

Low cost and open source

## Star Tracker: Your Gateway to Astronomy

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In Astronomy, star trackers provide a valuable function in countering the earth's rotation and making the platform rotate the same way as the sky. However, most star trackers require specialist knowledge to set up and are pricey. Which creates a barrier to entry to the rapidly growing astronomy hobby. We are in the progress of creating a 3D printable alt-az type star tracker [2] that works with budget off-the-shelf parts and will publish the software that controls it. Keeping the cost extremely low and as little input from users as possible, while provide the best possible image we can. We believe that our project have successful in lowering the barrier of entry towards the expensive and challenging astronomy hobby.

Additional Key Words and Phrases: Embedded system, Astronomy, Robotics

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### 1 INTRODUCTION

A traditional tracker for astronomy requires either strong knowledge of celestial objects, specialty knowledge to set up the tracker mount, or a deep wallet for fully automated tools [12]. We will be creating a smart star tracker that is capable of pointing to a star automatically and tracks it throughout the night with very minimal knowledge needed for the user. The tracker will allow the user to enjoy the dark sky with some simple user input for setup. After the calibration process, the tracker will be fully automated and capable of pointing and capturing any (bright) celestial objects like the milky way, nebulas, and even galaxies [4].

A Smart Star Tracker that is easy to set up will be created for the project. To reduce the user setup needed, we are gonna create an alt-azimuth mount, a mount that rotates up, down, left, and right from where the user stands. Alt-azimuth mount requires no special astronomy knowledge to set up and with some information about the user's location and time, the coordinates of a celestial object in relation to the user's location can be calculated and the mount could point to the correct location.

We 3D printed the main structure and purchased some other hardware like stepper motors, raspberry pi for the mount to rotate and point to stars. After pointing to a given location of a star, the mount will provide continuous tracking, as the sky rotates (more correctly the earth rotates), the target will rotate about 0.25 degrees per minutes with the earth's pole as the axis, the fastest for targets outside of our galaxy. However with our mount, it will need to adjust 2 axes differently throughout the night as the star's path will look like an arc for most of us who's not living in the north/south pole or the equator.

