# Designing Printers that Print onto Spherical Geometries: A Lo-Fi Prototyping Case

İnanç Şencan[1], Sema Alaçam[1], Sinan Mert Şener[1]

[1] Istanbul Technical University, Turkey
sencani@itu.edu.tr
alacams@itu.edu.tr
mert@itu.edu.tr

**Abstract.** This study presents a novel 3D printing mechanism specifically designed to print on spherical surfaces. Fused Deposition Modeling (FDM) is adopted. The initial prototypes of the designed 3D printer have been tested with a specific focus on rotational movement mechanism and developing G-code solutions. The results of the low fidelity prototyping process are discussed in the context of stability of the system, usability of the proposed tool, sufficiency of step motor torque, distance between nozzle and the printing surface, producibility with reasonable budget, and flexibility. The distinctive feature of this study, unlike robot-aided additive manufacturing applications, is that it can be achieved with a low budget. The study is expected to be useful for designers who are interested in designing bespoke additive manufacturing solutions for double-curved and spherical geometries.

**Keywords:** 3D Printers**,** FDM, rotational movement, spherical geometry, prototyping**.**

## 1 Introduction

Additive manufacturing techniques have rapidly become widespread in the last decades and turned into 3D printers that can be used at home. Gershenfeld (2005) defines this transformation as a shift from personal computers (PC) to personal fabrication (PF). Carpo (2017) identifies new generation 3D printers including the desktop scale as one of the influential breakthroughs in digital transformation in the 20th century. 3D printers have also started to gain importance not only in prototyping for testing, but also in the production of the final product (De Gier, 2015), due to many reasons such as its easy accessibility, low cost, ability to physically produce the digital model in a short time, and user-friendly interfaces. This proliferation also led to new explorations and the embodiment of concepts such as being hackable, adaptable to new functions,  and self-productability. In this sense, this study can be considered as an attempt to augment affordances of desktop 3D printers in a way that they can print onto spherical surfaces.

Most of the low-budget and accessible 3D printers employ 3 degrees-of-freedom (DoF) mechanisms such as translation-based cartesian or delta systems (Figure 1).  While these existing 3D printers allow production of 3D objects by using layer by layer printing technique, there remains several challenges in printing objects with spherical geometries from the points of continuity and smoothness of the surface. With this problem in mind, different from existing systems this study aims to adopt rotation-based movement systems to 3D printers. The main idea of investigating the feasibility of rotation-based movement systems is to design a 3D printer that prints spherical geometries effectively.

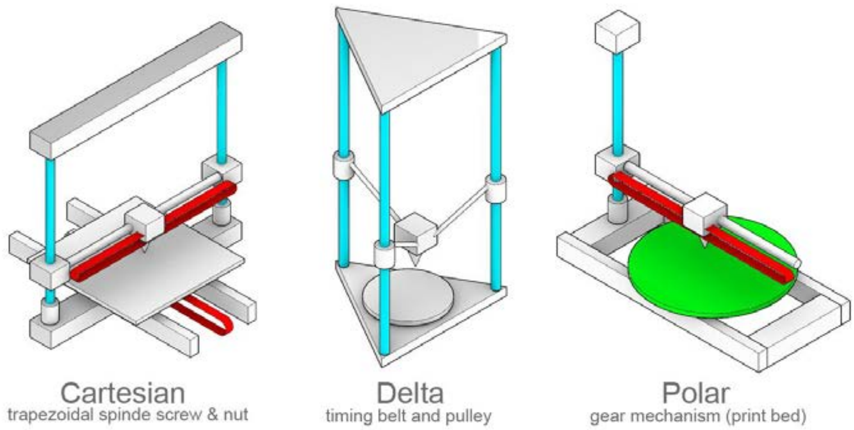


**Figure 1.** Mostly used movement systems in 3D printers.

The original contribution of this study can be listed as follows: a novel 3D printer design based on rotational movement, modifying existing G-code solutions for the designed 3D printer, prototyping and developing the physical components. The prototyping process includes two main phases: designing mechanical systems and physical components of the 3D printer and developing control solutions for the selected alternative from the previous phase. The first phase covers generating 3D printing mechanism alternatives as a combination of linear and rotational movement. The developed alternatives are evaluated according to the following criteria: Stability of the system, the effect of the gravity on the material extruded from hotend, the relationship between the weight of the spherical product and power of the step motors, the limitations of the print area and number of the sub-pieces. The second phase focuses on calibrating the qualities of the end product in correlation with the modified G-code generator.

