Telescope Report

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I. INTRODUCTION

With two lenses, Galileo was able to observe the night sky in more detail than any man before. Although one lens was convex and the other concave, our telescope uses two convex lenses in a similar fashion. This type of telescope is called an astronomical telescope. Its flipped image is inconvenient for viewing objects on earth but less of a bother when viewing astronomical objects. Our 3D printed telescope design features accurate focusing, easy lens insertion, and body rigidity to keep the lenses in line.

II. DESIGN

The focal length and dimension of each lens had to be identified to determine which combination of lenses would make the best telescope. The focal lengths of four lenses were experimentally measured by using the sun as a light source. We approximated the sun to be an infinite distance away, producing nearly parallel rays. We focused the lenses until they produced a single dot of light on the bottom of a metal support stand. The distance from the lens to the bottom of the stand was measured with rulers while the lens was tightly clamped at the focused position. This experiment had an error of ± 0.1 cm. The diameters of the lenses were measured using Vernier calipers which had an error of ± 0.05 mm.

II.1. Choice of Lenses

TABLE I. Lens Profiles

(1)	(2)	(3)	(4)

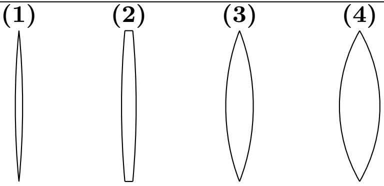


Table I shows the profile of the lenses relative to each other and how they were numbered. From now on, we will refer to the lenses using this numbering. Table II provides the dimensions of each lens.

TABLE II. Lens Specifications.

Identification	Focal Length	Diameter
(1)	50.3 cm	49.16 mm
(2)	25.9 cm	49.79 mm
(3)	9.60 cm	50.35 mm
(4)	5.40 cm	50.00 mm

FIG. 1. Set up used to determine focal length.

Two lenses were selected based on comparisons of effective magnification, clarity, and practicality in telescope length. The length of the telescope must be equal to the sum of the focal lengths of the chosen lenses in order to form a magnified image [1]. The length also needed to remain within the dimension limits of the 3D printer. Keeping these requirements in mind, we immediately eliminated lens (1) as a potential candidate due to its relatively large focal length. If this lens were to be used, the telescope would be long enough to produce a bowing effect, misaligning the lenses and preventing image formation. Further, the focal length would have pushed the telescopes dimensions outside the printable range. Aside from length limitations, lens (1) has a larger f-number than lens (2). A larger f-number produces a dimmer and less clear image [1]. f-number is calculated from the following equation

$$f\text{-number} = \frac{f}{D}$$

where f is the focal length of the lens and D is the diameter of the lens. Since the diameters of the lenses are approximately equal, the f-number of lens (1) is about two times that of lens (2). We eliminated lens (4) due to its odd geometry, which would add unnecessary difficulty while printing. This leaves lenses (2) and (3). Lens (2) is the objective lens and lens (3) is the eyepiece. This combination offered a good balance between clarity and telescope length.

II.2. Theory

The sum the focal lengths of lens (2) and lens (3) gives us a theoretical telescope length of 35.5 cm. The angular magnification of the telescope can be calculated using the equation

$$M = -\frac{f_1}{f_2} \tag{1}$$

where f_1 is the focal length of the objective lens and f_2 is the focal length of the eyepiece lens. The theoretical magnification is 2.70x.

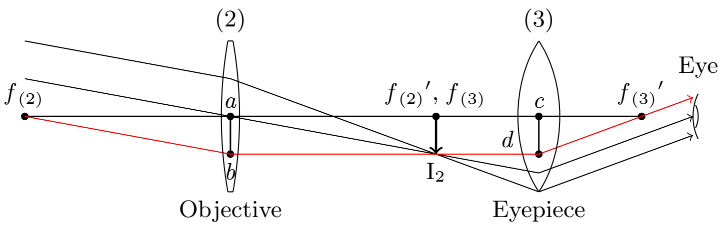


FIG. 2. Ray diagram

Figure 2 traces the behavior of light rays in the telescope. The figure is not to scale, however it accurately portrays the profiles of the lenses. The object is assumed to be at infinity, resulting in parallel incident rays. The image produced by the objective lens is the object for the eyepiece. The eyepiece then produces an inverted image at infinity when the resulting parallel rays are traced back by the eye.

