e-ISSN: 3062-1399

Journal of International Architectural Sciences

JIArcS, 2026, 3 (1): 53-68

Research Article

https://mimarlikbilimleri.com/ojs/index.php/architecturalsciences

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Design of a Low-Cost, Hand-Operated Centrifuge with Real-Time Monitoring

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Abstract

This study has developed a modular centrifuge system that is portable, low-cost and does not require electricity. It can be produced using 3D printing technology. The project aims to provide an economical, energy-independent solution for separating biological and chemical samples, particularly in environments where access to electricity is limited or laboratory infrastructure is inadequate. Findings obtained from the experiments suggest that the centrifuge can generate sufficient centrifugal force for basic separation processes at laboratory level, producing results consistent with the 2000×g range specified in the literature. The developed centrifuge supports the 'frugal science' approach due to its low production cost, modular structure, lack of energy requirements and ease of replication via 3D printing.

Keywords: *3D Printing Technology, Arduino-Based Systems, Low-Cost Design, Manually Operated Mechanisms, Real-Time Measurement.*

Düşük Maliyetli, Elektriksiz Çalışan ve Gerçek Zamanlı Ölçüm Yapabilen bir Santrifüj Tasarımı

Öz

Bu çalışmayla, elektrik gerektirmeyen, taşınabilir, düşük maliyetli ve 3B baskı teknolojisiyle üretilebilen modüler bir santrifüj sistemi geliştirilmiştir. Projenin amacı, özellikle elektrik erişiminin sınırlı olduğu veya laboratuvar altyapısının yetersiz bulunduğu ortamlarda biyolojik ve kimyasal numunelerin ayrıştırılmasını sağlayabilecek, enerji bağımsız, ekonomik bir çözüm sunmaktır. Deneyler sonucunda elde edilen bulgular, cihazın laboratuvar düzeyinde temel ayırma işlemleri için yeterli merkezkaç kuvveti üretebildiğini ve literatürde belirtilen 2000×g aralığıyla uyumlu sonuçlar verdiğini göstermiştir. Geliştirilen santrifüj, düşük üretim maliyeti, modüler yapısı, enerji gereksinimi bulunmaması ve 3B baskı ile kolaylıkla çoğaltılabilir olması sayesinde "tutumlu bilim" (frugal science) yaklaşımını desteklemektedir.

Anahtar kelimeler: *3B Baskı Teknolojisi, Arduino Tabanlı Sistemler, Düşük Maliyetli Tasarım, Elle Çalıştırılan Mekanizmalar, Gerçek Zamanlı Ölçüm.*

Citation: Haleve, R., Bahar, Y., Kılıç, T., Çukurkent, A., Akpınar, O., Şahin Diri, B. & Diri, B. (2026). Design of a low-cost, hand-operated centrifuge with real-time monitoring. *Journal of International Architectural Sciences*. 3 (1): 53-68.
DOI: https://doi.org/10.5281/zenodo.19668174

Received: *January 28, 2026 –* ***Accepted:*** *April 18, 2026*

1. Introduction

A centrifuge is a device that uses centrifugal force to separate substances of different densities within liquids (Sule et al., 2019). A common tool in laboratories, centrifuges play an important role in processes such as separating plasma from blood samples, detecting pathogens in biological fluids and isolating DNA (Haque et al., 2022).

Centrifugation involves spinning a sample around an axis to increase the gravitational field strength. This creates a relative centrifugal force (RCF), also known as 'g' force, which pulls cells and other particles towards the position farthest from the centre of rotation. RCF is proportional to the square of the rotor speed and radial distance, and can be calculated using the following equation (Haque et al., 2022) (Eq. 1).

$$RCF = 1.118 \times 10^{-5} \times \overline{r} \times \omega^2 \qquad \text{(Equation 1)}$$

Here, $\overline{r}$ is the average radial distance of the sample in the tube (in centimetres) and ω is the rotor speed (in revolutions per minute, RPM). The radial dimensions of the centrifuge tubes are given in Figure 1.

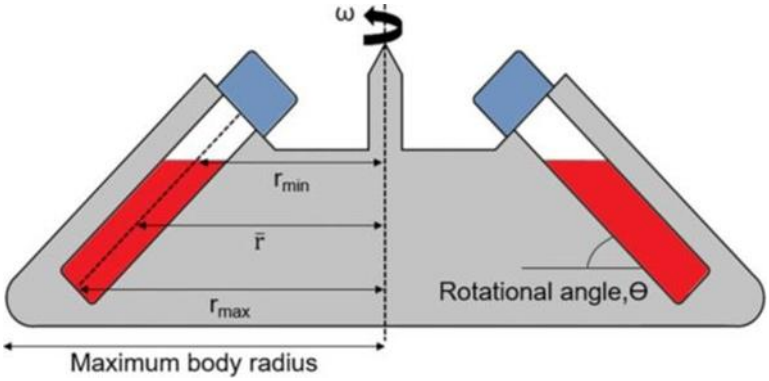


Figure 1. Schematic representation and radial dimensions of centrifuge tubes on a fixed-angle adapter (Haque et al., 2022)

From Equation 1, we can see that the RCF increases with rotor speed and distance from the axis. However, to achieve the highest RCF value, it is necessary to consider not only these two parameters, but also factors such as the moment of inertia, torque and aerodynamic drag. Changes in rotor geometry increase motor torque, leading to a decrease in rotational speed due to the inverse proportion between torque and speed. Since RCF is proportional to the square of the speed, a decrease in rotor speed significantly reduces separation efficiency. Therefore, centrifuge design must strike a balance between radial distance and speed. While increasing the radial distance raises the RCF, the rotational speed may decrease due to increased inertial moment and aerodynamic drag. In this study, the speed parameter was prioritised due to its square relationship with RCF, and the system was designed to be lightweight, compact and efficient. In addition, the rotational angle is an important factor in the separation process. As high-angle rotors tend to produce more compact pellet formation, 45° fixed-angle rotors are commonly favoured in commercial systems (Haque et al., 2022).

