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Open Source Completely 3-D Printable Centrifuge

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Abstract: Centrifuges are commonly required devices in medical diagnostics facilities as well as scientific laboratories. Although there are commercial and open source centrifuges, costs of the former and required electricity to operate the latter, limit accessibility in resource-constrained settings. There is a need for low-cost, human-powered, verified and reliable lab-scale centrifuge. This study provides the designs for a low-cost 100% 3-D printed centrifuge, which can be fabricated on any low-cost RepRap-class fused filament fabrication (FFF) or fused particle fabrication (FPF)-based 3-D printer. In addition, validation procedures are provided using a web camera and free and open source software. This paper provides the complete open source plans including instructions for fabrication and operation for a hand-powered centrifuge. This study successfully tested and validated the instrument, which can be operated anywhere in the world with no electricity inputs obtaining a radial velocity of over 1750rpm and over 50N of relative centrifugal force. Using commercial filament the instrument costs about US$25, which is less than half of all commercially available systems; however, the costs can be dropped further using recycled plastics on open source systems for over 99% savings. The results are discussed in the contexts of resource-constrained medical and scientific facilities.

Keywords: 3-D printing; additive manufacturing; biomedical equipment; biomedical engineering; centrifuge; design; distributed manufacturing; laboratory equipment; open hardware; open source; open source hardware; medical equipment; medical instrumentation; scientific instrumentation

1. Introduction

Adopting an open-source model of technological development enables equipment designers to quickly build upon one another's works [1-3]. This democratization of design assists many individuals to effectively work together by making a range of contributions over time using open source tools [4-6]. Some of the most effective tools for encouraging widespread open hardware designs are themselves means of digital distributed manufacturing [7,8]. For example, the open source nature of the self-replicating rapid prototyper (RepRap) 3-D printer [9-11] radically increased the accessibility to additive manufacturing (AM) while eviscerating the costs of rapid prototyping and product fabrication [12-16]. RepRaps and derivative commercial variants have obtained mechanical 3-D printed part strengths [17] and qualities of interest to the scientific community [18]. Many open source digitally fabricated devices are now widely used by the scientific community [19-21]. For example, 3-D printed parts are used in chemical mixing [22-25], optical and mechanical testing [26-28], water quality testing [29-32], and syringe pumping [33-36] (which can be in turn used

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for more complicated systems like fabricating microfluidics and metafluidics [37-39] or slot die deposition [40]). In addition to offering scientists the ability to customize their equipment and fully control its function, the open source 3-D printable tools are much less expensive than equivalent or inferior commercial systems [19,41, 42]. In general, these economic savings are greater for the higher percentage of the components able to be 3-D printed [43]. A high return on investment (ROI) is realized for distributed manufacturing with commercial polymer 3-D printing filament based on downloaded substitution values [44,45]. In order to continue to 'stand on the shoulders of giants' in open hardware [46] this paper describes the design of an open source completely 3-D printable centrifuge.

A centrifuge is a machine that holds rapidly rotating containers while applying centrifugal force to the fluids inside the containers to separate them based on different densities. Centrifuges are commonly required devices in medical diagnostics facilities because they are used for determining the concentration of pathogens and parasites in biological fluids, DNA preparation, and extraction of plasma from whole blood needed for immunoassays or haematocrit analysis. There are many commercial laboratory centrifuges and a number of open source variants including the open analytical ultracentrifugation (AUC) [47], the laser cut OpenFuge [48], Polyfuge [49], several variations of mini centrifuges [50-52], and one that uses a Dremel and 3-D printed chuck [53]. These open hardware tools do provide for those without access to more expensive proprietary tools [54], however, they all depend on access to electricity. Unfortunately, an estimated 1.1 billion people (e.g. 14% of the global population) do not have access to electricity [55]. In addition, even many of those that do have access to electricity, have unreliable power. For example, in Nigeria power outages over extended times have forced a shift to expensive and polluting captive power generation in the majority of businesses [56]. To overcome this challenge of reliable electric power, several open source hand powered centrifuges have been developed including the paperfuge [57], a salad spinner centrifuge [58], and an eggbeater centrifuge [59]. All of which are functional, but lack either large volume capabilities [57] or reliability. To overcome this, several companies have commercialized relatively robust hand-crank centrifuges, which cost US$60-100 [60,61]. These costs can still be prohibitive and as centrifugation is the first key-step for most diagnostic assays [62], there is a need low-cost, portable, human-powered centrifuge that can be used by scientists and medical personnel especially for diagnostics in resource-limited environments [62-64].

This study provides the designs for a low-cost 100% 3-D printed centrifuge apparatus, which can be fabricated on any low-cost RepRap-class fused filament fabrication (FFF) or fused particle fabrication (FPF)-based 3-D printer. In addition, a validation procedure for quantifying the rotational speed is provided, which makes use of a smart phone or web camera. The design is fabricated and tested and the results are discussed in the contexts of resource constrained medical and scientific facilities.