## 2 Related Studies

Gershenfeld (2005) considers 3D printers not only as tools to be used in the physical production of solid geometry, but also as an integrated structure consisting of logic, sensing, actuation and display layers. This perspective makes 3D printers more than a fixed tool, a new field of experimentation involving materials, geometry, logical and mathematical modeling, and motion mechanism parameters. Considering the problem of printing on a curved surface, direct-to-shape (DTS) or direct-to-object (DTO) have been emerging technology in terms of 2D print (Arango & Cifuentes, 2019; Thorp & Geddes, 2017; Trip et al., 2018). In the DTS studies, planes, cylinders, cones, spheres, and complex geometries are the most common geometry to be printed on (Thorp & Geddes, 2017). Although, there are crucial accumulation of knowledge such as calculation of print path, nozzle mapping (Thorp & Geddes, 2017), topology optimization (Arango & Cifuentes, 2019) that can be inherited from DTS printing technology, the following challenges remain unexplored for a 3D printer which is supposed to print onto spherical geometry:

- Material behaviour of ink in 2D printing and filament or other materials (such as clay) in 3D printing are quite different.
- In 3D printing material thickness should be considered, as well as the continuous change in the sphere topography.
- Calculating the distance between the nozzle and the surface of the printed object may require a different approach.

It is possible to group the experimental studies focusing on the fabrication of curvilinear surfaces by using additive manufacturing techniques of 3D printers under two headings: the slicing algorithm, thus the approaches developed at the G-code level (Ahler et al., 2019; Etienne et al, 2019; García Cuevas & Pugliese, 2020), and the studies suggesting structural changes in the motion mechanism (Demjen et al., 2019). Ahler et al. (2019) introduce a nonplanar toolpath generation method consisting of 3 steps: planar slicing, detection of curved surface and projecting the end points from edge of previously printed layers to a planar path, calculation of the projected vertices. However, in this solution (Ahler et al., 2019) in terms of surface smoothness there still remains discrete parts and a degree of roughness. Etienne et al. (2019) introduce CurviSlicer as an adaptive and iterative slicing algorithm that enables noozle’s change in the Z direction while printing the same layer and remapping the layer surface in a way that it results with curvature. Both of these solutions can be adapted to existing 3 axis FDM printers (Ahler et al., 2019; Etienne et al., 2019). García Cuevas & Pugliese (2020) introduce methods and examples of curvilinear slicing in Grasshopper, not only for FDM but also clay printing. Considering the movement mechanism, Demjen et al. (2019) present a novel 3D printer proposal that adopts semi-sphere form, while providing inverse kinematic equations and solution apart from a CAD model. However, Demjen et al.’s (2019) study does not cover detailed solutions, implementations or prototyping in the context of the physical components of the movement mechanism.

## 3 Modelling and Prototyping

This section presents the design and development process of initial prototypes. Movement mechanisms and G-code solutions that can print on an existing spherical form/object with the FDM method have been investigated. The findings and outcomes of each trial have informed the design process recursively.