Unlike commercial centrifuges, the system developed in this study allows the tubes to move to a 0° position parallel to the radial distance during centrifugation. This ensures that the centrifugal force acts entirely in a horizontal direction. The ability of this innovative design to increase pellet formation speed and improve separation efficiency has been investigated.

Traditional centrifuges typically operate under fixed laboratory conditions and rely on electrical power. They are also high-cost devices (Byagathvalli et al., 2019). With a capacity of 20–100 tubes, these devices have rotor diameters ranging from 20–40 cm and weigh an average of 120 kg.

In weight. Prices start at 1,500 US dollars. Although smaller microcentrifuge models are available, these are generally limited to samples with a volume of less than 1.5 ml and are not compatible with clinical tubes (Haque et al., 2022).

Around 14% of the global population — approximately 1.1 billion people — still lack access to electricity. Even in areas where electricity is available, frequent power outages can disrupt laboratory work. In Nigeria, for example, prolonged power outages force many laboratories to use generators, which leads to high costs and an adverse environmental impact. To overcome these issues, alternative manually operated centrifuge systems have been developed. These include paper centrifuges (paperfuges), salad spinner-based centrifuges and egg beater-based centrifuges. However, Sule et al. (2019) found that these systems cannot provide sufficient durability and efficiency for high-volume samples.

In recent years, open-source and low-cost scientific devices have grown in popularity within the scientific community. Components produced using 3D printing technology are used in applications such as chemical mixing, optical testing, measuring water quality, and microfluidic systems. This technology enables the development of economical, customisable, modular solutions (Sule et al., 2019).

One of the most notable studies in this area is the 'Paperfuge' project, which was developed by Manu Prakash and his team at Stanford University. Inspired by a toy pinwheel, this motorless centrifuge costs only 20 pence to produce and can reach speeds of 125,000 RPM when powered by humans. The Paperfuge has brought innovation to diagnostic processes in areas with limited resources by performing basic biological procedures such as separating blood from plasma (Bhamla et al., 2017).

Similarly, the '3B-Fuge', developed by Byagathvalli et al. (2019), can be produced on a 3D printer for less than 1 USD and can reach speeds of 6,000 RPM (approximately 2,000 g). These are successful examples of the 'frugal science' approach that has emerged in recent years, aiming to make scientific devices more accessible, portable and affordable. The proliferation of 3D printing technology has also enabled the quick, cheap and practical production of such devices (Byagathvalli et al., 2019).

This study begins with the premise that centrifuges, which are widely used in laboratories, are expensive, require electricity and are not portable. This limits scientific research, particularly in rural areas and schools with limited resources. Where access to electricity is limited, there is a need for an economical, accessible solution that can enable the separation of biological samples.

The aim of this study is therefore to develop a prototype centrifuge that can be produced using 3D printing technology. This centrifuge should have a modular structure, be low-cost and be manually operable. The prototype is intended to measure speed in real time via an Arduino microcontroller and operate independently of energy sources.

This will result in the creation of a portable, innovative and sustainable laboratory tool for researchers and students, thereby increasing access to scientific tools and promoting the adoption of a frugal science approach.

2. Material and Method

Within the scope of this project, a prototype of a manually operated, low-cost, portable centrifuge that does not require electricity has been developed. The system can be produced modularly using 3D printing technology and measures speed in real time using an Arduino microcontroller. This innovative centrifuge is intended to facilitate biological analyses in rural areas and laboratories with limited resources.

2.1. Materials and Equipment Used

The materials used in the production of the device are listed below;

PLA filament (UZARAS 1.75 mm White PLA Plus™ Filament); Arduino infrared sensor (Easy Electronics 2-piece IR); Arduino LCD screen (SANEC Arduino 2x16 LCD Screen (I2C Module)); Pin-separable jumper cable; 10 mm diameter x 3 mm neodymium magnet (NdFeB magnet); 8 pieces; One each of:

- 20 cm iron rod with an 8 mm diameter;
- 10 cm iron rod with an 8 mm diameter;
- 08 cm iron rod with an 8 mm diameter;

8 pieces of bearing (608zz) with an 8 mm inner diameter; 300 mm x 150 mm x 3 mm transparent plexiglass sheet; M3 x 5 mm bolt and nut. The material cost analysis is shown in Table 1.

Table 1. Material cost analysis (Created by the authors)

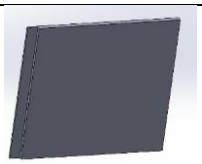
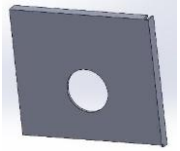
Material Name	Aim of Use	Quantity	Unit Price	Total Cost
PLA Filament	Body and gear production with a 3D printer	0.4 Kg	300 TL/Kg	**120 TL**
Arduino Nano (Clone)	Speed measurement and data processing	1 Piece	120 TL	**120 TL**
LCD Screen (16x2 I2C)	Instantaneous display of RPM value	1 Piece	50 TL	**50 TL**
PIR Sensor	Detection of number of revolutions	2 Piece	25 TL	**25 TL**
Bearing (608zz)	Reducing friction and rotational movement	8 Piece	15 TL	**120 TL**
Neodymium Magnet	Sensor trigger	8 Piece	10 TL	**80 TL**
Connecting Elements	Assembly (Screws, Nuts, Washers, etc.)	1 Package	35 TL	**35 TL**
TOTAL				**550 TL**