2. Materials and Methods

2.1 Design

The design goal for this apparatus was to provide 1200 rotations per minute (rpm) with a handle rotational speed of the operator (N_1) of 120 rpm (i.e. 2 rotations in 1 second). This centrifuge apparatus uses one set of spur gears and one set of bevel gears to achieve the desired gear ratio.

2.1.1. Gear designing and final drive calculations

Considering the rotational speed of the handle by the operator, N_1 is 120 rpm the rotational speed for the 2nd spur gear, N_2 is:

$$N_2 = N_1 T_1 / T_2 \qquad (1)$$

With the following teeth for the four gears:

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Teeth on 1st Spur gear : $T_1 = 60$

Teeth on 2nd Spur gear : $T_2 = 15$

Teeth on 1st Bevel gear : $T_3 = 50$

Teeth on 2nd Bevel gear : $T_4 = 20$

So N_2 is 480 rpm and as the 2nd spur gear and 1st bevel gear are coupled together,

$$N_2 = N_3 \quad (2)$$

Thus,

$$N_4 = N_3T_3 / T_4 = N_2T_3 / T_4 \quad (3)$$

So, N_4 is 1200 rpm. Similarly, for N_1 of 150 rpm (i.e. 2.5 rotations of the handle per second) the final rotor speed is 1500 rpm.

Thus, for this apparatus the number of test-tube rotations (r_t) is given by

$$r_t = Cr_h \quad (4)$$

Where the hand rotations per minute (r_h) can be measured and C is a constant of 10. With these parameters it is also possible to calculate the relative centrifugal force (RCF), which is the amount of acceleration that is exerted on the sample in the apparatus. The RCF is dependent on the speed of the rotor and the distance of the matter in the test tubes from the center of the rotation. When the unit of rotation (N_4) is in rpm, RCF is given by:

$$RCF = 1.118 \times 2 \times 10^{-6} \times R\,[mm] \times N_4^2\,[rpm] \quad (5)$$

Where R is the radius of rotor to the center of test tubes used added to the test tube length (mm) and N_4 is given by equation 3. In the example shown here with the radius of the rotor (50mm) test tubes used and length of test tubes (100mm) providing a total of 150 mm and N_4 of 1500 rpm the RCF is 755.

2.1.2 Operation of design

1. Rotating the handle will rotate the bigger spur gear, which will start the motion. The two spur gears in contact have equal modules. Module is the ratio of the reference diameter of the gear to the number of teeth on the gear. The bigger spur gear has 60 teeth and a module of 2. Although a larger spur gear would have yielded a higher gear ratio, it would also have increased the size of the casing and in turn the size of whole apparatus. A spur gear with 60 teeth and a module of 1.5 module was chosen considering the need of the final required rotations of the rotor (N_4). Meshed to the bigger spur gear is a smaller spur gear with an equal module. To mesh and rotate a set of any gears, it is necessary that both the gears should have the same profile and an equivalent module. This smaller spur gear is coupled with a larger bevel gear to eliminate the overhang and also another component required to hold the two together. The bigger bevel gear has 50 teeth and a module of 2. The bevel gear is used to transmit the motion in perpendicular direction. A smaller bevel gear is then meshed with the large one to increase the rotations per minute of the test tubes.

2. High rotational speeds of 1200-2000 rpm are required to carry out typical medical tests. Thus, this gear train is designed in such a way that, with every two rotations per second, the rotor will rotate at 1200 rpm. With every two and half rotations per second of the handle, the rotor will rotate at 1500 rpm and with three rotations per second, it can do 1800 rpm. The commercial equivalent products are capable of rotating at 1800 rpm, which is equal to the rotational capability of this 3-D printed centrifuge apparatus. The speeds can be easily increased if the number of teeth on either of the bevel or spur or both bigger gears are increased and the source code in FreeCAD is made available for those that need this capability.

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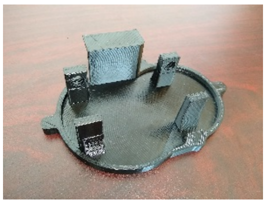
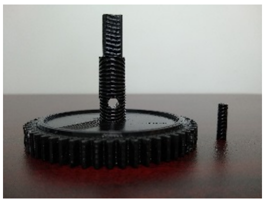
3. The dimensions of the handle is designed in such a way that, it will not interfere with rotation of the test tubes. The grip is designed keeping the ergonomics of the human hand and its motion while rotating the handle in mind. Enough grip is provided on the grip bar that freely rotates around the centerpiece of handle. The horizontal motion of grip is constrained by implementing a ball-socket joint at the end of the handle.

4. Test tubes are placed in the test rings, which are specifically designed for standard test tubes. However, there is a wide variety of test tubes that are available on the market. All the part files in FreeCAD are made available and open source so that others can adapt the tube holders to meet other sizes of test tubes. The test rings that hold the test tubes are locked in the rotor by using rotor snaps. These snaps can easily withstand the high centrifugal forces acting on them as they are tightly fit in the rotor itself. The rotor diameter is 120 mm, which is enough to generate high centrifugal force following equation 4.