### 3.1 Prototyping Alternatives

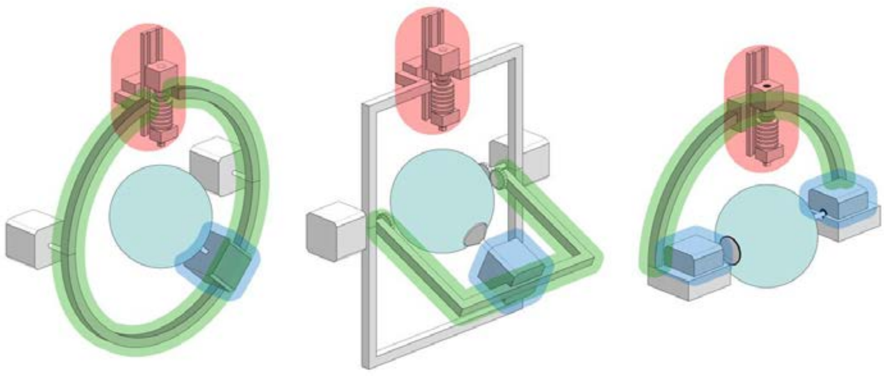


**Figure 2.** Initial alternatives

At the beginning of the study, three alternatives were considered, prototyped and compared (Figure 2). The advantages and limitations of each alternative are explained as follows.

a: Z axis module, which moves the hotend up and down, is attached to a circular sigma profile. Y axis movement is provided by rotating the spherical print-bed, which is attached to the Y axis stepper motor. Two stepper motors (left and right) move the Y axis stepper motor on the circular sigma profile via belts (Figure 2), which completes the X axis movement.

b: Spherical print bed is attached to Y axis stepper motor. This stepper motor is attached to a frame, which is being rotated by two stepper motors on a vertical frame. Z axis module is attached to this vertical frame.

c: Spherical print bed is attached to two stepper motors at each side, rotating the print bed in Y direction. A half circle sigma profile is attached to those stepper motors. Z axis module moves along the sigma profile in a circular path, providing the X axis movement.

In the prototyping phase, existing 3D printers (30x30x30 cm) were used to fabricate circular sigma profiles and details. For linear profiles, metal and ready-made profiles were used. Similarly, components such as control board, display module, hotend, and power supply were taken from an existing 3D printer (Creality Ender-3 Pro).

### 3.2 Movement Mechanism

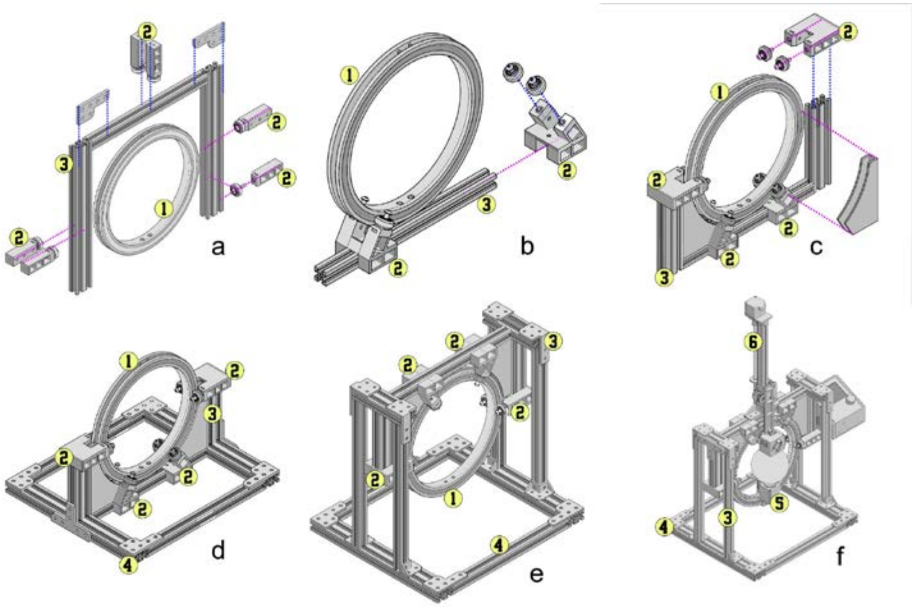


**Figure 3.** Experimenting with rotational movement mechanisms. 1. Circular sigma profile, 2. Joint, 3. Vertical frame, 4.Horizontal frame, 5.Y axis module, 6.Z axis module

While from Figure 3a to Figure 3e, only the x axis is examined, the x and y axes are examined together in Figure 3f. In the context of FDM printers, geometrically speaking, converting a linear motion- based system to a rotational motion system can be achieved by remapping parameters with a basic trigonometric function. However, at the same time, different parameters such as gravity, direction of extrusion, the effect of nozzle weight on the system also affect the performance of the mechanism. In addition, the simulation of the behavior of the mechanism, which becomes more complex when factors such as the cohesiveness of the two printed layers and the structural strength of the system are added, requires advanced engineering knowledge. Instead, each alternative was physically fabricated, and the evaluation of the system empirically made.

