print them anywhere at any time, which can provide additional savings from avoided shipping costs as well as various taxes and tariffs. These savings are perhaps most stark when distributed manufacturing using 3-D printing (which enables material minimization coupled to free complexity) is tied to some form of automation. For example, radial stretching systems with force sensors [19] or a sample rotator mixer [20] can save hundreds of dollars per scientific tool, a mobile water quality testing platform [21] or a syringe pump [22] saves thousands per tool, and a robot-assisted mass spectrometry assay platform [23] and an automated peptide synthesizer [24] can save over $25,000. Scientists can now design, share and build on one another's work to develop advanced scientific tools [25], such as devices to enable digital microfluidics [26,27], large stage probing [28], and microscopy [29]. These tools can all be easily maintained, modified, upgraded, or repaired because the full assembly instructions and bill of materials (BOM) are included.

To continue this development of low-cost open hardware tools, this paper describes the development of a desktop nutating mixer, which provides a fixed 20° platform tilt angle for a gentle three-dimensional (gyrating) agitation of samples. Such devices agitate liquids for chemical or biological scientific procedures by repetitively moving the vessels holding the liquids. Although, open hardware methods to mix samples have been developed in the past (e.g., rotating mixing and shaking [20], orbital shaker [5,6], as well as using a 3-D platform for stirring and custom shaking [30]), they were either too violent to ensure foam free mixing in tubes or too large for conventional portable use. Proprietary nutating mixers cost hundreds of dollars and lack the ability to either repair or upgrade with digital files, as well as to accommodate custom sample sizes and mixing velocities. These shortcomings are overcome here with the development of an open source nutating mixer, which can be fabricated with a conventional fused filament 3-D printer capable of printing both hard and flexible thermoplastics and off the shelf electrical components. This study describes how the system was designed and manufactured in way that is universally replicable. The operation of the mixer is tested, and the technical performance is compared to conventional systems and an economic comparison is made with the closest commercial alternatives. Finally, future work will be detailed to enhance the performance of the system.

2. Materials and Methods

As open source hardware for science [31,32], the full BOM, manufacturing, assembly, and operation instructions are provided.

2.1. Bill of Materials

The full BOM is shown in Table 1 for the 3-D printed components, and Table 2 for the remaining components. First in Table 1, the 3-D printed components are listed for fabrication with a hard thermoplastic polymer (e.g., polylactic acid (PLA)) or an elastomer (e.g., NinjaFlex). The filament used was 1.75 mm diameter filament at a cost of US$18.33/kg for PLA [33] and US$86.67/kg for the more expensive 3 mm diameter filament of NinjaFlex for flexible components [34]. The open source CAD software, FreeCAD and STL files (STereoLithography format is a file format that describes only the surface geometry of a three-dimensional object used for 3-D printing) for the 3-D printed components are available at the Open Science Framework [35] under a GNU General Public License 3.0 license and are detailed below. The ordered components from Table 2 are readily available online. Prices shown in Table 2 were all sourced from Amazon and shipping was not included as free Amazon Prime was assumed.

Table 1. Bill of materials (BOM) for three-dimensional (3-D) printed components including material, mass and cost.

Sr. No.	Component	3-D Printing Material	Quantity	Mass (g)	Cost (US$)
1	Rod	PLA	1	7	0.15
2	Bearing holder	PLA	1	8	0.18
3	Base	PLA	1	60	1.32
4	Cover	PLA	1	126	2.77
5	Platform	PLA	1	76	1.67
6	Dimpled Bed	Ninja Flex	1	67	5.80
7	Slit	Ninja Flex	1	4	0.34
		Total Filament Cost			12.23

Table 2. BOM for ordered components.