2.1.3 Bill of Materials

The bill of materials (BOM) is made up of all 3-D printed components, which are summarized in Table 1.

Table 1. Bill of materials for the 3-D printed open source centrifuge.

Component	Quantity	Description	Image of Component
Part A	**1**	**Front plate**	
Part B	**1**	**Back plate**	
Part C	**1**	**Bigger spur gear with locking pin**	
Part D	**1**	**Smaller spur gear with large bevel gear**	

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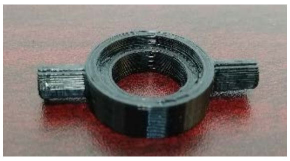
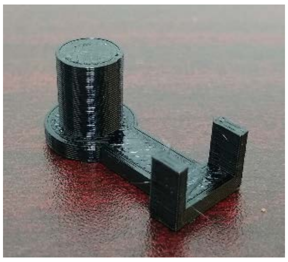
Part E	1	Smaller bevel gear	
Part F	1	Clamping ring for smaller bevel gear (Part E)	
Part G	1	Rotor for test tubes	
Part H	1	Clamping for Part D	
Part I	4	Rings for test tube	
Part J	8	Snaps for rotor	

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Part K	2	Bolts for clamping body	
Part L	2	Base clips for the bolts	
Part M	1	Smaller bevel gear holder	
Part N	1	Handle	
Part O	1	Grip for handle	
Part P	1	Locking clip for handle	

153 *2.2 Fabrication*

154 The components shown in Table 1 and available on the Open Science Framework [66] in both
155 and are released under a GNU General Public License (GPL) 3.0 [67]. Parts K and L are borrowed

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from a creative commons-licensed C-clamp design [68]. All of the parts were 3-D printed with glycol-modified polyethylene terephthalate (PETG) IC3D filament of diameter 2.85mm on a Lulzbot TAZ 6 (Aleph Objects, Loveland CO). The objects were sliced with Cura Lulzbot edition v.3.6.3 [69] using the standard settings summarized in Table 2.

Table 2. Slicer settings for each 3-D printed part

Part Name	Pre-defined settings (layer height)	Infill (%)
A	High speed (0.38 mm)	40
B	High speed (0.38 mm)	40
C	Standard (0.28mm)	65
D	Standard (0.28mm)	60
E	Standard (0.28mm)	60
F	High speed (0.38 mm)	90
G	High speed (0.38 mm)	40
H	High speed (0.38 mm)	40
I	Standard (0.28mm)	50
J	Standard (0.28mm)	60
K	Standard (0.28mm)	50
L	High speed (0.38 mm)	50
M	High speed (0.38 mm)	65
N	High speed (0.38 mm)	75
O	High speed (0.38 mm)	45
P	High speed (0.38 mm)	40

2.3 Assembly

All the parts of the centrifuge apparatus are shown in Table 1 from Part A through part O. The assembly of the open source centrifuge can be accomplished after the printed parts are prepared as follows. Part C is the big spur gear whose end part (square shaped) needs to be scraped with a knife or any sharp object before starting the assembly. Make sure to scrape a little material from the four edges on the square shaped end of Part C to ensure a tight fit between Part C and the handle (Part N). This is an important step as a tight fit will make rotating the handle easy and effective. All the holes on Part A and Part B need to be scraped a little to ensure smooth rotations of the respective gears. This problem is created due to non-uniform printing by the FFF printer. The four sockets on Part A are to be scraped as well for perfect fitting of the ball joints of Part B. Carefully remove small amount of material from all four sockets if the ball joints are not fitting inside the sockets. This operation may require some extra force. Part A and Part B are the two casings, which cover the gear train of the apparatus. Start assembling with Part B as the gears are meshed inside this part.

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Figure 1. Assembling Parts B and C

Part B has two holes of equal diameters where the gears are placed in order to carry out correct meshing. The right hand side of the part B has smaller diameter casing than the left hand side. Place Part C, which is the bigger spur gear through the hole on the right hand side (smaller casing side as seen in Figure 1). Lock the spur gear from the backside with the small connecting pin, which is included in the Part C. This will help to constrain the horizontal movement of the spur gear and will keep the shaft in place while rotating.

Figure 2. a) Inserting Part E into Parts B and b) inserting Part D.

Now insert Part E through the bigger circle situated on the top of Part B and hold it at the top (Figure 2a). Then insert Part D, which is the part with coupled gears, through the hole on the left side of Part B (Figure 2b).

Figure 3. a) Attaching Part H and b) Part E.

Attach part H from the backside of the Part B in the Part E's hole, which will hold the couple gears in one place and stop it from swiveling abruptly while rotating (Figure 3a). Then, place Part F , which is a small ring or clamp to constrain the vertical motion of Part E (Figure 3b).