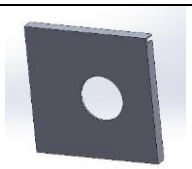
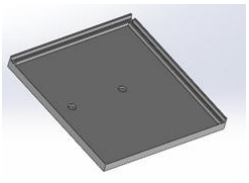
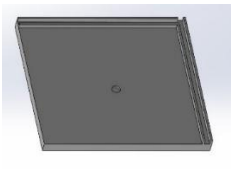
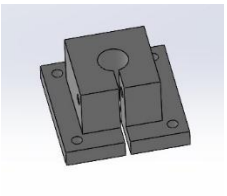
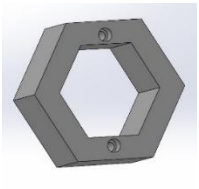
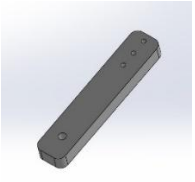
The equipment used consists of a 3D printer (Creality Ender 3 Pro), a microcontroller, (Arduino UNO) and a digital Laser RPM Tachometer (TLS Robotik DT-2234C).

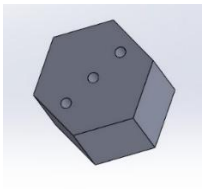
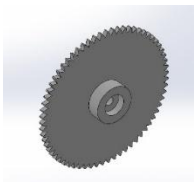
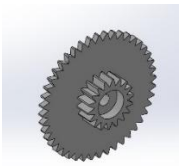
2.2. Modelling and Printing Process

All of the 3D-printed components of the centrifuge were designed using SolidWorks software in a 3D modelling (CAD) environment and manufactured using fused deposition modelling (FDM) technology. The printing processes were carried out using a Creality Ender 3 Pro 3D printer. Polylactic acid (PLA)-based UZARAS 1.75 mm White PLA Plus™ filament was used to produce the centrifuge's main components. All parts were prepared using standard printing parameters via Ultimaker Cura 15 slicing software and transferred to the printer. Table 2 presents the basic components of the designed centrifuge and information about the function of each component.

Table 2. List of the main components of the modular centrifuge produced using 3D printing technology (Created by the authors)

Components	Quantity	Role	The Appearance of Components
Segment 1	1	Left rear wall	
Segment 2	1	Right rear wall	
Segment 3	1	Left ceiling	

Segment 4	1	Right ceiling	
Segment 5	1	Right side wall	
Segment 6	1	Left side wall	
Segment 7	1	Bottom right base	
Segment 8	1	Bottom left base	
Segment 9	3	Shaft holder	
Segment 10	1	Hexagonal nut	
Segment 11	1	Centrifuge rotating arm	
Segment 12	1	Centrifuge rotating arm extension	

Segment 13	1	Hexagonal rotating arm	
Segment 14	2	Rotating roller	
Segment 15	1	Sample rotating roller	
Segment 16	1	64-tooth disc (150 mm diameter)	
Segment 17	2	44, 18-tooth compound disc (100 mm and 40 mm diameter)	
Segment 18	1	Sample holder table	
Segment 19	1	Sample holder tray cover	
Segment 20	12	Sample ring (rotor)	

2.3. RPM Meter (Tachometer)

An Arduino-based tachometer system has been designed to monitor the rotation speed (RPM) of samples in a modular centrifuge in real time.This system consists of three main components: a sensor module (Arduino Infrared Sensor (Easy Electronics 2 Pcs IR)), an Arduino UNO microcontroller, and an LCD screen (SANEC Arduino 2x16 LCD Screen (with I2C Module)).The sensor detects signals from the rotor's rotational movement and transmits them to the Arduino board. The data processed by the Arduino is then displayed as RPM values on the LCD screen.The connection layout of the tachometer system are presented in Figure 2, and circuit diagram of the tachometer system are presented in Figure 3.

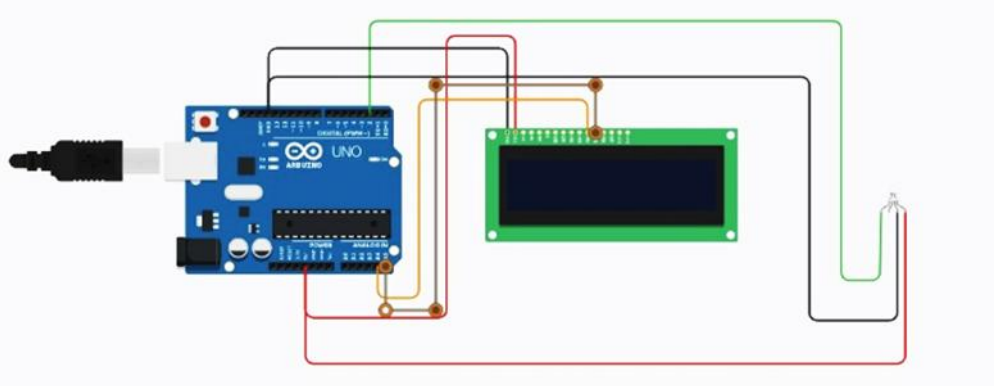


Figure 2. Connection diagram of the RPM (tachometer) system.This is a circuit diagram showing the physical layout of the connections between the Arduino UNO board, the LCD screen, and the sensor module.This system allows for real-time measurement of the centrifuge's rotation speed (RPM) (Created by the authors)

