Polarisation Experiments Using 3D Printed Components

2340413P

Abstract

This experiment took advantage of 3D printing techniques and computer-aided design to create high-precision components at a low cost. Together, these components were used in polarisation experiments to verify Malus' law, measure the optical activity of chiral materials, and to measure birefringence. To perform these experiments, the following components were required: a polariser, analyser, photodiode, LED mount, and sample tube holder. These components were designed with holes at the base to attach a bracket attached to a magnetic board. The design of the sample tube holder used simple shapes, such as cuboids and cylinders, to create a V-shaped top, stand, and base. The sample tube holder was made using 3D printing techniques to perform a polarimetry experiment on various samples; this experiment measured the optical properties of water, fructose, Irn Bru, D-Limonene, and sucrose. In the polarimetry experiment, water was used as a control as it is optically inactive, as it is achiral. However, the chiral materials displayed optical activity due to the specific rotation, which differed for the various solutions. D-limonene showed optical activity by the change in colour, caused by the increase in angle, shifting the incident light's wavelength. Moreover, an intensity versus angle of rotation graph was plotted for various solutions, which followed a cosine function as expected from Malus' law.

1 Introduction

Rapid prototyping is a method of layering materials [1] to construct 3D objects; this technique was used to create the components required to perform polarisation lab experiments. 3D printing of the components proved to be a highly precise and cost-effective method. Firstly, the test pieces were printed to calibrate the offset, reducing the likelihood of errors while printing the experimental components. The design of all the components was made using Openscad software by translating and subtracting simple shapes such as cuboids and cylinders to create complex shapes. These components were printed using a bottom-up methodology, where one layer is printed at a time. Therefore, simple designs were necessary to overcome the limitations of 3D printers, such as overhang. The sample had to be position at an exact height to line up with the polariser and analyser; this required a sample tube holder of highly specific dimensions. The sample holder was designed with a V-shaped top, stand and base with two cylindrical by taking the measurements of the sample tube, bracket, and the height of the other components. The results of this experiment were plotted as a graph of the intensity of light at the detector against the relative angle of rotation; this graph was a cosine function, in accordance with Malus' law.

2 Background Theory

2.1 3D Printing

Constructing an object by layering materials using a machine such as a 3D printer is known as rapid prototyping or additive manufacturing. This process of creating a 3D design is relatively more convenient and cost-efficient than making prototypes or replicas [1]. The 3D printing technologies are categorised depending on the materials and the methods using in printing the objects, such as extrusion, direct energy deposition, and sheet lamination [2]. Besides, anything that could be designed is possible to be printed on-demand using the 3d printer. However, there are several limitations to printing complicated designs due to limited materials, restricted build size and, design inaccuracies[3]. Technical difficulties such as overhang might also pose an issue, but it is possible to resolve by not exceeding an overhang angle of 45 deg [4]. There are several modeling software that are available to build a 3D design which could then be printed out . For this group project, a 3D modeling software called Openscad was used to design the polarisation experiment components.

2.2 Polarisation experiments

A transverse wave can be in any direction perpendicular to the direction of propagation. However, when its displacement is restricted to one line, it is said to be linearly polarised. When an unpolarised light hits a polariser, only part of the light oscillates in the sample plane as the polarisation filter travels through; this is referred to as the plane of polarisation[5]. Some materials such as chiral solutions and sellotapes affect the polarisation of light, exhibiting optical activity and birefringence.

Malus' Law

This law states that the intensity of transmitted light from the analyser is equal to the square of the cosine of the angle of the axes of transmission between the polariser and the analyser[9]. The mathematical expression of Malus' law is given by equation 1.

$$I = I_0 \cos^2 \theta [11] \tag{1}$$

Polarimetry

Optically active substances such as chiral materials (e.g., sugars) rotate the plane of polarised light. One of the properties of these chiral materials is called the specific rotation. This property is defined as the change in orientation of plane-polarized light, per unit distance–concentration product, as the light passes through a sample of a compound in solution [10].

Birefringence

The optical property of materials such as plastic and sellotapes exhibits mechanical stress and anisotropy. This stress in the polymer causes double refraction, where the incident ray is split into two components. The different phases of the split light are the main parameter that causes birefringence[8].