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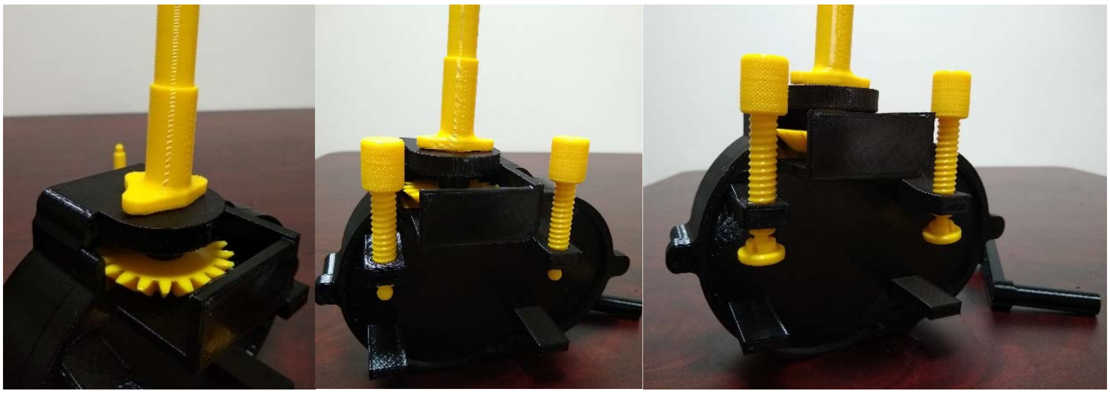

Figure 4. a) Inserting part M and b) assembling Parts K and c) L.

Part A is the other half of the casing, which is used to cover the gear train and clamping. Part A and Part B are clamped to each other using four ball-socket joints. Insert Part M through the Part E's square end and fix it to the casing through the three given holes (Figure 4a). This will help the small bevel gear to align perfectly in the vertical direction during rotations. Part K and Part L are used to clamp the whole centrifuge body to any even surface. Join both parts after the Part K is passed through the Part A's internal threading. Join Part K and Part L using the ball-socket joint (Figure 4b).

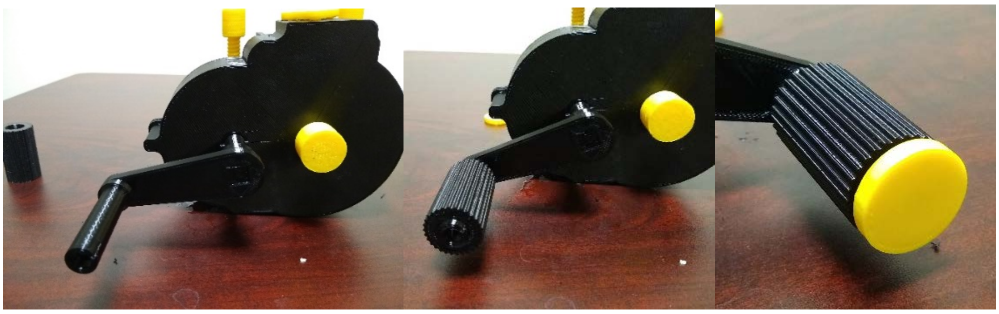

Figure 5. a) Attaching handle N, and b) grip and c) lock.

Part N, Part O and Part P are the components of the handle. Lock the Part N in the square end of Part C. Make sure to scrape some material with the help of knife or any sharp object from the Part C's square end to tight fit Part C with Part N. If sufficient material is not scraped then Part C will not fit with Part N, and if it is scraped more than the handle will fit loosely which will create snapping problem while rotating the handle. Part O is the grip, which is used to rotate the handle. Fix Part O and Part P with the ball-socket joint to fix the Grip.

Figure 6. Assembling a) Part G, b) Part I and c) Part J.

Part G, Part I and Part J are the parts of the rotor assembly. Part G is the rotor that will hold the rings (Part I) and the snaps (Part J). Place the rings in the rotor and clamp the rings by placing the snaps into the rotor. This will prevent the rings from falling during the motion due to high centrifugal force.

2.4 Operation

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After completing the assembly, clamp the centrifuge apparatus on one side of a table (preferably a rectangular table and not a circular one). Place the test tubes in the test tube rings carefully. It is extremely important to balance the weight of the test tubes equally. Leaving out test tubes or heavily loading one will cause vibrations and will make the whole apparatus unstable while in operation. If only 3 of the test tubes are used for sample testing, make sure to fill the fourth test tube with water or a liquid that is of similar density that of the sample. This will ensure equal distribution of weight. Crank the handle, which is equipped with a grip.

2.5 Validation

As the working part of the centrifuge rotates at a speed of up to 2,000 rpm, it may be difficult to track its motion since the majority of regular web cameras are operating at a frequency of 25-30 Hz. Thus, as the whole system represents a mechanical transmission with the fixed gear ratio, an indirect method was chosen to calculate the angular velocity of the tubes based on the speed of rotation of the centrifuge handle (Figure 7).

A Python-based software was developed to automatically measure the rotational speed of the centrifuge. The OpenCV library [70] for segmentation and tracking a visual marker located on the centrifuge handle, and PyQt library [71] were used for creating an open source guided graphical user interface (GUI) application (Figure 8) [72].