Sr. No.	Component	Qty	Cost (US$)
1	Skateboard bearing [36]	1	0.73
2	DC barrel connector [37]	1	1.00
3	Switch DPDT [38]	1	1.19
4	12 Volt DC Motor—25 RPM [39]	1	13.95
5	DC adapter [40]	1	6.99
6	M3 Fasteners (2 M3 7 mm, 2 6 mm, 3 M3 16 mm and 1 M3 10 mm and bolts)	1	<1.00
	Total Ordered Material Cost		24.86
	Total Cost of Equipment (Tables 1 and 2)		**37.09**

2.2. Design

The design and fabrication followed a completely free and open source software toolchain, which maximizes the ability for the replication of the results. All of the 3-D printable components are designed by using the open source CAD software, FreeCAD [41], and can be further edited to customize the equipment for any scientific lab. They were designed to provide the mechanical integrity necessary for the component while still being 3-D printable without support. Exported STL files were sliced with the open source slicer, Cura [42]. Most of the components are printed using PLA, which is the most popular 3-D printing material, being available for the majority of 3-D printing supplies vendors. PLA has been shown to be a safer alternative to toxic acrylonitrile butadiene styrene (ABS) plastic fumes, the second most widely available 3-D printing material [43,44]. PLA has a relatively low melting point (150 °C to 160 °C), so it may not be appropriate for high temperature applications. For such applications, a higher melting point thermoplastic such as ABS or polycarbonate can be substituted and printed in a fume hood or a well-ventilated area by using the same designs shown here. All of the PLA filament designs were printed using a MOST Delta 3-D printer [45] running Franklin [46], which is a RepRap [1–3]. All of the PLA components were built with the following print settings: infill 25%, layer height 0.25 mm, shell thickness 1 mm, print temperature 185 °C, and 70 mm/s print speed (with the exception of the rod that was printed with 0.15 mm layer height and 35% infill to improve the mechanical properties). The slit and dimpled mat were printed using Ninja Flex on a commercial RepRap, the Lulzbot Mini with a Flexystruder Extruder (Aleph Objects, Loveland, CO, USA) [47,48], with print settings: infill 20%, layer height 0.325 mm, shell thickness 0.6 mm, print speed 14 mm/s, and print temperature 230 °C. The final design for the 3-D printable components focused on minimizing the filament quantity used while still achieving high torque despite the offset of the rotating axis. If the design needs to be scaled up, all of the components can be scaled, as well until the limit of the DC motor is reached and then will need to be substituted for a higher torque DC motor. Figure 1 shows all of the 3-D printed parts that are required for the open source nutating mixer.

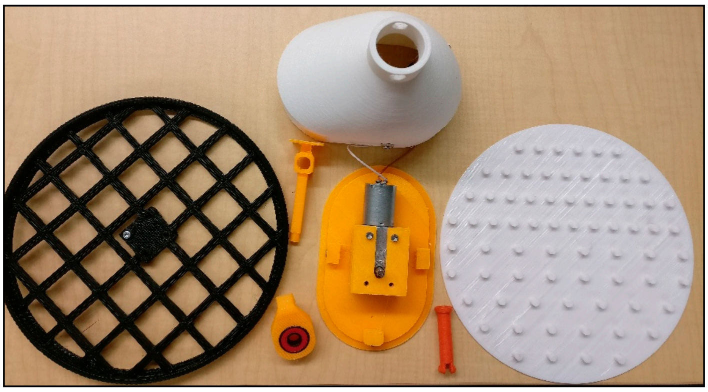


Figure 1. Disassembled 3-D printed components of the open source nutating mixer.

The functionality for each 3-D printed component is described below:

(1) Base (Figure 2): The base of the equipment holds the 12 V 25 RPM DC geared motor, which is the main load bearing component of the equipment.