II.3. Telescope Frame

After choosing our lenses, we began designing the frame, which went through several design changes. The first design consisted of the telescope made up of three seperate screwable components, each halved giving a total of six pieces, with each component screwing into the next to allow tolerances for error in measurements and the print job. This idea was scrapped due to a possbile bowing effect between the two ends of the telescope as a result of the large length to radius ratio of the object. The next design consisted of two cylindrical cases that are halved to allow for lenses to be inserted into ridges and rejoined using pegs or brackets. At their junction matching threads will allow for fine length adjustments of up to an inch in either direction from our prediction. This design was abandoned for a simpler sliding joint which provided more stability and rigidity for fine adjustments. Instead of clunky brackets or pins, the halves were held together by a set of cantilevers. To reduce strain in the beam of the cantilever, we tapered the height of the beam, filleted the base of the cantilever, and gave the cantilever a width [2]. We reinforced these design choices with BASF's *Snap-Fit Design Manual* which provided detailed equations for strain and maximum deflection of a cantilever [3]. The two canisters would slide in and out of a third sleeve and be fixed in place with nuts and bolts. This design gave much a much larger range in the possible lengths of the telescope and an easier method of constructing, adjusting, and deconstructing the telescope.

We put a lot of emphasis on the ability to fine tune the built telescope. This is because we were aware of the errors in our measurements, which are a result of the tools and methods used to make our measurements as well as the errors in 3D printing. We wanted to allow as much tolerance as possible to account for these errors.

III. CONSTRUCTION

Construction was very simple with minimal troubleshooting involved despite a misprint. One of the four halves were double but the minor differences in the design of the ridge for holding the lenses was negligible. Paper shims replace the function of the original bolt and set screw fasteners that were planned. The shims also help to align the canisters. The total telescope length (between the two lenses) was 37 cm. while our theoretical sum of focal lengths was 35.5 cm. The inconsistency easily can be traced back to initial focal length measuring experiment and our thin lens approximations. Regardless, this is extremely close to our prediction and falls easily within the 30.5 cm to 43.5 cm range of expansion of our telescope.

IV. RESULTS

IV.1. Magnification

The following equation was used to calculate the magnification of the lenses:

$$M = \frac{y'}{y} \tag{2}$$

where y' is the size of the image and y is the size of the object. The magnification experiment compared two pictures of a line taken from the same distance. One was taken without telescope (Figure 3) and the other was taken with the telescope (Figure 4). The actual magnification can be calculated by comparing the number of pixels of both lines. The two pictures yielded 115.07 pixels without the telescope and 444.28 with the telescope, resulting in a 3.861x magnification.

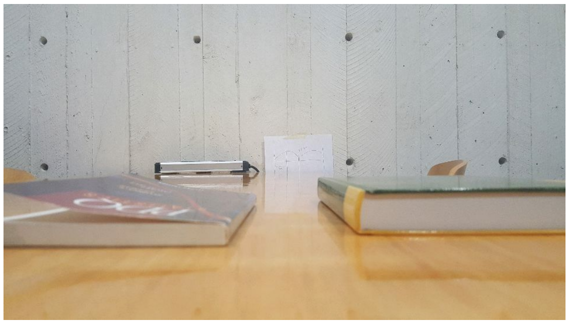


FIG. 3. Picture of object without the telescope.

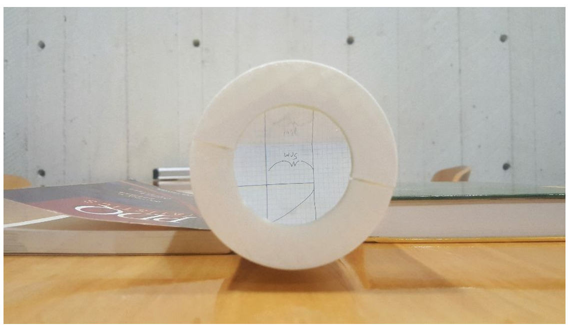


FIG. 4. Picture of image prodcued by the telescope.