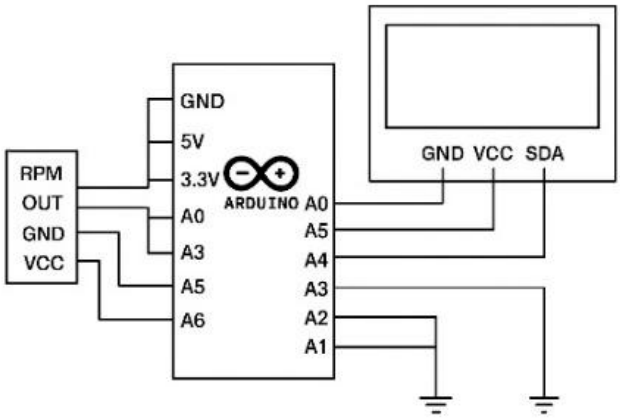


Figure 3. Circuit diagram of an RPM (tachometer) system.This is a technical drawing showing the electronic connections of the basic components (Arduino UNO, LCD screen, and sensor module) used in a tachometer system.This diagram illustrates the system's circuit-level setup and the data flow between the measurement components (Created by the authors)

Special software has been developed to enable the Arduino-based tachometer to measure the rotational speed (RPM) of the centrifuge rotor in real time.This software calculates the number of revolutions per minute over a specific time interval by counting the digital signals received from the sensor and displays the resulting value on an LCD screen.The primary goal of the code is to accurately and reliably measure rotational speed while also enabling the system to respond quickly to instantaneous changes.The code section is based on the code found in the forum post titled "Arduino IR Tacho" ("Arduino IR Tacho", 2022).The software code for the tachometer system is given in Figure 4.

```
#include<LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd (0x27, 16.2);//
float value=0;
float rev=0;
int rpm;
int oldtime=0;
int newtime;
void isr() //interrupt service routine
{
rev++;
}
void setup()
{
lcd.begin();
lcd.clear();
lcd.backlight();
attachInterrupt(digitalPinToInterrupt(2),isr,RISING);}
void loop()
{
delay(1000);
detachInterrupt(0);//detaches the interrupt
newtime=millis()-oldtime;//finds the time
int wings = 1;// no of wings of rotating object, for disc object use 1 with white
tape on one side
int RPMnew = rev/wings;//here we used fan which has 3 wings
rpm=RPMnew*(60000/newtime);//calculates rpm
oldtime=millis();//saves the current time
lcd.clear();
lcd.setCursor(0,0);
lcd.print("___TACHOMETER___");
lcd.setCursor(0,1);
lcd.print(rpm);
lcd.print("RPM");
lcd.print(" ");
lcd.setCursor(8,1);
lcd.print(rev);
lcd.print(" rev");
lcd.print(" ");
rev=0;
attachInterrupt(digitalPinToInterrupt(2),isr,RISING);

}
```

Figure 4. Software code for an Arduino-based RPM measuring system ("Arduino IR Tacho", 2022).The figure shows the program flow that enables reading sensor signals, using timer functions, and displaying the measured RPM values on the LCD (Created by the authors)

2.4. Centrifuge Assembly

The modular centrifuge that was designed was assembled by combining the components modeled in a CAD environment.The assembly process was carried out in four main stages: rotor system, drive mechanism, fuselage components, and cover system.

First, the motor and gear system that provide the basic movement of the centrifuge were placed on the lower platform and axial alignment was performed.Next, gears are mounted to connect the rotor

shaft to the motor shaft, providing rotational transmission.The sample carrier rotor and tube holders are fixed to the upper platform, ensuring stable placement of the samples.

The centrifuge body consists of modular panels produced using 3D printing.These panels are assembled to hold the lower and upper platforms together, after which the protective side covers and front panel are secured.In the final stage, the electronic components (tachometer sensor, LCD screen, Arduino board) were installed and the wiring was completed.Finally, the system was enclosed with transparent plexiglass.Figure 5 shows the assembled mechanical components of the centrifuge and their assembly sequence, while Figure 6 shows the fully assembled version.

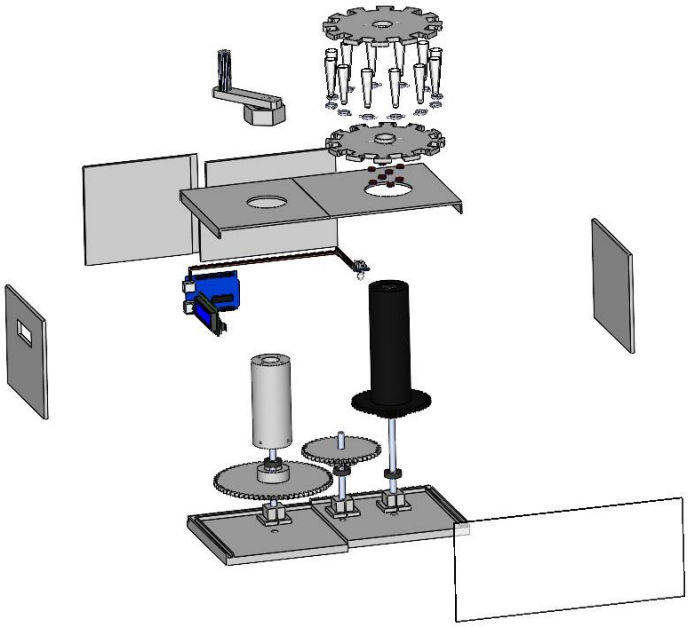


Figure 5. Exploded 3D view showing the assembly stages of the modular centrifuge.The figure schematically shows the assembly sequence and positions of the centrifuge's rotor, gear system, motor, housing panels, and sample carrier components (Created by the authors)