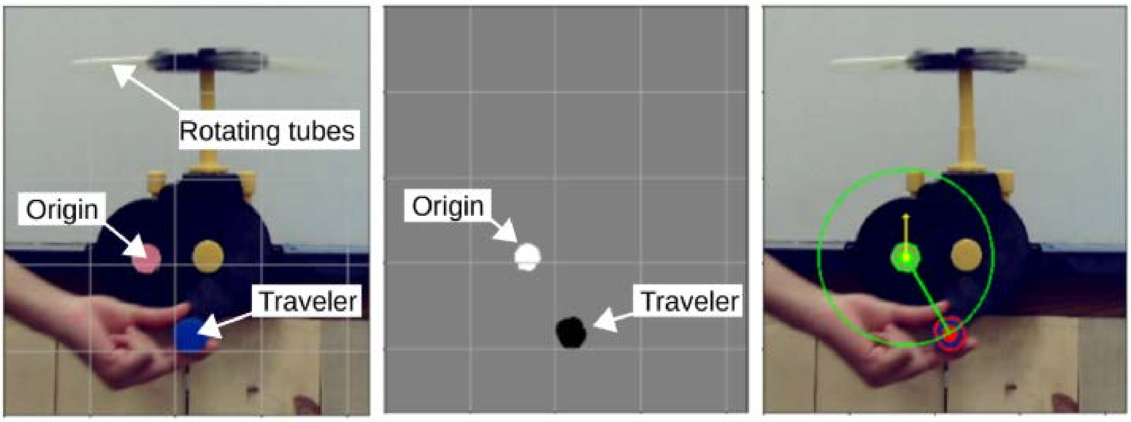

Figure 7. Image-based markers segmentation a) Cropped frame of the centrifuge with the visual markers, b) Masked image c) Calculated handle orientation.

The developed application allows users to crop an arbitrary region of interest of the captured camera frame and set RGB thresholds for tracking the visual markers of any distinctive colors. It counts the number of centrifuge handle revolutions and calculates angular velocity of the tubes. With the given information about the tube length, the program also computes its relative centrifugal force. In the case of normal manual rotation, the central marker will be periodically covered by the hand/arm of the user, so it is possible to set the x and y coordinates of the origin point in the program code.

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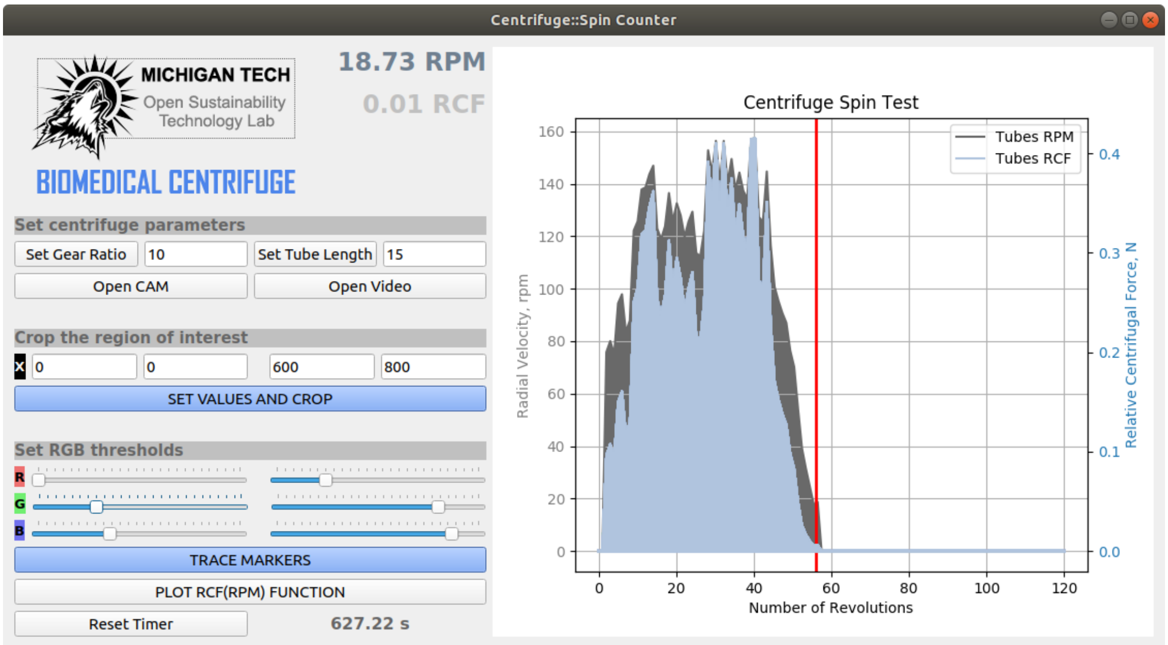

Figure 8. A screenshot of the open source biometical centrifuge interface for camera-based RPM and RCF calculations.