IV.2. Cone of Vision

The same experiment can be used to measure the cone of vision of the telescope. The cone of vision can be calculated by measuring at what distance the 5 cm black line on the wall begins to disappear from the range of vision. The angle θ of the field of vision can be calculated using the following formula

$$\theta = 2 \cdot \tan^{-1}\left(\frac{r}{l}\right) \tag{3}$$

where r is the radius of the cone of vision and l is the height of the cone of vision (i.e. the length from the telescope lens to the screen).

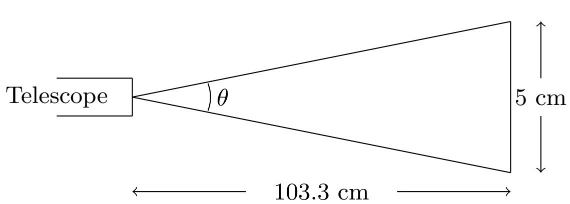


FIG. 5. Cross section of the cone of vision.

The experiment found that the 5 cm line begins to disappear when the telescope is 103.3 cm away from the line. The cone of vision sweeps a full 2.77°, fanning out 1.39° from the center line of sight.

IV.3. Percent Error

The percent error in the magnifcation of our telescope follows the equation

$$\%\ Error = \frac{|M_{\text{theoretical}} - M_{\text{experimental}}|}{M_{\text{theoretical}}} \tag{4}$$

which produces a percent error of 43%. This percent error can be explained by the thin lens assumptions made by Equation 1 and Equation 2. A thin lens is a lens with a thickness much smaller than its focal length. Lens (3) has a much higher thickness to focal length ratio than lens(2), making it less ideal than lens (2). This factor most likely outweighs all other possibilities such as imperfections within the lenses and errors in experimental measurement.

V. CONCLUSIONS

Overall, the product exceeded our expectations. It functions as it should by producing a clear and magnified image.

The focal length measurements proved to be accurate enough for the purposes of designing and constructing the telescope frame. The exact focal lengths are unneccesary considering the telescope can be set to any length between 30.5 cm and 43.5 cm.

The planning and designing of the frame took the longest amount of time. In attempt to find the best balance between sturdiness and ease of construction/destruction, it went trhough multiple design changes as we researched more into snap-fit designs and stress/strain minimization. Based on the final product, that time was well spent.

Despite a misprint, the telescope was able to be put together without any issues. The plastic was splitting immediately after being printed, however, this was fixed with paper shims and hot glue. After these quick fixes, the product is now easy to put together as well as take apart without any risk of damaging the product.

The telescope has a magnification of about 3.8x and the product is only about 37 cm long. It is portabale and can be used to make basic observations. Across the entirety of the project, not a single penny was contributed towards the development and production of the telescope.