3 Personal Contribution to the Project

3.1 Design overview

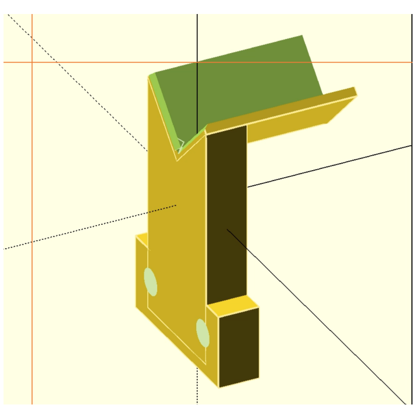
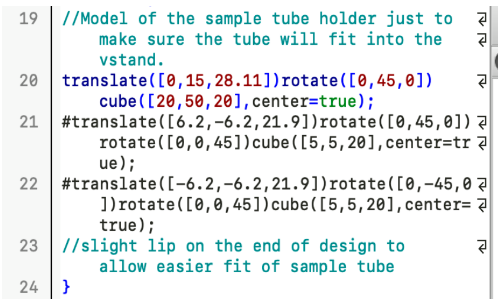


Figure 1: Openscad design of the sample tube holder.

A sample tube holder was designed using Openscad software to print with the help of a 3D printer. This component was then used to perform polarimetry experiments by utilising other printed pieces such as the bracket, polariser, analyser, and photodiode.

The vial holder was an essential requirement because the sample tube containing chiral solution had to be kept in alignment with the polarised light path to carry out the experiments effectively.For this purpose, the holder was designed in 3 parts, firstly the V-shaped top, which holds the sample tube. Secondly, the central component is shaped like a slab, placed on the end corner of the V-shaped top—finally, a base component attached to the magnetic board. The approach to design this component was to ensure a simple design of the, and the holder's shape had to be designed to fit the sample tube to stay flat on the surface. Moreover, the stand had to be designed to have two cylindrical holes to attach a bracket.

3.2 Openscad



```
//Model of the sample tube holder just to make sure the tube will fit into the vstand.
translate([0,15,28.11])rotate([0,45,0]) cube([20,50,20],center=true);
#translate([6.2,-6.2,21.9])rotate([0,45,0]) rotate([0,0,45])cube([5,5,20],center=true);
#translate([-6.2,-6.2,21.9])rotate([0,-45,0])rotate([0,0,45])cube([5,5,20],center=true);
//slight lip on the end of design to allow easier fit of sample tube
}
```

Figure 2: Openscad code showing the translation of shapes to create the sample tube holder design.

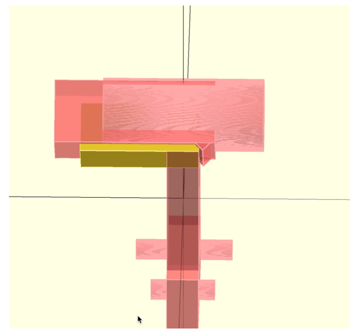


Figure 3: The resulting design due to commenting on the code to view the elements that make up the final design.

The sample tube holder's design was created using simple shapes such as cylinders and cubes on Openscad software. These shapes were translated along their respective axes to create the top component, stand, and base, as seen in the figure 2. Likewise, complicated shapes such as the V-shaped top and bracket holes were created by taking these shapes' differences. The shapes that make up the sample tube holder's structure, as represented in the figure 3, make use of the comment code function in Openscad. Moreover, this software proved to be an efficient software to design shapes for 3d printers due to its simplicity in coding by taking elementary shapes to produce complex designs such as the sample tube holder.

3.3 Top component

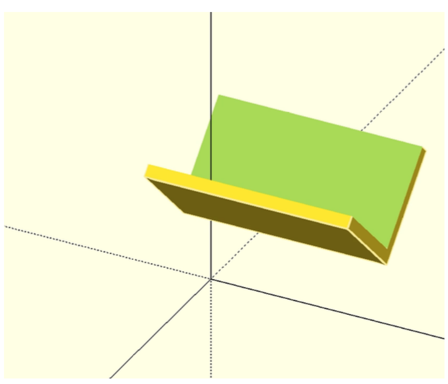


Figure 4: V-shaped top designed to place the sample tube.

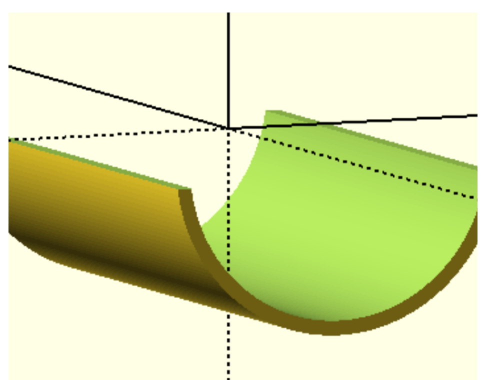


Figure 5: Spherical shaped top used in the draft design.