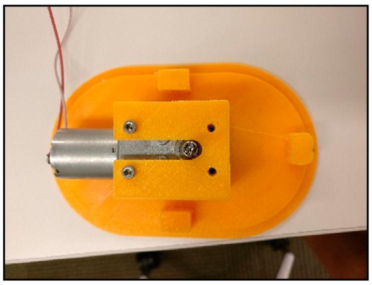
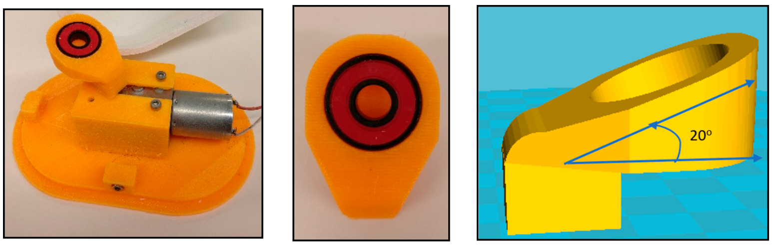


Figure 2. Base of the open source nutating mixer printed with PLA and showing the 12 V 25 RPM DC geared motor mounted in place.

(2) Bearing holder (Figure 3): The bearing holder is designed at a 20-degree tilt angle. A skateboard bearing is mounted on the top on a flat surface, which further holds the rod and the platform, hence enabling 3-D rotation of platform at 20 degrees.



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

Figure 3. Bearing holder printed with polylactic acid (PLA). (**a**) in base; (**b**) detail; (**c**) FreeCAD side view showing 20° tilt angle.

(3) Rod (Figure 4): The rod is mounted on the bearing holder and fits in the bore of the bearing, so that when the motor rotates, the rod rotates at 20 degrees with some offset. The slit hole in the rod is designed specifically for 20-degree angle and calculated based on the height of intersection of the rod with the center of the rotating shaft. It should be noted that the FreeCAD model can be adjusted for different angles, but if the mixer needs to be customized at a different angle, the slit hole position in the rod will change, respectively. 30% infill, with a lower layer height results in the

mechanical strength needed for this component that has a relatively small cross-sectional area at the top. Polymer use could also be reduced by using a slicer capable of variable height infill settings.

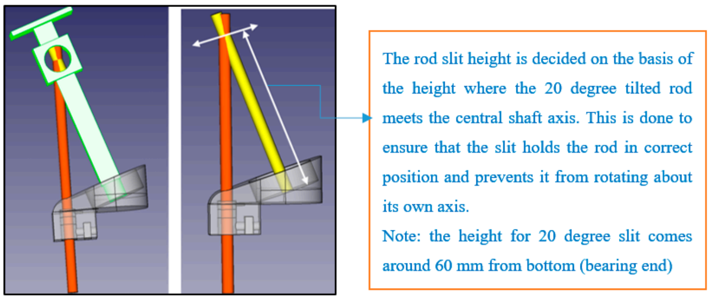


Figure 4. Rod design for the open source nutating mixer.

(4) Cover (Figure 5): The shell of the mixer is a functional component and is thus designed to fit on the base as well as hold the rotating rod exactly at the center of the slit hole position. Hence, the neck on the cover consists of a slit hole to accommodate a rubber (NinjaFlex slit), which passes through the cover and through the rotating rod such that it prevents the rod from rotating about its own axis. The height of the equipment is determined based on this slit height as it must be aligned with the rod slit hole after the assembly. Thus, again for customizing, the design of the cover will need to be modified in FreeCAD.

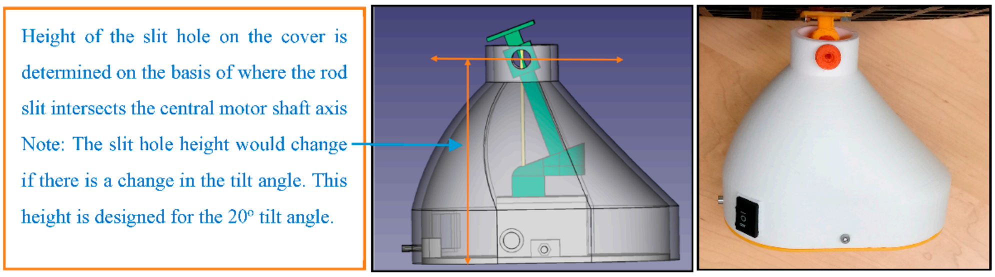


Figure 5. Cover design (left) and 3-D printed cover assembled detail (right).