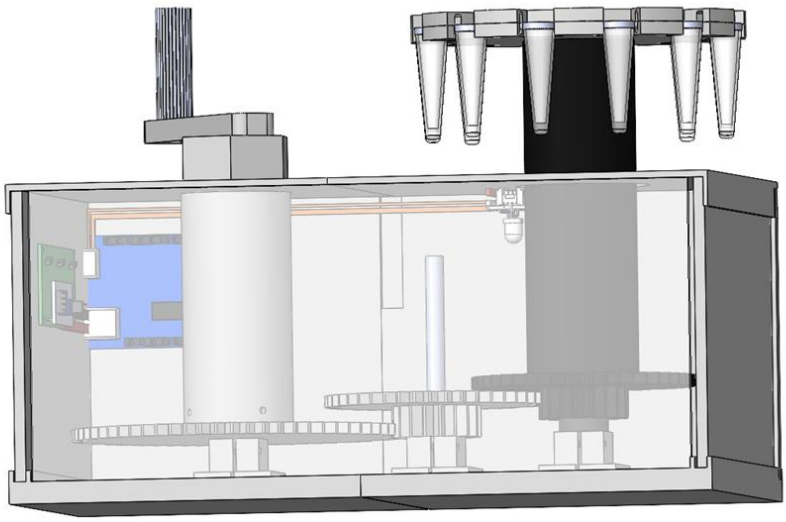


Figure 6. 3D view of the assembled modular centrifuge (310 x 155 x 135 mm) (Created by the authors)

2.5. RPM Calculation of the Gear System of a Modular Centrifuge

The gear system of the modular centrifuge, which generates the centrifugal force necessary for pellet formation of the samples, is positioned as shown in Figure 7.

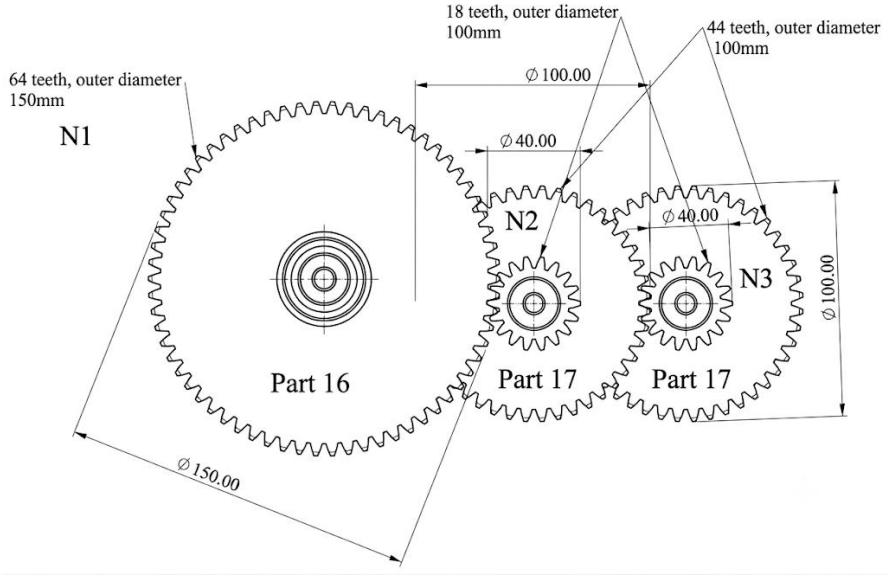


Figure 7. Diagram showing the layout of the gear system of a modular centrifuge (Created by the authors)

The RPM output of the gear system of the modular centrifuge has been theoretically calculated using the following formula. Number of teeth: (Eq. 2)

$$N_1 = 64, N_{2a} = 18, N_{2b} = 44, N_3 = 18 \quad \text{(Equation 2)}$$

When the first gear is rotated one full turn (revolutions per second), the rotation of the last gear is found as follows.$\Delta\theta_1 = 1\Delta\theta_3$

The basic relationship between two gears (for gear pair A–B) (Eq. 3):

$$\omega_A N_A = -\omega_B N_B \Longrightarrow \frac{\omega_A}{\omega_B} = -\frac{N_B}{N_A} \quad \text{(Equation 3)}$$

And since angular velocity and angular displacement (number of rotations) are directly proportional, the same ratio applies to the number of rotations (Eq. 4):

$$\frac{\Delta\theta_A}{\Delta\theta_B} = -\frac{N_B}{N_A} \quad \text{(Equation 4)}$$

In the system, since the two teeth of the second combined gear are on the same shaft and similarly Accordingly (Eq. 5): $\omega_{2a} = \omega_{2b} = \omega_2 \Delta\theta_{2a} = \Delta\theta_{2b} = \Delta\theta_2$

$$\Delta\theta_2 = -\frac{N_1}{N_{2a}}\ \Delta\theta_1 \quad \text{(Equation 5)}$$

and (Eq. 6),

$$\Delta\theta_3 = -\frac{N_{2b}}{N_3}\ \Delta\theta_2 \quad \text{(Equation 6)}$$

Since two minus signs cancel each other out (two contacts = two changes of direction), for magnitüde (Eq. 7):

$$\boxed{\Delta\theta_3 = \frac{N_1}{N_{2a}} \cdot \frac{N_{2b}}{N_3}\ \Delta\theta_1} \quad \text{(Equation 7)}$$

The formula above shows how many revolutions N3 makes in one second if N1 makes one revolution in one second.To obtain the standard 1 revolution/min result of N3 to which the samples are attached, the result of Equation 7 is multiplied by 60 (1 min = 60 s) to find the RPM value.

To test the accuracy of the modular centrifuge's RPM measurement system, the device's measurements were compared with those of a tachometer (TLS Robotik DT-2234C Digital Laser RPM Tachometer).

2.6. Modular Centrifuge Testing Method

To evaluate the performance of the developed modular centrifuge, experimental applications were carried out on two different sample types: one biological and one chemical.A solution of Saccharomyces cerevisiae (yeast) was used as the biological sample, and a saturated calcium carbonate (CaCO3) solution (0.5 M, 100 mL) was used as the chemical sample.