The main computer vision algorithm is provided below. The RPM and RCF calculations are based on tracking the coordinates of the traveler marker located on the centrifuge handle. By applying the specified color thresholds and morphological operations of “opening” and “closing” to a cropped camera frame the user can mask the marker as a single separated color region. To find the coordinates of its centroid the method of moments is employed, which will allow the centrifuge handle orientation relative to the center of rotation to be calculated. To do this RPM_T, the rotational velocity of the tubes in rpm is given by:

$$RPM_T = G \cdot \frac{60}{\Delta t} \quad (6)$$

where, G, is the gear ratio and Δt is the time interval for a single revolution in seconds. The RCF in Newtons is given by:

$$RCF = 1.118 \cdot 10^{-6} \cdot D \cdot RPM_T^2 \quad (7)$$

Where D is the length of the test tube with the radius of the centrifuge rotor in mm. A series of eight experiments for various rotational speeds for an RCF(RPM) plot are performed to compare the theory to experiment. Such a validation experiment is recommended for those building their own centrifuge before deployment. Depending on the critical nature of the application of the open source centrifuge, users may wish to record and run the validation for every experiment or simply keep track of the approximate number of rotations and rotations/minute of the handle to obtain an approximate RPM/RCF.

As can be seen in Figure 8, the user can set the RGB thresholds and crop the region of interest in the video. Users can also set the tube length and gear ratio to calculate the RPM and RCF. The RCF and relative velocity are plotted in real time. The pseudo code is given as follows:

Computing angular velocity and relative centrifugal force

Input: an image frame from a camera or a video sequence
Output: RPM and RCF values for the test tubes

while a camera is open or a video is reading **do:**
    get a single frame as an RGB image

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```
        crop the region of interest of the image frame
        apply linear filtering to blur the cropped region
        mask color marker using RGB thresholds
        apply operations of opening and closing to remove noise after RGB masking
        find the contours of the masked area

        if the traveler marker is detected do:
            find the centroid location of the color marker applying the method of moments
            calculate the radius of rotation and the angle of the centrifuge arm