(5) Platform (Figure 6): The platform of the mixer is designed to provide a solid base for the dimpled mat, which is printed in flexible material to hold the test tubes. To reduce the amount of filament consumed, it is designed as a mesh, which is strong enough to hold the dimpled mat and the test tubes. The platform is attached to the rod with the M3 nuts and bolts.

Figure 6. Platform printed with black PLA. The underside of the platform showing the attachment of the rod with M3 nuts and bolts is shown on the left and the platform mounted on the mixer assembly without the dimpled mat is shown on the right.

(6) Dimpled mat (Figure 7): The dimpled mat is built using NinjaFlex, which provides flexibility to hold test tubes of various sizes. The shown design can hold the test tubes with 13 mm, 16 mm, and 20 mm diameter. The design can be easily modified for any custom tube size (or assortment of tube sizes) by changing the location of the cylinders as per the requirement and test tube sizes. Finally, the diameter of the dimpled mat, as shown is 200 mm, and can be modified to a larger or smaller size to accommodate more samples or to save on equipment costs (as this is the most expensive 3-D printed component as shown in Table 1), respectively. Thus, the dimpled mat can be customized for any type of vessel include glass or plastic tubes, bottles, flasks, and microplates.

Figure 7. Dimpled mat 3-D printed with NinjaFlex. The spacing of the dimples can be adjusted to hold various tube sizes.

(7) Slit (Figure 8): The flexible slit is built using NinjaFlex so that it not only holds the rod in place and prevents it from rotating about its own axis, but also acts as a damper to give smooth rotation to the mixer. This component needs to be added to the mixer after it is assembled.

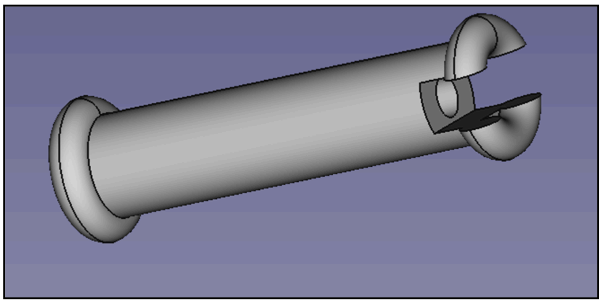


Figure 8. NinjaFlex slit design.

2.3. Assembly and Testing

2.3.1. Procedure to Assemble the 3-D Printed Open Source Nutating Mixer

(1) Print all of the components listed in the BOM (Table 1) for the mixer, which can be downloaded at the Open Science Framework [35]. Acquire the remaining BOM components from Table 2.

(2) Assemble the motor to the base, as shown in Figure 9. Use only two 6 mm M3 hex bolt screws to fit the motor to the base, as mentioned below. Adding the all 4 hex bolts restricts the movement of the bearing holder.

Next, fit M3 nuts on all three blocks, as shown below. A little glue can be used to prevent slipping if necessary.

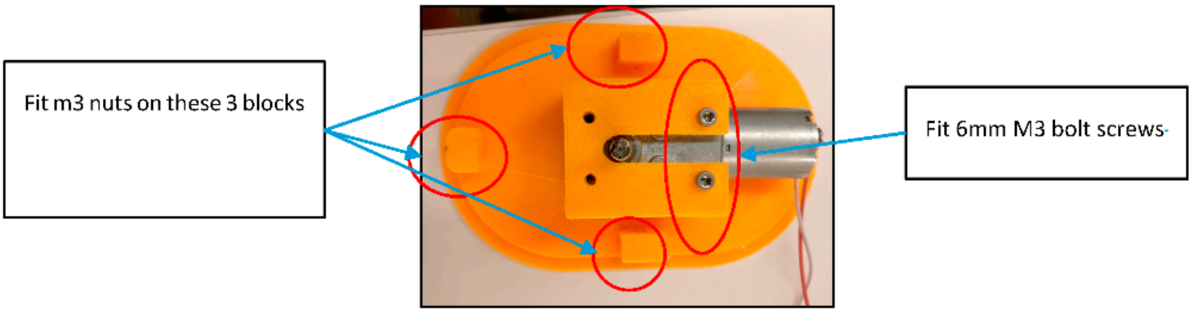


Figure 9. Base assembly.