Both sample types were distributed in equal volumes (2 mL) into Eppendorf tubes, and care was taken to maintain rotor balance.During the experiments, the rotational speed of the 64-toothed rotor was adjusted to one full revolution per second and its multiples, and the sedimentation behavior of the samples was observed at different RPM values.

In the yeast solution, the time it took for cells to gather at the bottom was used as the evaluation criterion, while in the CaCO3 solution, the rate of decomposition of solid particles was used.Thus, the device's ability to perform effective separation on both live biological samples and chemical solutions was investigated.

To test the accuracy of the modular centrifuge's RPM measurement system, the device's measurements were compared with those of a tachometer (TLS Robotik DT-2234C Digital Laser RPM Tachometer).In addition, parallel experiments were conducted with a commercial laboratory centrifuge (ISOLAB Refrigerated Centrifuge) to evaluate the overall performance of the device.

3. Findings and Discussion

The modular centrifuge, which forms the basis of the project, was first designed in a three-dimensional (3D) modeling (CAD) environment using SolidWorks software, 2022 version. The components, whose design has been completed, were manufactured using fused deposition modeling (FDM) technology, and all parts are listed in detail in Table 2.After assembling the mechanical components, the electronic elements such as the tachometer sensor, LCD screen, and Arduino board were installed, and the wiring was completed, resulting in the final assembly of the system as shown in Figure 8.

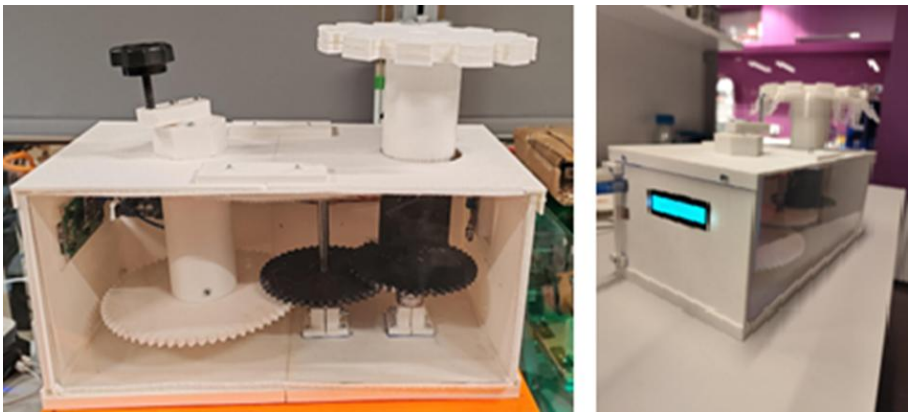


Figure 8. The modular centrifuge assembled and ready for use (Created by the authors)

A working video of the modular centrifuge shown in Figure 8, in its ready-to-use state, has been uploaded to the system with the file name “2204-A project report attachment.mp4”, a size of 8.094 KB and the “mp4” extension.

3.1. Theoretical and Experimental Calculation

According to the formula given in Equation 7; If we substitute the number of teeth in the system consisting of parts 16 and 17 (rotation):$\Delta\theta_1 = 1$

$$\Delta\theta_3 = \frac{64}{18} \cdot \frac{44}{18} \cdot 1 = \frac{2816}{324} = \frac{704}{81} \text{ rotatıon} \approx 8.6913580247 \text{ rotatıon/second}$$

According to this result, the 64-tooth gear (N1, Part) attached to the turning handle16) When rotated 1 turn per second, N3 (Part17) It has been calculated that the wheel rotates 8,691 revolutions per second.

In centrifuge systems, the rotational speed is usually expressed in RPM (repeats per minute), so this value is converted as follows:

$$8.691 \text{ revolutions/second} \times 60 = 521.46 \text{ RPM}$$

Therefore, theoretically, the system's output speed has been calculated as 521.46 RPM.

During the experimental studies, an Arduino-based tachometer integrated into a modular centrifuge was used for real-time speed measurement.Measurements revealed that the system rotated at an average speed of 572 RPM (see Figure 9). Similar results were also measured with a tachometer (TLS Robotics DT-2234C Digital Laser RPM Tachometer).

This result shows that a value quite close to the theoretical calculation was obtained and that the mechanical efficiency of the system is high.

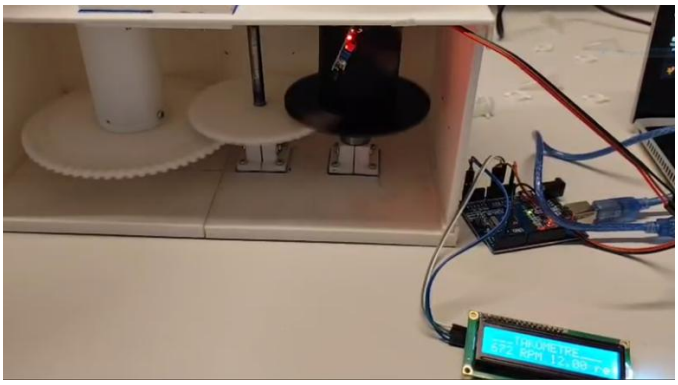


Figure 9. Experimental measurement with an Arduino-based tachometer integrated into a modular centrifuge (Created by the authors)

3.2. Testing the Modular Centrifuge on Samples

The performance of the developed modular centrifuge system was evaluated on two different sample types: one chemical and one biological.A saturated calcium carbonate (CaCO3) solution (0.5 M, 100 mL) was used as a chemical sample, and a yeast (Saccharomyces cerevisiae) suspension was used as a biological sample.2.0 mL samples were taken from each sample, placed in Eppendorf tubes, and centrifuged at approximately 2,000 RPM for 5 minutes.Centrifugation was performed at room temperature (approximately 25 °C).