The top part of this holder's design was a V-shaped top that holds the sample tube as seen in figure 2. The V- shape was considered functional because it holds the tube in a good alignment compared to a spherical-shaped top. This V-shaped top was designed using the sample tube's dimensions using OpenScad software by taking the difference between two cuboids, which was translated in the y axis by 45 degrees. Furthermore, the radius and the sample tube's length were calculated to obtain these cuboids' dimensions. The draft design made for the sample tube holder had a cylindrical-shaped top to allow the sample tube to be slot into it as seen in figure 3. The length and the radius of the sample tube were used to make a hollow cylinder. However, this design might pose an issue while printing due to its shape, as it is easier to print simple shapes with the 3d printer to reduce errors with the printed pieces effectively.

3.4 Stand

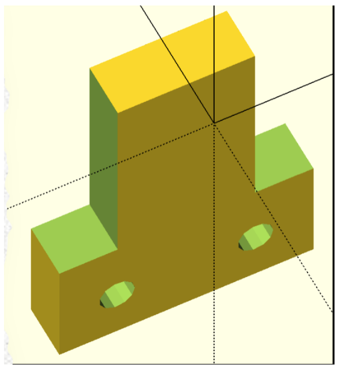


Figure 6: Cuboidal stand giving height to the sample holder.

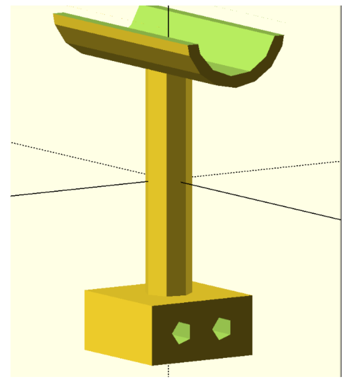


Figure 7: Cylindrical stand used in the draft design .

The middle part of this design was a cuboidal stand aligned to the very end of the cylindrical top, giving rise to the sample holder to an appropriate height as shown in figure 4 . This stand's height was measured to align the holder better with the rest of the experimental components. However, due to the nature of 3d printer printing designs from the bottom up, a slab structure was aligned to the top part's edge to avoid overhang. The previous design had a cylindrical middle component that was aligned to the centre of the cylindrical top as seen in 5. Nevertheless, that design would not be advantageous as a 3d printing design due to the shape being complicated for a 3d printer to print without errors.

3.5 Base

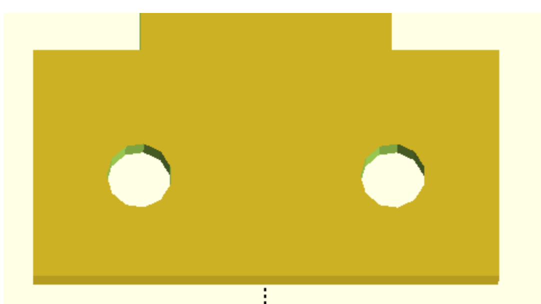


Figure 8: Base component containing two cylindrical holes for attaching a bracket.

This design's base part was a slab-like structure with two holes for attaching a bracket to the sample tube holder as seen in figure 8. The base had to be designed to be highly stable as instability could impact the results' accuracy by changing the incident light's path. The base slab was designed on OpenScad using a cuboid structure and taking another cuboid's difference on either side. The base, which was aligned to the end of the stand, would not provide much support to hold the structure without collapsing it. Therefore, it was required to be attached using a bracket to the magnetic board. The bracket holes were created by subtracting two cylindrical holes by taking the bracket's measurement and adjusting it to fit the base slab.

4 Polarimetry

4.1 Aim and Procedure

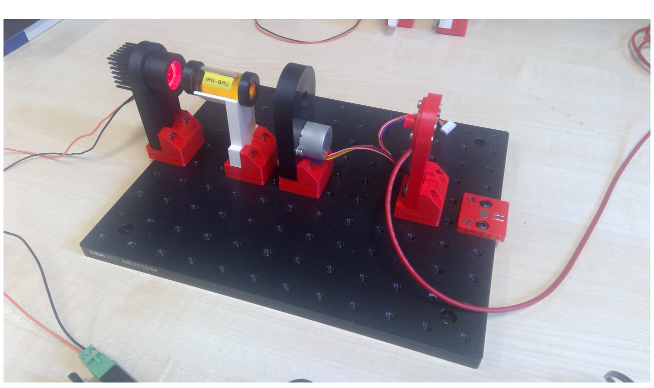


Figure 9: Experimental setup for polarimetry using the sample tube holder

The sample tube containing several chiral solutions such as fructose, sucrose, Irn Bru, and D-limonene was placed on the sample tube holder to observe these solutions' optical rotation and verify Malus' law. In addition, water, an optically inactive solution, was also used to compare optically active and inactive solutions by measuring the light intensities relative to the incidence angle. The experiment was conducted using apparatus such as the polariser, analyser, photodiode, sample tube holder, and sample tube. The arrangement of these components was made by slotting them onto the magnetic board. Care was taken to align these components to follow a straight line, allowing the incident light to pass through each of these components, as shown in figure 9.