(3) Fit the bearing holder to the motor shaft using 10 mm M3 hex bolt.
(4) Fit the double pole double throw (DPDT) switch and DC barrel connector on the printed cover. Note: Do not solder it before assembling it to the cover.
(5) Solder the DPDT switch to the barrel connector and the DC motor following the circuit shown in Figure 10.

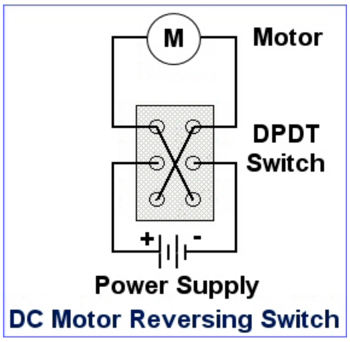


Figure 10. Circuit for DC motor with double pole double throw (DPDT) switch and power connector.

(6) Tighten the cover to the base using three 16 mm M3 hex screws. Make sure that the wires are out of the way of the bearing holder or else it might mess up when the bearing holder rotates.
(7) Assemble the 3-D printed platform with the printed rod using M3 7 mm hex screws, as shown in Figure 11. Two screws should be enough for the assembly.

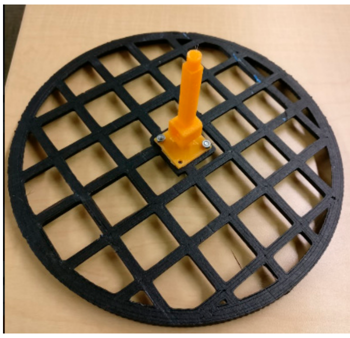


Figure 11. Rod assembled to the platform.

(8) **Important:** Turn on the mixer using the adapter and make sure that the bearing holder is in parallel position to the base as shown in Figure 12. This step is important so that the rod and slit can be assembled with ease. It should be noted that if the bearing holder is not in this position while assembling the rod, the rod might break or it might not assemble properly.

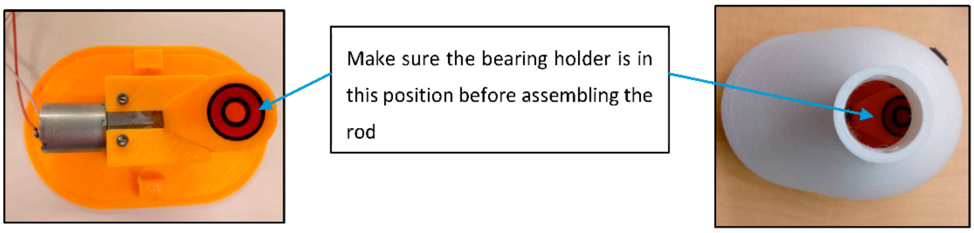


Figure 12. Bearing holder position should be parallel to the base and the motor.

(9) Assemble the rod platform assembly to the cover such that the rod tip fits exactly at the center of the bearing bore.
(10) Make sure that the rod fits properly in the bearing bore by aligning the slit hole of the cover with the rod hole, as shown in Figure 13.

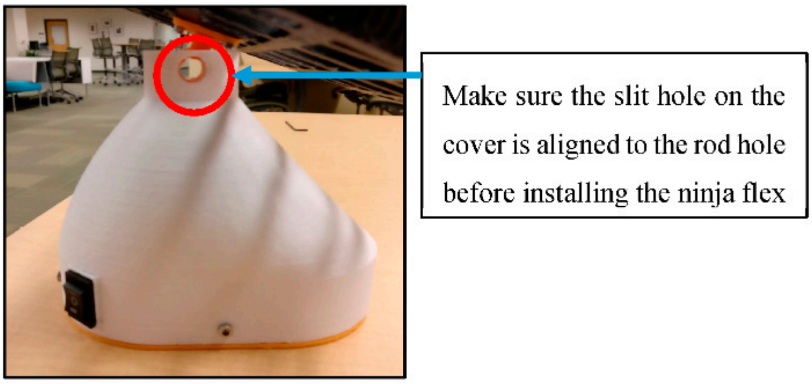


Figure 13. Visual check needed to determine if the rod hole is aligned with the cover holes.