### 3.3 G-code

The process of converting a 3D digital model file into a file that a 3D printer can use is called slicing. This process is mostly done by means of programs called slicers on the computer. Software such as Cura, Simplify3D, Slic3r are examples of slicers. With these programs, it is possible to prepare files for cartesian or delta type 3D printers. These programs, after dividing the object into slices on the Z axis, create a route for each slice and store the motor movements necessary for the hotend part to follow this route, as relevant data such as coordinates and speed. After slicing, a file in G-code format is obtained. The equipment that processes the G-code file and sends the necessary signals to the electronic components is called the "control card". This piece, which is under the control of a microprocessor, contains a firmware. In the scope of this study we used "Marlin" as firmware. Step numbers of motors, limit switch directions, minimum and maximum dimensions, hotend and heating plate temperatures, etc. settings are adjusted through this firmware.

Since the printing surface is a spherical surface instead of a plane, in a rotational 3D printer, the Euclidean coordinate system needs to be adapted to this sphere. This situation is solved by defining the XY grid in the plane as parallel and meridians on the sphere.

Two problems were observed while planning the 3D printing process on a spherical grid: Speed problem and shortest path problem.

- Distance between two points on different parallels are not the same, unlike in the Euclidean coordinate system. To fix this, print speed should be adjusted according to the current X coordinate. Extrusion amount should also be adjusted because of the speed change.
- To reduce travel time of hotend between extrusions, hotend should take the shortest path from any given point A to point B.

Three alternative solutions are suggested:

- Modifying Marlin firmware: To fix the speed problem, location data can be stored in Marlin and print speed can be adjusted in relation to this data.
- Modifying 3D model: To fix the mapping problem, a spherical 3D model can be morphed/projected into a planar model and sliced in a generic slicer software.
- Modifying the G-code: Since, G-code file contains the location, speed and extrusion rate information, distance between points can be calculated and used to adjust speed and extrusion rates.
- Creating custom slicing algorithm: In a 3D modeling environment (Rhino/Grasshopper), 3D model information can be used to create G-code specific to the rotational 3D printer.

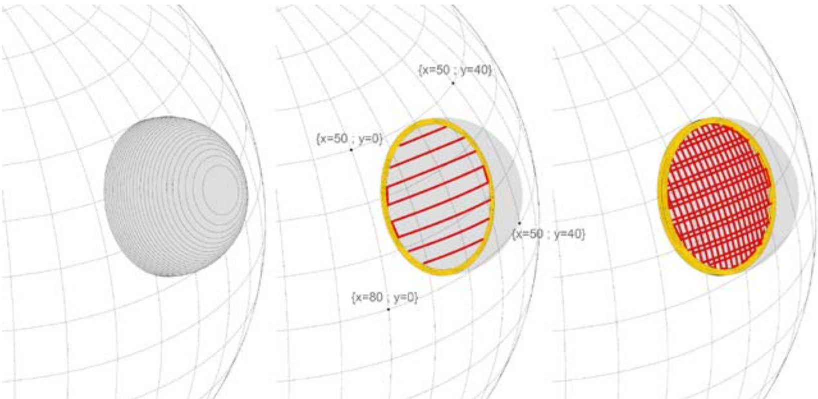


**Figure 4.** Toolpaths (shell and infill) generated in Grasshopper.

A grasshopper algorithm which generates toolpaths specific to the rotational 3D printer is developed for the study. It slices the geometry with spherical surfaces which are offsets of the spherical print bed. Toolpaths (Figure 4) are generated from these slices and converted into X, Y and Z coordinates, which are compiled into a G-Code file.

### 3.4 Evaluation Criteria

Based on the observations and gained experience during the prototyping process, 6 evaluation criteria have been prioritized that can be used in future studies.