            if the angle is in a specified zero range do:
                increase number of revolutions by one
                update timer and compute the time period for one revolution
                calculate the tubes RPM
                calculate the tubes RCF
            end if
        end if
    end while
```

2.6 Economic Analysis

In order to determine the costs for the apparatus the entire device was massed on a digital scale +/-0.01 kg. The total cost (T_c) of the apparatus can be determined by:

$$T_c = mC_e + mC_p \quad (8)$$

Where m is the mass of all the 3-D printed parts (e.g. the whole apparatus), C_e is the cost of the electricity per kg to print and C_p is the cost of plastic per kg. The electricity to operate the Lulzbot Taz 6 is about 9.11 kWh per kg as measured by a multimeter +/- 0.01 kWh. The average cost of commercial electricity in the U.S. is $0.1029/kWh [73]. This value was used assuming that the device was fabricated at a university or government laboratory, which would be considered a mid-range value between those fabricating it using residential electricity rates (higher) and distributed solar photovoltaic electricity (lower). The cost of IC3D filament from Lulzbot was US$45/kg [74].

3. Results

All of the parts of the open source centrifuge can be printed on the standard RepRap-class FFF-based 3-D printer. Here all the parts were printed on a Lulzbot Taz 6 using standard print settings in PETG. Part A and Part B are the longest prints, which take more than 8 hours to complete each. All the gears are printed with more than 60 % fill, thus they have the printing times of more than 3 hours. The total printing time for all the parts is about 35 hours. The printing time can be reduced if the 'High speed' (0.28mm z height) pre-defined setting is used with reduction in the infill percentage up to certain level. In addition, a nozzle with a larger orifice would also speed printing.

The open source centrifuge takes about 30 minutes to assemble after printing all the parts if all the instructions in Section 2.3 are carefully followed. The open source centrifuge is shown fully assembled in the pre-spin state clamped to a desk in Figure 9. The complete system with filled test tubes is shown during rotation in Figure 10a and a screen capture of a centrifuge cam used for the GUI is shown in Figure 10b. Note the blue tape on the handle end to enable easy computer vision analysis. The same functionality can be obtained using a different colored 3-D print for part P, coloring it with a marker, or using a sticker. To see the device in operation see the Video S1: MOST_CENTRIFUGE_VIDEO.avi.

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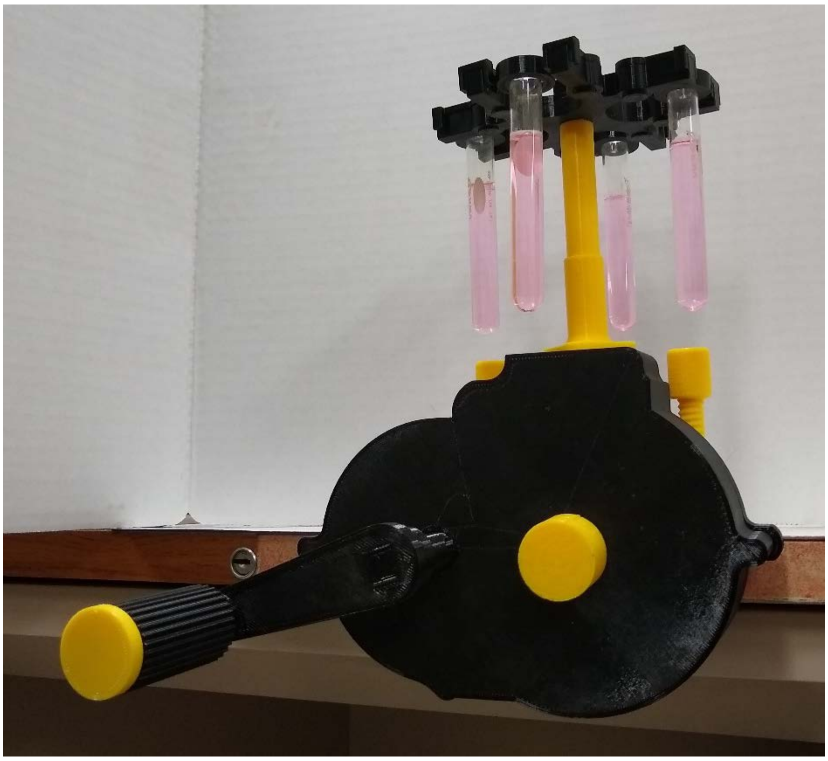

Figure 9. Fully assembled open source centrifuge in the pre-spin state.

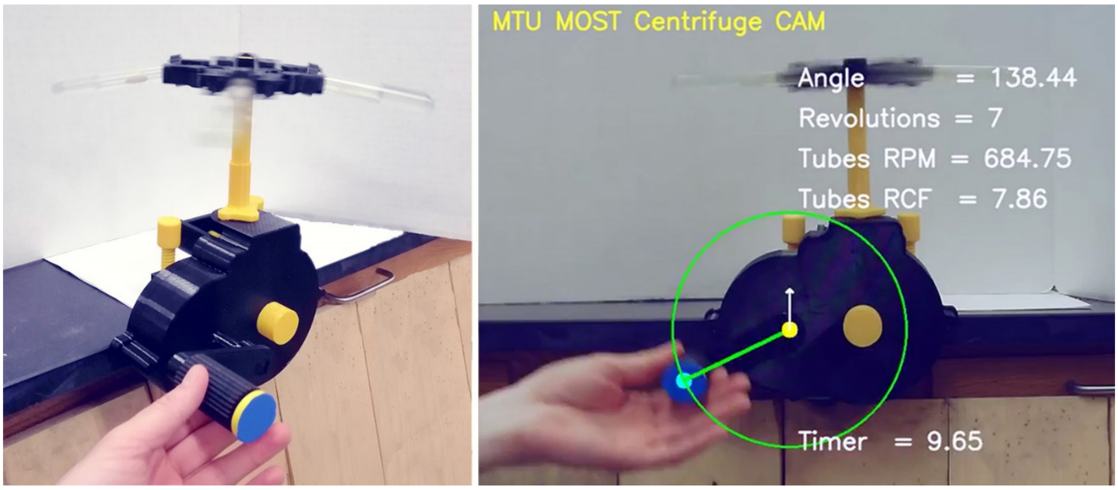

Figure 10. a) complete system with filled test tubes during rotation and b) a screen capture of a centrifuge cam used for the GUI. Tracking of the handle marker, time, angle, number of revolutions, RPM and RCF are all shown in real time.

During validation experiments with filled test tubes, the RCF(RPM) function was obtained for a wide range of rotational velocities and compared to theory (Figure 9). As can be seen in Figure 9 the apparatus performs as expected from a start at stationary to over 1750 rpm.

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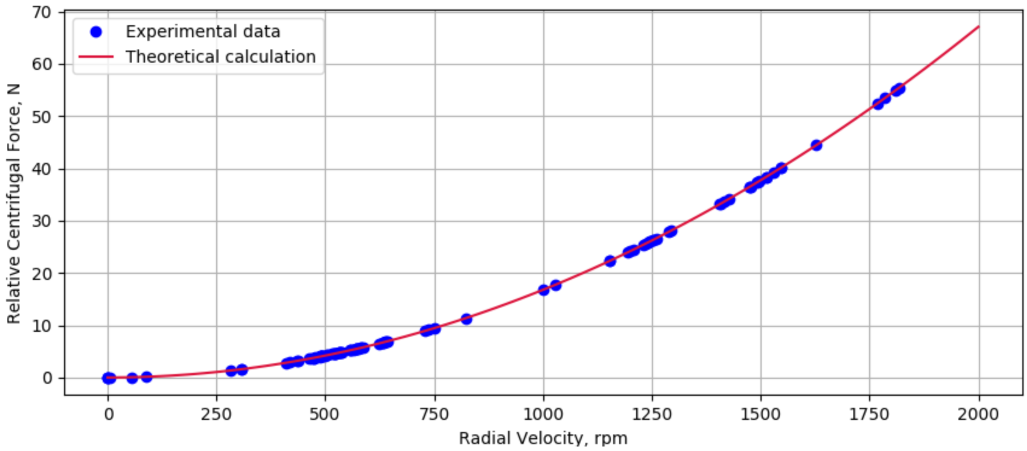

Figure 11. Relative centrifugal force as a function of the rotational velocity of the centrifuge test tubes.

4. Discussion

This study successfully described, tested and validated a completely open source centrifuge, which can be fabricated using only open source tools, validated with a laptop computer with webcam using only free and open source software, and operated anywhere in the world with no electricity inputs. In addition, this device can be fabricated for far less than commercial proprietary tools. The total mass of the apparatus is 0.550 kg, which results in about US$0.50 in electricity costs and $24.75 in commercial costs of filament for a total cost of US$25.26. This compares to commercial systems, which cost US$60-100 [60,61] and do not have a means of easy field validation without the use of the open source GUI disclosed here. Thus, a considerable saving of 57-75% decrease in cost can be achieved with this device. However, as this device is primarily developed for applications in resource-constrained settings, further cost reductions are needed.