(11) Install the slit passing it through the cover and through the rod.
(12) Place the dimpled mat on top of the cover. If required use some glue to fix it firmly to the platform.

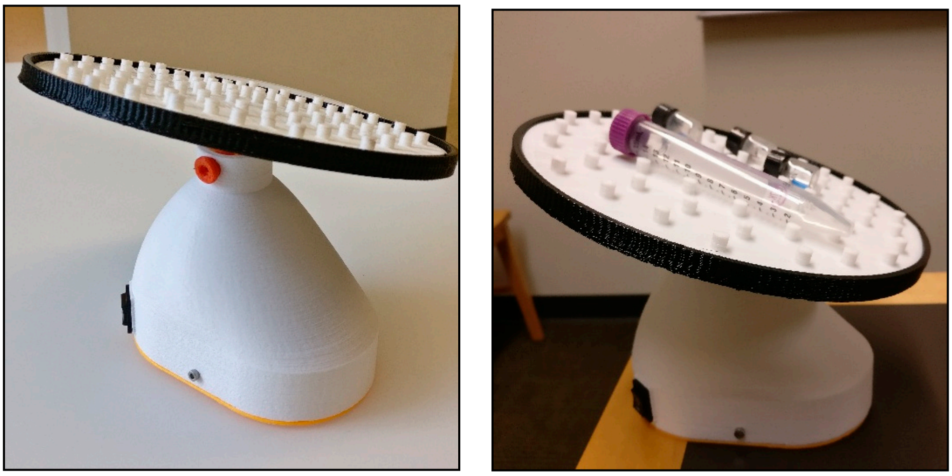
2.3.2. Testing

The system was timed for 100 rotations three times to determine the rotation speed in the forward and reverse directions. In addition, mass was applied to the system until failure to determine the maximum mixing capacity.

3. Results

After printing, all of the parts and assembling following the instructions in Section 3, the mixer is finished as seen in Figure 14a and is capable to mixing samples of various sizes (Figure 14b). The switch used to turn the equipment on/off is a double pole double throw (DPDT), which allows clockwise and counter clockwise rotation of the platform. The motor used is 25 RPM DC motor, which can be changed to a different RPM motor usually available from 6 RPM to 45 RPM based on the application. The operation of the open source nutating mixer can be seen in the Supplemental Information video.

The open source nutating mixer can rotate successfully at 25 RPM with up to a 3 kg mass applied. The dimpled mat design can be modified in FreeCAD by changing the X values of the dimples (cylinders) to fit the test tube sizes as per any experimental requirements. The current design can hold 13 mm, 16 mm, and 20 mm test tubes, and the dimpled mat can be removed for cleaning with soap and water. The part which is the most likely to need replacement over a long time period of usage would be the NinjaFlex slit, and it can be 3-D printed and replaced at a cost of US$0.34. In addition, the entire mixer is easily disassembled/re-assembled to replace any other broken part or to upgrade the apparatus, as discussed below.



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

Figure 14. (**a**) Fully-assembld 3-D printed open source nutating mixer; (**b**) with samples of various sizes.