Stability: During the 3D printing process, the parts that enable the movement of the 3D printer are expected to fulfil a desired quality. For instance, minimizing the vibration of the print bed and hotend module can be considered as parameters.

Usability: It is the ability to print a 3D object in a computer environment on a spherical object, from the digital model to the final product, in a reasonable time and with a reasonable budget.

Sufficiency of stepper motor torque: It is about whether stepper motors are sufficient to operate the whole system, considering forces such as gravity and friction.

Distance between print bed and nozzle: To achieve a successful first layer, the distance between the nozzle and the printing surface must be constant at different coordinates on the sphere. With long distance, the print does not stick to the surface, while short distances can cause extrusion problems and prevent movement by creating a friction force between the nozzle and the print surface.

Reasonable budget: This item is about choosing components that are widely used in 3D printers, easily available and at the same time affordable, as well as easy to be replaced.

Flexibility: It indicates the capability of facilitating the applications in the next stage within the part-whole relationship. The motion systems in the X, Y and Z axes can be designed independently, and it can respond to solutions for more than one function with its modular structure.

# 4 Testing and Evaluation

## 4.1 Constraints

The following hardware, software and equipment were used in the preparation of the prototype of the 3D printer proposal developed within the scope of the study:

- It was considered in the design of circular sigma profiles that it could be produced with a medium-sized 3D printer of 30x30x30cm. Creality Ender-3 Pro and Cura interface was used to print circular sigma profiles and relevant components.
- 20x20cm aluminum sigma profiles were used.
- M3 and M4 T-Nuts and bolts were used for connections.
- The prototype was adapted to use 1.75mm PLA and 0.4mm nozzle
- Creality Ender-3 Pro was also used by disassembling components such as control board, display module, hotend, and power supply to be used in the new 3d printer.
- Marlin firmware was used as a G-code platform.
  Moreover, the following points were taken into consideration while testing the designed 3D printer.
- Rhinoceros 7.0 and Grasshopper were used to generate testing G-codes. Some samples from García Cuevas & Pugliese's (2020) book were useful to comprehend manual G-code generation.
- The designed 3D printer was tested only with basic sphere geometry, complex geometries containing topography information were excluded from the scope of the study.
- The radius of the spherical print bed affects the radius of the circular sigma profile and maximum print height from the print bed. As a test model, a base sphere with radius of 50mm is used. With the 110mm inner radius of circular sigma profile, 60mm maximum print height from the print bed can be achieved.

## 4.2 Test

The operability of the X, Y and Z movement modules has been tested, as well as the cable connections and synchronization with the computer. It was tested whether the distance between the printing surfaces and the nozzle is maintained constant for each axis range (Figure 5).