In the CaCO3 solution (Figure 10-A), a homogeneous white suspension was observed before centrifugation.After the process (see Figure 10-B), a dense white pellet formed at the bottom of the tube, while the clear supernatant phase became visible at the top.This result demonstrates that the system can effectively precipitate solid particles in the solution.

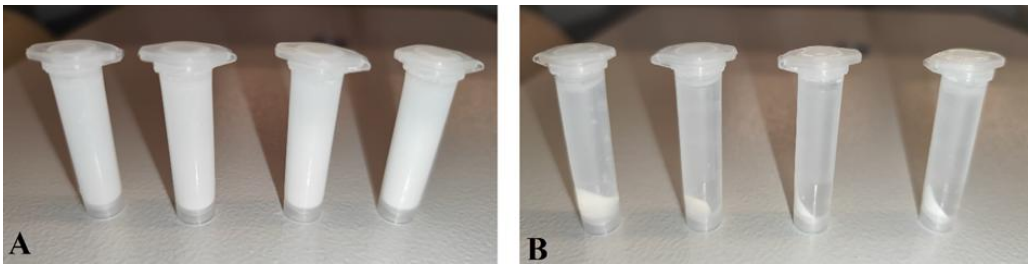


Figure 10. Pre-centrifugation of saturated calcium carbonate (CaCO3) solution (A) and after the developed modular centrifuge (B) image.After centrifugation, white pellets formed at the bottom of the tubes and a clear supernatant phase formed at the top (Created by the authors)

Similarly, a cloudy and homogeneous mixture was observed in the yeast suspension before centrifugation (see Figure 11-A), a light beige yeast pellet formed at the bottom of the tube after centrifugation (see Figure 11-B), and the upper phase became clear.This indicates that the system can also successfully precipitate biological cell suspensions.

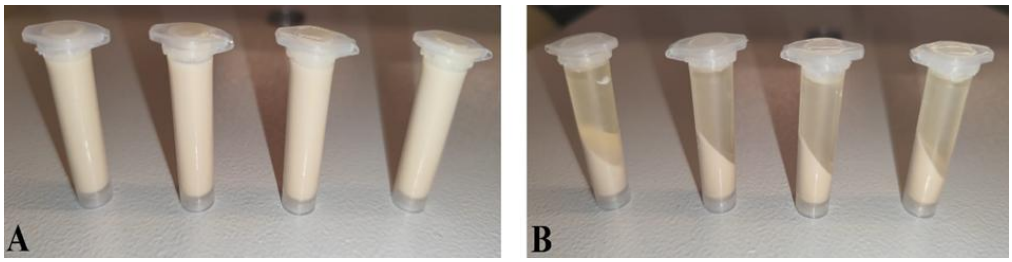


Figure 11. Pre-centrifugation of yeast (Saccharomyces cerevisiae) suspension (A) and after the developed modular centrifuge (B) image.After centrifugation, light beige yeast pellets formed at the bottom of the tube, while the liquid phase was observed to have separated in the upper phase (Created by the authors)

Before the centrifugation process(A) and thereafter(B) The images taken visually demonstrate the separation performance of the modular centrifuge.

4. Conclusion and Suggestions

Within the scope of this project, a modular, low-cost, and manually operated centrifuge prototype that can be produced using 3D printing technology has been successfully designed and manufactured.The project stems from the need to develop an energy-independent system capable of separating biological and chemical samples in regions with limited access to electricity.The designed device is capable of real-time speed measurement via an Arduino microcontroller, allowing the system's rotational performance to be monitored in real time.

The system uses an Arduino-based microcontroller to measure the speed in real time and display it to the user as RPM on an LCD screen. All components of the centrifuge were produced using PLA filament in a 3D printer, and the total cost of the assembled system was found to be 550 TL. Experimental tests revealed that the system could reach an average range of 1710–2280 RPM, effectively precipitating yeast (Saccharomyces cerevisiae) and calcium carbonate ($CaCO_3$) solutions at these values.

As a result of the experimental studies, it was determined that the system has 64 gears connected to the crank handle, N1 (Part).16) When rotated 1 turn per second, N3 (Part17) that its wheel rotates 8,691 revolutions per second;It has been calculated that it can reach speeds of approximately 570 RPM per minute.

When the N1 component of the centrifuge is rotated at 3-4 revolutions per second, the modular centrifuge reaches a speed of 1710 – 2280 RPM, as measured by an Arduino microcontroller and a tachometer (TLS Robotics DT-2234C Digital Laser RPM Tachometer).These results show that the Arduino-based RPM meter integrated into the modular centrifuge provides accurate and real-time results.It has been observed that successful precipitation (pellet) formation is achieved in Saccharomyces cerevisiae (yeast) and CaCO3 solutions at this rate.In both examples, the formation of dense and compact pellets at the bottom of the tubes after centrifugation demonstrates that the centrifugal force generated by the system is sufficient for laboratory-level separation processes.In the literature, it is reported that ~2000–3000×g (3–5 minutes) range is generally used in cell harvesting protocols for Saccharomyces cerevisiae (Brown et al., 2017; Loock et al., 2023).However, successful sedimentation has also been reported in chemical solutions containing particles such as CaCO3 at similar rate ranges (Sabri et al., 2016).These findings demonstrate that the modular centrifuge developed within the scope of this project can be effectively used in multi-purpose laboratory experiments.