4. Discussion

4.1. Performance and Future Work

The open source nutating mixer is designed to perform the basic gentle 3-dimensional nutating rotation in both CW and CCW directions. The mixing provided by the nutating mixer is thorough yet gentle mixing that prevents foaming. This functionality is enough for most basic mixing needs, such as mixing blood samples or biological DNA samples. Both the speed and the tilt angle of the open source nutating mixer are fixed to provide appropriate agitation for mixing samples in small containers. However, some laboratories may want other tilt angles, as discussed above, or may need the ability to vary the speed of mixing. This open source system can be modified to a variable speed adjustable mixer in the future by adding a potentiometer to the circuit. In this case, a 45 or higher RPM motor can be used, and the potentiometer can adjust the speed from 0 RPM to 45 RPM according to the requirements of the experiments. This modification would have only a modest additional cost associated with the cost of the motor (<US$20, which would substitute for the as-designed motor) and potentiometer (US$2). To go further, it is possible to add an Arduino and LCD display to adjust the time and the speed of rotation, which would again increase costs further (e.g., US$10 display and $20 microcontroller or less if using the ATmega168 microcontroller with a custom PCB fabricated with an open source mill [45]) and provide functionality well beyond what is currently commercially available. In addition, as the mixer as designed can operate with up to 3 kg of load. This is well above what would be expected of a fully loaded sample platform. Thus, the platform can be redesigned to hold multiple mats in a vertical stack simultaneously to mix more samples using the same instrument. The nutating mixer can already be used in cold rooms, but for use in incubators, a high-temperature 3-D printed polymer can be substituted for the PLA used here. As these potential future upgrades make clear one of the major advantages of open source 3-D printed scientific equipment, is that users can customize the equipment to meet their needs with minimal additional costs.

4.2. Cost Analysis

The overall cost of the 3-D printed and purchased equipment based on the BOM in shown in Tables 1 and 2 is US$37, which can be compared to other nutating mixers commercially available on the market, as summarized in Table 3. The closest available commercial products on both instrument suppliers' websites and Amazon cost on average US$373, which is 10 times the cost of the open source nutating mixer, thus saving 90% of the commercial cost. These cost savings are in agreement with the savings observed in other scientific tools in past studies [6,11,12,31]. Finally, a point should be made about the range in costs of the commercial systems shown in Table 3. The most expensive system also included variable speed, which are not included in the lowest cost models. As noted above, this functionality could be added to the open source system, while maintaining the same cost advantage in percent for the materials costs.

Table 3. Commercial nutating mixers cost and cost saving percent for the use of the open source nutating mixer.

Commercial Proprietary Product	Cost (US$)	Cost Savings for OS Nutating Mixer (%)
Labnet GyroMini Nutating Mixer [49]	291.65	87.3
Benchmark BlotBoy 3-Dimensional Rockers [50]	381.65	90.3
Benchmark Scientific B3D1008 Mini [51]	322.15	88.5
Boekel 201100 Mini Orbitron [52]	491.00	92.4
Globe Nutating Mixer [53]	443.03	91.6
Globe Scientific 522-230 Nutating Mixer II [54]	420.60	91.2
Benchmark Mini BioMixer 3-D Shakers [55]	313.65	88.2
Chemglass CLS-4029-100 3D Nutating Mixer [56]	325.00	88.6
Average	373.59	90.1

These cost savings, however, assume that there is no labor cost for the purchasing of components, 3-D printing, and assembly. Zero labor costs are relevant in the following situations: (1) where the 3-D printing and the assembly of the device is used as a learning tool in order to provide students with experience in the construction of scientific equipment or open hardware [57,58]; (2) where the labor is provided by unpaid interns or volunteers (e.g., undergraduates volunteering for research to gain experience and improve their resume/CVs); or, (3) where there is no opportunity cost to using existing salaried employee (e.g., the use of a lab manager or RA, TA, or other position that is paid a fixed cost, and for which there is no opportunity cost for them working on the fabrication of the device.

In general, in academic institutions these conditions can be readily met in most labs. In the labs, however, where this is not the case (e.g., industrial labs) it is instructive to look at the potential cost of labor for the fabrication of the open source desktop nutating mixer. The labor involved is represented by three tasks: (1) purchasing the six primary components, as outlined in Table 2; (2) 3-D printing the seven 3-D printed parts listed in Table 1; and, (3) assembling the device when all of the components have been gathered. The labor for each of these tasks will be analyzed separately.