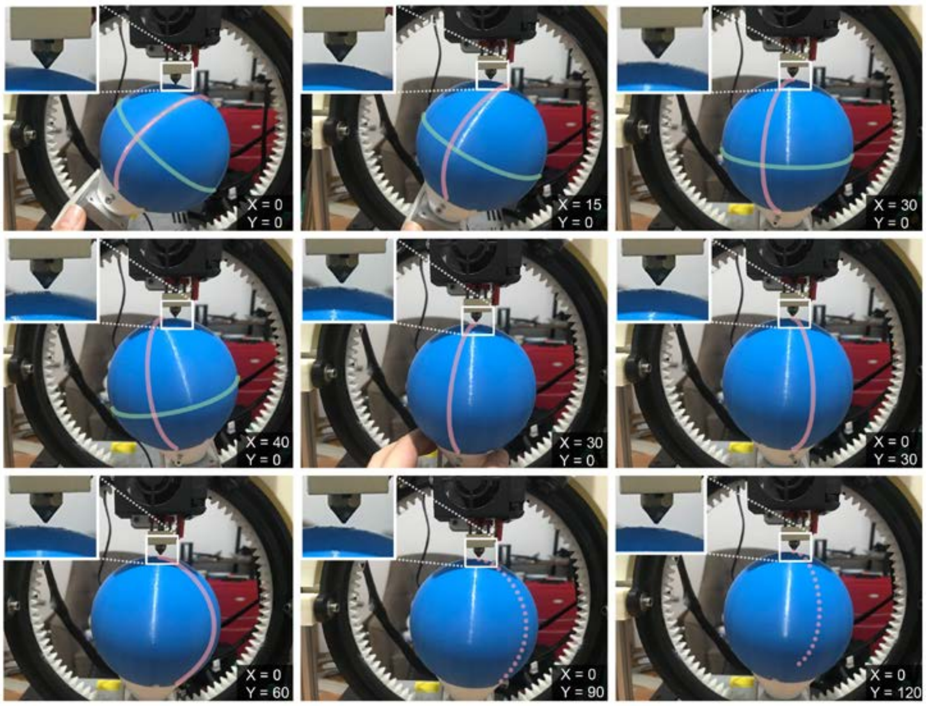

**Figure 5.** Testing the movement mechanism.

### 4.3 Evaluation

The evaluation process has been mostly based on empirical evidence and observation (Figure 6). Regarding stability, the frame of the prototype, and its joints fulfilled the expected performance. However, the threshold situations have not been tested exhaustively. It was observed that movement in the X, Y, Z axes has been carried out accurately without any stop or jamming. The G-code generated in Grasshopper has been successfully transferred into the prototype and run. Therefore, the workflow from the digital file to the 3D fabrication has been accomplished in the context of usability. The stepper motors and extruder stepper motors in the X, Y, Z axes have been fully worked out both individually and in an integrated way (Figure 6, Figure 7). Necessary step/mm, acceleration and vibration calibrations were made on each axis.