The device's key advantages include not requiring any power, being 3D-printed, having interchangeable (modular) parts, and having a very low production cost.With open source systems in the literature (Bhamla et al., 2017; Byagathvalli et al., 2019; Sule et al., 2019). Compared to Haque et al. (2022), this study offers a unique contribution in terms of integrating both a mechanical system and an electronic measurement module.They stated that the ability to produce low-cost centrifuges through 3D printing strengthens applied learning in engineering education.This situation shows that the developed system can be evaluated not only as a scientific tool but also as an educational tool.

The N1/N3 ratio used in the centrifuge's gear mechanism enabled the manual input movement to be accelerated by 8.6 times, allowing for efficient torque transfer.In addition, the device called “Mobilefuge” developed by Bhupathi and Devarapu (2021) presents an open-source design of a 3D-printed centrifuge that is cost-effective, simple, stable, safe, robust, consumes less power, and can therefore be operated even from mobile phones (Bhupathi and Devarapu, 2021).In this project, the modular centrifuge developed is manually operated, so it requires very little electrical energy.Therefore, this project, in line with the concept of frugal science, aims to create a user-friendly device that does not require energy.

The PLA-based biopolymer material used in the production of the device supports a sustainable engineering approach with its environmentally friendly and recyclable properties.Thanks to the design flexibility offered by 3D printing technology, the system can be easily rescaled for different rotor sizes or sample volumes.In this respect, the project serves as a parallel example to efforts on the localization of sustainable laboratory technologies.

An examination of the production cost of the developed modular centrifuge revealed that the entire system could be realized with a relatively low budget.The total cost of all components used in the production of the prototype, including 3D printing filaments, the Arduino UNO microcontroller board, the infrared (IR) sensor module, the LCD screen unit, the mil, and neodymium magnets, was approximately 550 TL.This figure represents only a small fraction of the cost of commercial laboratory centrifuges (approximately 2–3%), demonstrating that the system successfully meets its goal of being a “low-cost engineering solution”.

It is believed that the developed prototype could be a practical educational tool used in science and biology laboratories, especially in rural or resource-constrained schools, for teaching fundamental physics concepts such as the relationship between "mechanical energy and centrifugal force".All the findings indicate that the developed modular centrifuge can be effectively used not only in educational settings but also in low-resource laboratory applications such as field research, microbiological preliminary tests, and water quality analyses.Therefore, the system is considered a portable, accessible, and economical scientific instrument.The SWOT analysis of the study is shown in Table 3.

Table 3: SWOT analysis

STRENGTHS	**WEAKNESSES**
1. Cost Advantage: While commercial centrifuges cost around 60,000 TL, this prototype can be produced at a very low cost of 550 TL (Frugal Science). **2.** Energy Independence:It can operate entirely manually without needing to be connected to the electrical grid (an advantage for disaster areas and rural regions). **3.** Real-Time Data (Critical Power):Unlike its competitors (Paperfuge, etc.), it allows the instantaneous RPM speed to be displayed on the LCD screen thanks to the Arduino and sensor, ensuring standardization. **4.** Repairability & Modularity:The parts can be 3D printed and interchangeable anywhere.	**1.** Human Factors and Fatigue:Manual turning systems can cause physical fatigue in the operator and make it difficult to maintain a constant speed during prolonged operations. **2.** Speed Limit:The achieved speed of 2280 RPM may be insufficient for advanced molecular biology studies requiring very high speeds (such as DNA/RNA isolation). **3.** Material Strength:PLA material has lower long-term resistance to heat and mechanical stress compared to other industrial plastics.
OPPORTUNITIES	**THREATS**
1. Educational Kit Potential:It can be used as a "STEM Education Kit" in schools to teach the working principles of centrifuges.	**1.** Raw Material Supply:Logistical problems that may arise in rural areas regarding the supply of electronic components such as filament or Arduino.

STRENGTHS	WEAKNESSES
2. Mobile Health Services:It can be used in mobile health screenings in African countries without electricity or in war/disaster zones. **3.** Technology Integration: The system has the potential to be converted into a hybrid (both manual and electric) configuration with the addition of a simple battery or solar panel module.	**2.** Alternative Simple Solutions:"Salad dryers" or very simple "string systems" are creating competition at a lower cost (but not at a metric level). **3.** Calibration Needs:Sensors can become dusty or shifted over time, increasing the risk of measurement errors.

In conclusion, this project;By integrating 3D printing technology, open-source hardware, and mechanical design principles, a domestically produced, accessible, and sustainable laboratory tool has been created.This system is capable of supporting scientific research in regions with limited access to laboratory infrastructure, and serves as a concrete example of the "science everywhere" concept.Future studies are proposed to increase the system's speed capacity, add automatic timer and data logging modules, optimize the rotor geometry, and adapt all components for domestic production.With these improvements, the device's usability can be expanded into different fields such as biotechnology, environmental engineering, and educational technologies. Furthermore, the system can be considered an educational tool that encourages applied learning in engineering and science education.

The modular centrifuge system developed in this project has demonstrated that basic separation processes can be performed in non-laboratory environments thanks to its low cost and portable design.Various improvements can be made in the future to enhance the system's performance and adapt it to different applications.Increasing rotational speed by optimizing rotor geometry and gear ratios will allow for the generation of higher centrifugal forces, thereby expanding its usability in advanced biotechnological applications such as DNA isolation, protein precipitation, or microparticle separation.In addition to a manual turning mechanism, integrating pedal or spring-based power transmission systems can increase turning continuity while reducing the operators physical effort.

Furthermore, by adding temperature, time, and vibration sensors to the Arduino-based electronic system, a digital interface can be developed that automatically records the parameters of the centrifugation process.This system will therefore make significant contributions to data analysis and experimental reproducibility in both educational and research settings.Besides 3D printing, using injection molding or bioplastic materials can enhance the device's durability and environmental sustainability.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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