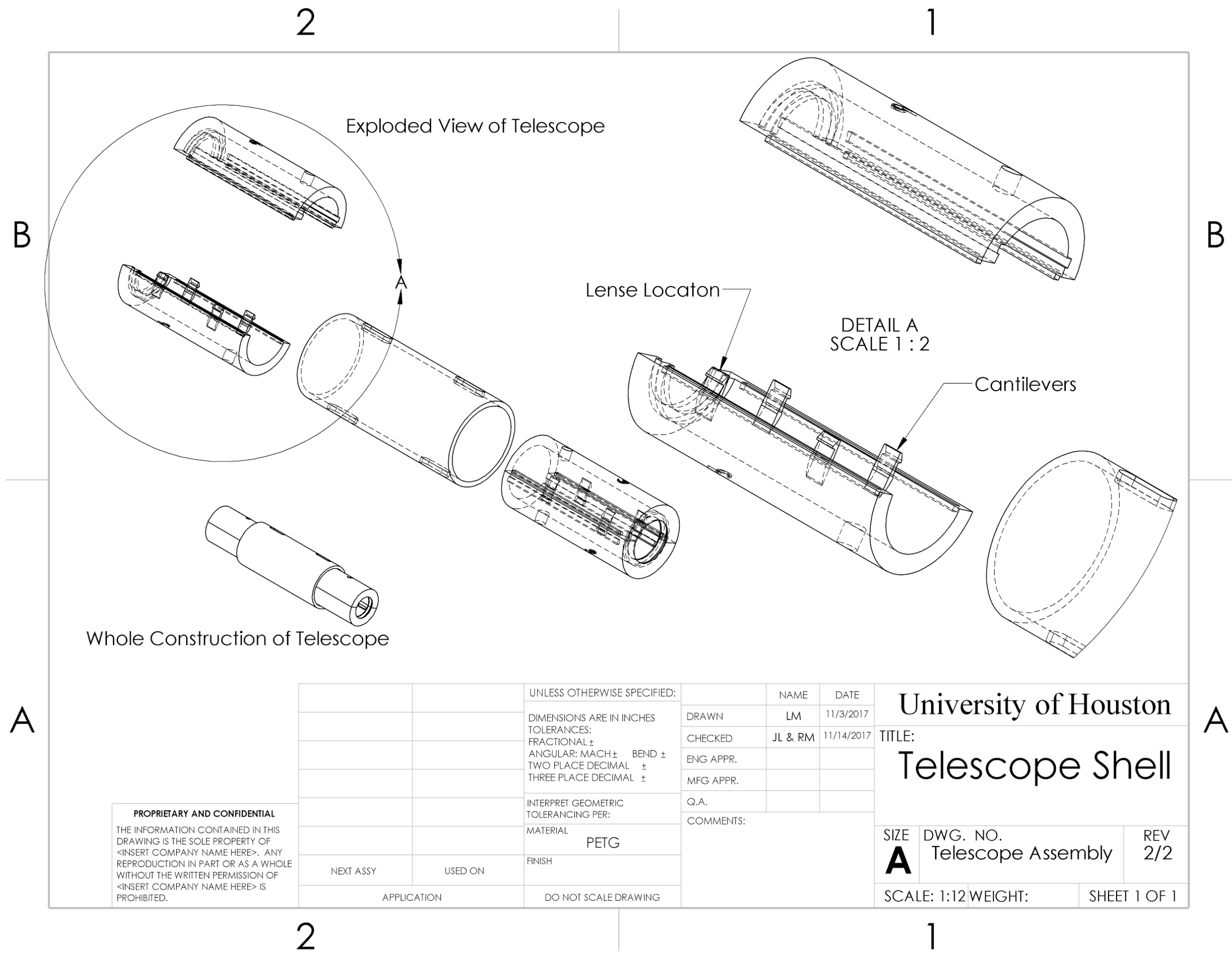
VI. CONTRIBUTIONS

Jonathan Liu added critical design features to the telescope shell, proposed the focal length experiment, participated in the focal length experiment, designed and conducted the magnification experiment, fixed cracks in the shell of the telescope, and wrote Section I, Section III, and Section IV of the paper.

Laura Malcotti-Sanchez participated in the focal length experiment, helped design the telescope shell, completed the prototype construction in SolidWorks 2017, designed the cantilevers along with Reed Masek, conducted the 3D printing, helped outline the paper, wrote Section VI of the paper, edited the paper, and did the scheduling for the group.

Reed Masek participated in the focal length experiment, helped design the telescope shell, constructed the report in LaTeX, drew the ray diagram, helped design the cantilevers along with Laura Malcotti-Sanchez, helped with paper outline, and wrote Section II and Section V of the paper.

Appendix A SOLIDWORKS BLUEPRINTS



[1] Hugh D. Young and Rodger A. Freedman, *Sears & Zemansky's University Physics with Modern Physics*, Pearson Education Inc., 14$^{\text{th}}$ edition, 2016.
[2] James Low, *How to design snap-fit joints for 3D Printing* [article], 3D HUBS, at https://www.3dhubs.com/knowledge-base/how-design-snap-fit-joints-3d-printing
[3] BASF - The Chemical Company, *Technical Expertise: Snap-Fit Design Manual* [PDF], p. IV-3, IV-4, 2007, retrieved from http://web.mit.edu/2.75/resources/random/Snap-Fit%20Design%20Manual.pdf