Furthermore, the sample tube containing chiral solutions was placed on the sample tube holder between the polariser and the analyser. Subsequently, the polarised light that transmitted through the sample tube containing solution was incident on the analyser. The light incident's intensities on the analyser were measured for angles between 0 to 360 by the photodiode.

4.2 Results and Discussion

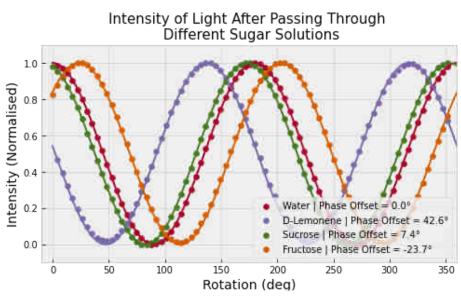


Figure 10: Rotation versus intensity graph for various solutions[15].

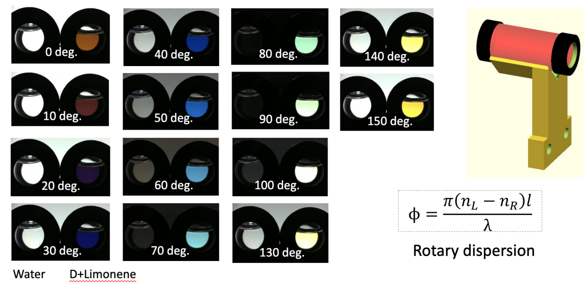


Figure 11: Comparison of optical activity between D-limonene and water

The plane of polarisation of the transmitted light from the sample solution was rotated due to the optically active solution. This rotation of the polarisation plane resulted in different values of intensities corresponding to its relative incident angle on the analyser. Hence, a graph was plotted using the values of intensities against each solution's relative angle in figure 10 . The graph follows a cosine function verifying Malus's law given in the equation 1 .Irn Bru's solution showed very little shift in cosine function due to the specific rotation of the chiral molecules present in the solution. Furthermore, fructose solution resulted in a significant shift in cosine function due to its maximum intensities measuring between 20 degrees to 30 degrees. Conversely, the cosine function observed for water does not shift due to being optically inactive, suggesting that water does not rotate the polarised light's plane of orientation.

However, the resulting intensities due to the sucrose solution did not vary significantly compared to other solutions. The specific rotation of these solutions depends on the materials' thickness and the incident light's wavelength [12]. Therefore, the theoretical values of the specific rotation of sucrose and fructose are +66.47 and -92.0, respectively [9]. The cosine function's transformation in the fructose solution is consistent with the counterclockwise rotation (-ve) observed in the theoretical value. D-limonene's solution exhibited a colour change when the incident plane of polarised light passed through the solution as seen in 11. This phenomenon resulted from the change in wavelength of light due to the angle of incidence being proportional to the solution's thickness [13]. The maximum intensity was observed for an angle between 140 degrees to 320 degrees. However, the limitation of performing the polarimetry experiment to qualitatively analyse the solutions arises due to factors such as birefringence noise, the motion of the components, and sensitivity to the scattering of light [14].

5 Conclusion

This project has proven that complex lab equipment can be produced relatively easily and cheaply from a 3D printer and a CAD program. The components were designed with Openscad software and produced using 3D printing techniques, resulting in components of precise dimensions for the experiments; several polarisation experiments, polarimetry, birefringence, and verification of Malus' law, were performed using these components.

Several major changes were made in terms of component design from the previous year's project. One such change was brackets and a magnetic board to attach the pieces, instead of screwing them into a breadboard; this reduced the wear and tear experienced by the components, increasing the longevity of the equipment. The sample tube required a holder to set up the polarisation experiments effectively; the chosen design was a V-shaped top attached to a cuboidal stand and a base attached to the bracket. The initial draft involved a spherical top; however, the V-shape was selected due to difficulty producing the spherical top, as it was too complicated to print accurately. The components the 3D printer made facilitated several optical experiments, which demonstrated the optical behaviour of various samples; this gave the required data for figure 10 to be plotted. Figure 10 demonstrates that Malus' law is a cosine function with a phase shift dependent on the specific rotation of the material in question.

6 References

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