The economics of using commercial 3-D printing filament are somewhat attractive, however, they can be improved by using filament fabricated with a recyclebot [75-77] from recycled waste polymers. Former 3-D printed polymers can be recycled with acceptable mechanical strengths for about five cycles [78,79]. Thermopolymers, which already demonstrated with recyclebot processing, include: polylactic acid (PLA) [77-81], PET and PETG [82-84], high-density polyethylene (HDPE) [76,84-89], acrylonitrile butadiene styrene (ABS) [84,88-92], polystyrene (PS) [84], polypropylene (PP) [84,], elastomers [93] as well as polypropylene blends [94] and composites like waste wood biopolymers [95] and carbon fiber reinforced plastics [96]). Modern recyclebots can make filament from waste plastic for electricity costs between 2.4 [92] and 3.6 [77] cents/kg. As the design here massed as 0.550 kg, it would cost between 1.3 and 2 cents in recycled filament and about 91 cents to print, which results in a total cost of about US$0.92-$0.93. This provides savings of 98-99% compared to commercial offerings. However, there are two ways these costs can be even further reduced. The first involves using a previously acquired solar photovoltaic powered recyclebot [80,89,91] and solar powered 3-D printer [89,91,97-99]. The electricity costs are then avoided dropping the marginal costs of materials and energy near zero, although the capital cost would need to be amortized by printing many valuable products or be given as a donation. In addition, direct fused particle fabrication (FPF) or fused granular fabrication (FGF) can be used to recycle a wide range of materials including PET, PP, ABS, and PLA [100]. Directly printing shredded waste plastic takes the cost of the materials and processing of the open source centrifuge down under US$0.50. The commercial open source FPF/FGF systems have high capital costs although they can fabricate generally large valuable products that provide users with a high return on investment if they are used frequently [101].

This study indicates several areas of future work. First, more research is needed to make small-scale FPF/FGF 3-D printers to fabricate waste plastic into open source centrifuges for resource constrained areas. Such systems would ideally be solar photovoltaic powered. Future work could

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also look at the potential for a 3-D printable waste plastic shredder – again ideally solar or manual powered that could be used to complete the entire tool chain from waste to finished scientific instrument. It should be noted in the cost calculations above, the labor costs were not included. Future work can address the labor costs in a range of contexts, however, past analysis of open hardware for science by Trivedi et al. [102] have shown that zero labor costs are relevant for several scientific instrument situations where: i) there is no opportunity cost to using existing salaried employee (e.g., lab managers, research assistants, teaching assistants 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); ii) fabrication of the instruments is used as a learning aid [103,104]; or iii) the labor is provided by unpaid interns or volunteers (e.g., undergraduate students volunteering for research experience). In general, in resource-constrained settings as well as most academic institutions these conditions can be met. For those settings where this is not the case, the tasks to order and deploy a commercial product should be compared to the relatively low-time investment of printing (only set up and take off necessary as the 3-D printers can be left unattended) and assembling the open source centrifuge.

5. Conclusions

This paper provides the complete open source plans including the BOM, instructions for fabrication and operation, and open source software for a hand-powered centrifuge. This study successfully described, tested and validated this completely open source centrifuge, which can be fabricated using only open source tools (e.g. RepRap-class 3-D printer). Further, the validation itself uses only open source and readily available tools of a computer with webcam. The instrument can be operated anywhere in the world with no electricity inputs obtaining a radial velocity of over 1750rpm and over 50N of relative centrifugal force. Using commercial filament the instrument costs about US$25, which is less than half of all commercially available systems; however, the costs can be dropped further using recycled plastics on open source systems for over 99% savings.

Supplementary Materials: Video S1: MOST_CENTRIFUGE_VIDEO.avi.

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