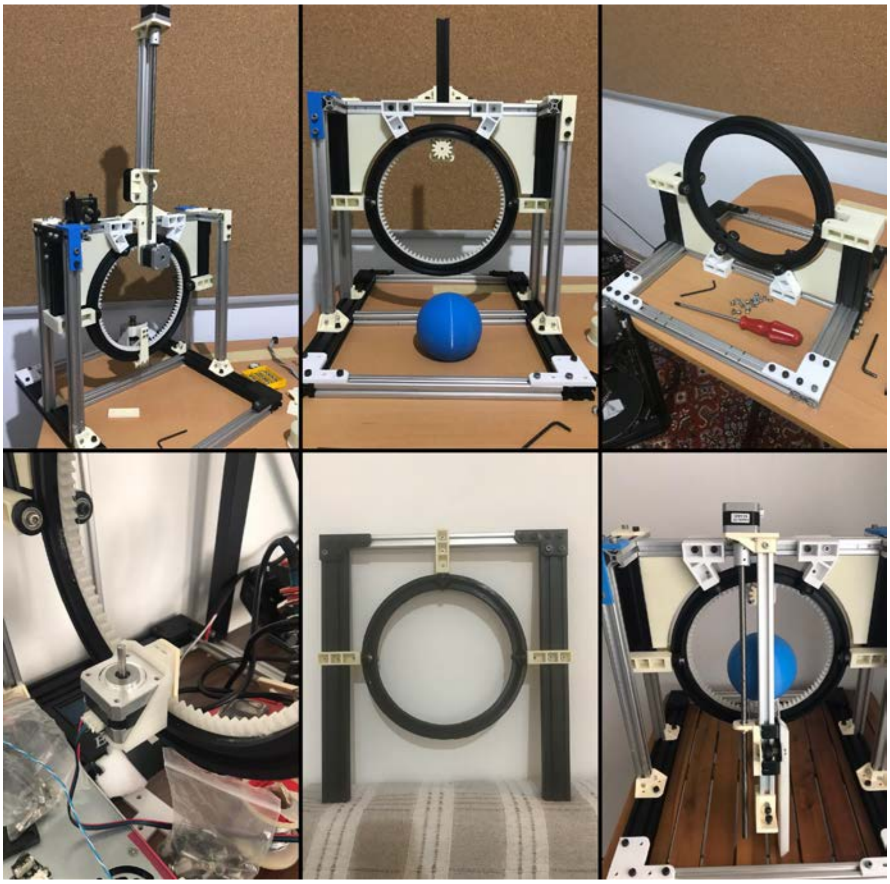

**Figure 6.** Some photos from the prototyping process

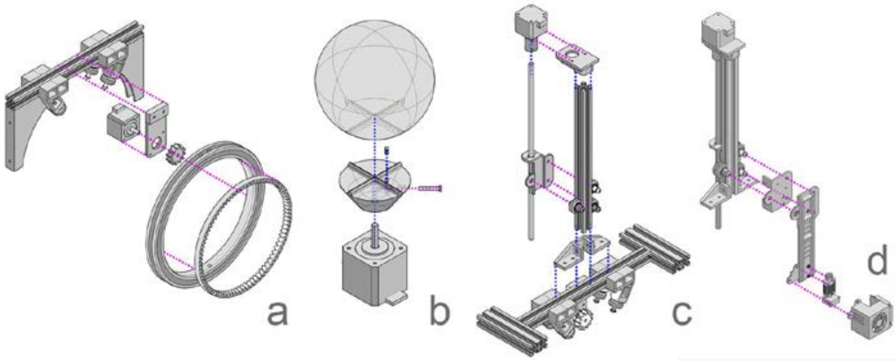


**Figure 7.** (a) X axis movement system, (b) Y axis movement system, (c) Z axis movement system, (d) Hotend connection.

It has been observed that the distance between the nozzle and the printing surface is not constant at varying X and Y points when the Z value is kept constant. In this case, it was not possible for the first layer of the print to adhere to the print surface. In addition, the printing process could not be started due to collisions that may occur between the printing surface and the nozzle. It has been seen that it is necessary to make additions to X and Y motion systems that will enable the rotational motion center point to be adjustable. In order to keep the cost low and replace the parts when necessary, prototypes were produced from easily available parts in low-cost printers. With Y and Z axis movement systems, the hotend is designed as modular and can be added or removed when necessary. The development of modularity was left to the future studies by adding a socket system to the cables.

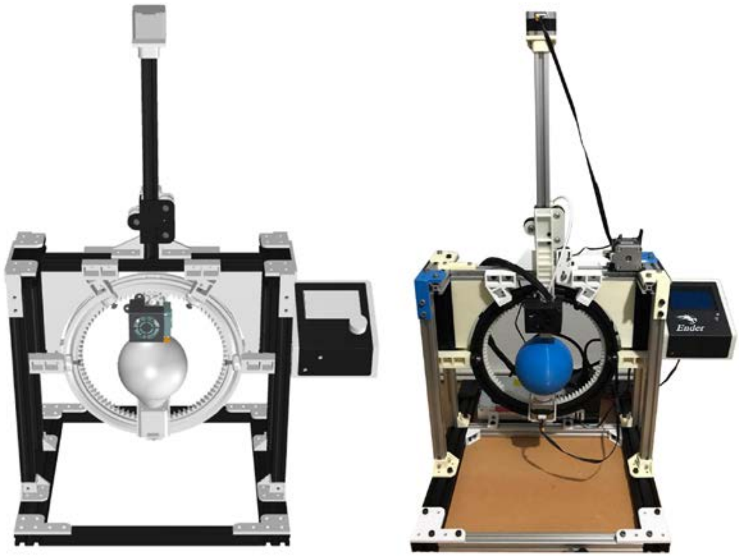

**Figure 8.** The photo and digital model of the final prototype.

## 5 Conclusion and Future Works

This study focuses on investigating whether it is possible to print curvilinear surfaces of spherical objects more efficiently at the mechanism, tool and prototype levels. One of the crucial contributions of the study is the proposal of a movement mechanism based on rotational movement in the printing of double curvature surfaces with additive manufacturing methods. The 3D printer prototype, which is produced based on the rotational movement mechanism, is flexible enough to be adapted to the production of geometries of different details and complexity with the FDM technique. The manufacturability of the rotational movement mechanism has been tested. It has been concluded the proposed

G-Code generation process and rotational movement systems for the designed rotational 3D printer works as intended. However, more robust frame and accurate dimensions are needed for improving the print quality. This research will lead to new tool designs for fabrication of challenging geometries with intended geometric accuracy, structural properties and minimal post-processing by providing alternative methods with lower budget and complexity than already existing tools.

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