First, purchasing the components is a low-skill task, particularly when the Amazon hyperlinks in references [36–40] are still active and purchasing is occurring in the United States (U.S.). The total time for this task would be about 5 min for anyone with an existing Amazon account and shipping is free for those with Amazon prime. In the future, if these components are no longer available on these hyperlinks than they will need to be sourced from other websites, which will have an additional time cost. It should also be pointed out that it may be possible to decrease the cost of the device by careful comparison shopping for the components, and many of the components are probably already available for no cost at institutional Fablabs [59,60]. Regardless, this subtask can be undertaken by the lowest-cost worker in an organization (e.g., a receptionist at a company) and represents a trivial or non-existent cost.

Next, the 3-D printing of the components listed in Table 1 can be considered a moderate skilled task (although FFF 3-D printing is a rapidly expanding skill set seen in young workers in a wide array of disciplines). However, it would appear challenging for those with no experience in 3-D printing. For those with experience and access to a basic RepRap or similar the time investment for setting up a print again is trivial. For example, although only the two flexible components were printed out on a Lulzbot Mini here, all of the components could have been. The first five components can be printed on any such hard plastic FFF 3-D printer using default settings, or the settings recommended here. There are hundreds of thousands of these 3-D printers deployed globally, which are thus readily accessible to most labs. A tuned DIY RepRap or a commercial self-bed leveling 3-D printer can be left unattended after the file has been sent to print just as long as 2-D print jobs can be left to print without the printer being monitored by a user. Thus, although the actual 3-D print time is much longer, the time that labor is focused only on printing is less than half an hour. The two flexible 3-D prints must be made on an advanced (or upgraded) 3-D printer (e.g., the Lulzbot Mini with the Flexystruder) and may not be available even in every workshop with a 3-D printer. In these cases, the local FabLab [59,60], makerspaces [61], hackerspaces [62], and even public libraries [63] often have 3-D printing services available either for free, or for the cost of materials. Most universities now have at least basic 3-D printing capabilities somewhere on campus. For researchers wishing to fabricate the open source desktop nutating mixer with no access to 3-D printers locally, an on demand quasi-local 3-D print service can be used, such as MakeXYZ [64]. The costs for a 3-D printing service will be more than the costs of the materials alone, but in general reasonable, because of the high degree of competition, quotes are available immediately for users in any given area.

Lastly, once all of the components are gathered they must be assembled. Having designed the system, the researchers in this study could build the device in about 10 min. To remain conservative, it is estimated that for a novice builder the build time would be under 30 min. (with the assembly instructions in this paper).

Thus, the overall cost in labor to source, print, and assemble a 3-D printable open source desktop nutating mixer is about 1 h. This indicates that it is profitable for an organization to use the open source version if their labor costs are under $250/h, even for the least expensive commercial equivalent (or under $330/h for the average commercial system). Finally, a point should be made about the life cycle cost advantages of the open source mixer. As all of the files are shared and the BOM is known, regardless of the failure mode of the device it is easily repaired from readily available components (e.g., reprint a broken plastic component or replace the DC motor). This ease of repair and upgrading is simply not available for all of the commercial systems, which would demand the purchasing of a replacement device. Thus, the value of the open source tool can be considered higher than the commercial functional equivalent, even though the open source tool costs less money to build upfront.

5. Conclusions

This study successfully described the development, design, assembly, and operation of a 3-D printable open source desktop nutating mixer, which provides a fixed 20° platform tilt angle for a gentle three-dimensional (gyrating) agitation of chemical or biological samples. The device can be fabricated from US$37 in parts, which is 1/10th of the cost of proprietary nutating mixers with similar capabilities. In addition, the open source nutating mixer was found to operate under 3 kg loads, which provides the opportunity to expand the sample carrying capacity of the device in the future. The open source nature of the device allows it to be easily repaired or upgraded with digital files, as well as to accommodate custom sample sizes and mixing velocities with minimal additional costs.

Supplementary Materials: The following are available online at https://osf.io/bqysc/, Video S1: Open Source 3-D Printed Nutating Mixer demonstration video.

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