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## 2 SYSTEM OVERVIEW

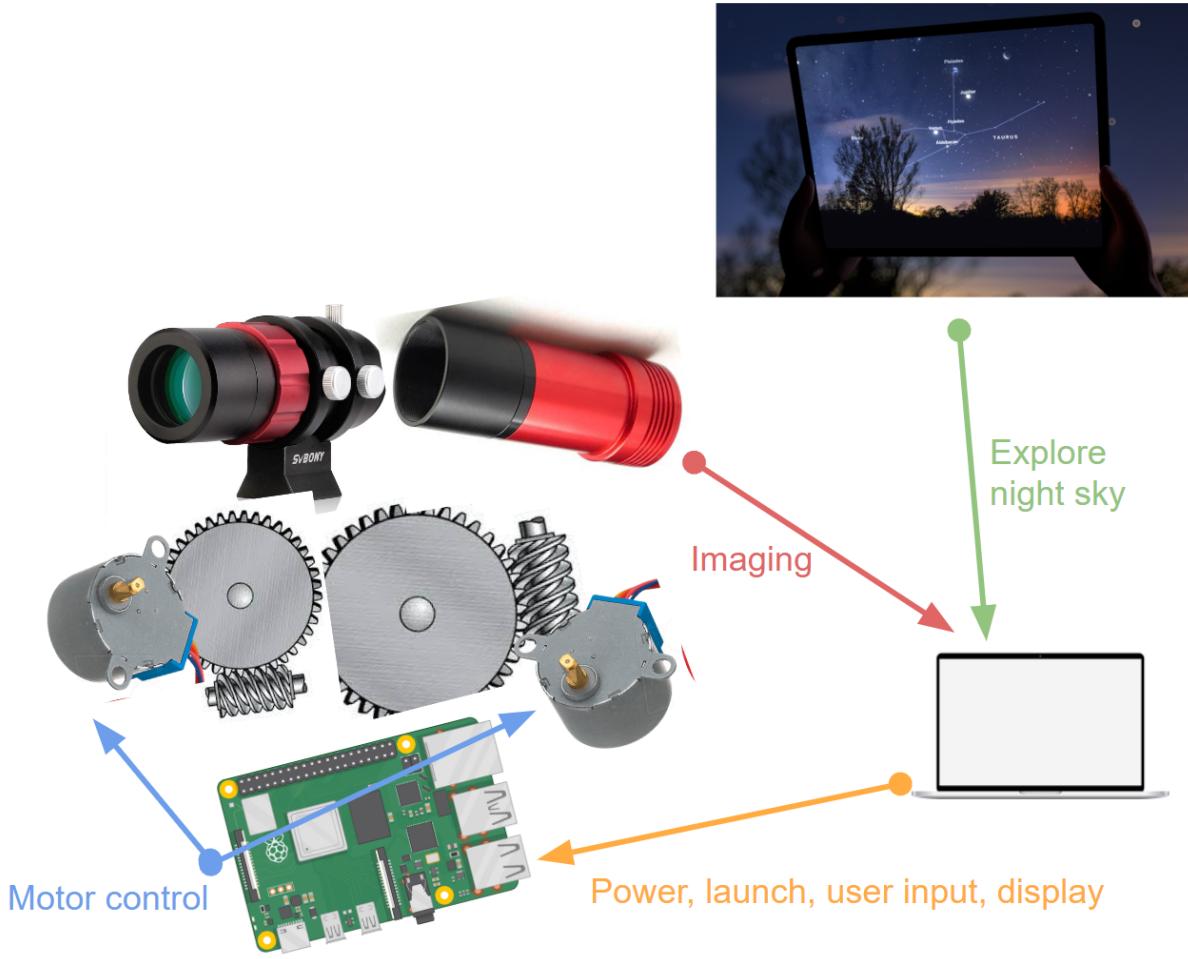


Fig. 1. System overview for star tracker

The diagram shows a rough idea of how the system works and how user interacts with it. The user will first use a app (not provided by us) to explore the dark sky and select what they are interested. Almost all astronomy app would display an Ra-Dec coordinate, a constant number for most deep sky-objects. Then the user can input the Ra-Dec coordinate to the computer.

The computer that provides an interface to send over commands and power to the raspberry pi. Then the raspberry pi would be controlling the mount via the motors because during field testing and the expected place for using such a star tracker will hardly have the luxury of plugging the device into a wall outlet and have a keyboard and screen, so a laptop solves all our need to operate the raspberry pi.

In order to make the camera able to point to any celestial objects, the mount needs to be able to rotate 360-degrees horizontally, and 90-degree vertically, which will cover the whole sky, except when it's below the horizon,

which is an uncommon situation. Then to drive the gears and point to the target with accuracy, we have decided to use worm gear and stepper motors to drive both of the axes so it would have a huge gear reduction ratio and therefore a very fine angle control and very strong torque able to apply to lift any heavy camera. Additionally by making the gear as big as possible we can make the print less demanding on the 3D printer, especially when printing the worm gear and ensuring the strength of the parts at the same time.

Lastly the star tracker is able to carry on other imaging systems in addition to its pi camera setup, which can be a smartphone or extremely small scope. The pi camera is planned to be used as a guiding camera which proves correctional feedback and the mount speed could adjust accordingly.

### 3 RELATED WORK

As this field is quite old, and tracking stars on earth is been a solve problem, but it remain expensive and mostly a research equipment. In recent years it have became more mainstream as the equipment become more affordable, still relatively expansive for most people [1] [5]. Additionally some open-source effort on making astronomy software also make our task simpler, namely Astropy [8], which we have used it for the coordinate system conversion. with quality off-the-shelf parts[3] being great and 3D design software being available for free[6], we believe that we can make affordable star tracker to open up more people to this astronomy hobby.

#### 3.1 Market Position

There are a number of commercially available star trackers, also known as telescope mounts, which can be classified into a couple of different types, which include barn door style trackers, equatorial mounts, Alt-Az mounts, and some fully automated all-in-one solutions. Which have all their specialties and differ greatly in terms of performance, ease of use, price, and weight. I have created a diagram showing the rough characteristics of each different type of mount and their DIY variants.

For Alt-Az mount, it is a type of mount that rotates up down left right in relation to the ground it stands on, using it would require a leveled platform which usually can be achieved by adjusting the tripod which holds the mount. The non-motorized version is the choice of way to mount a large mirror-based telescope as often time included with the telescope, as they are low-cost, simple to make, and handle weight well if the telescope is balanced correctly, which is done by the manufacturer. However, it is only common in visual astronomy or planetary astronomy. One flaw of such mounts is field rotation, which is the rotation of the astronomy target rotating a bit throughout the night from the view of the scope (“What is field rotation? How does it affect my scope’s viewing and image”). This effect of field rotation in a short period of time is quite minimal and is able to be solved by using a shorter exposure time and a star alignment before stacking [7]. As a result, all commercially available all-in-one fully automated observation stations use a 2-axis motorized Alt-Az mount.

For Equatorial Mounts, which include all their variants like the most common German Equatorial Mounts (GEMs), and Center balanced Equatorial Mounts (CEMs). Are the most common mount in the astrophotography community and some research observatories, As the mount counteracts the field rotation problem that happens in the Alt-Az mount. However, it requires a specific axis of rotation to be aligned with the pole of rotation of the earth, which requires specialized knowledge and specialized equipment like polar scope or a special 3-star alignment process if the mount is motorized on both axes. Personally, I (Sing) have owned a Sky-Watcher Star Adventurer 2i Pro Pack, a beginner 1 Axis motorized German Equatorial Mount, and this process takes me about 15 minutes with a clear view of the polar star, polar scope, and an app on my phone to align my personal mount \*. However the process is impossible without the polar star, and it will be extremely difficult in the southern hemisphere, as they do not have a bright star to align to. The requirement of specialty knowledge for setting up this mount drove us away from using the equatorial mount design.

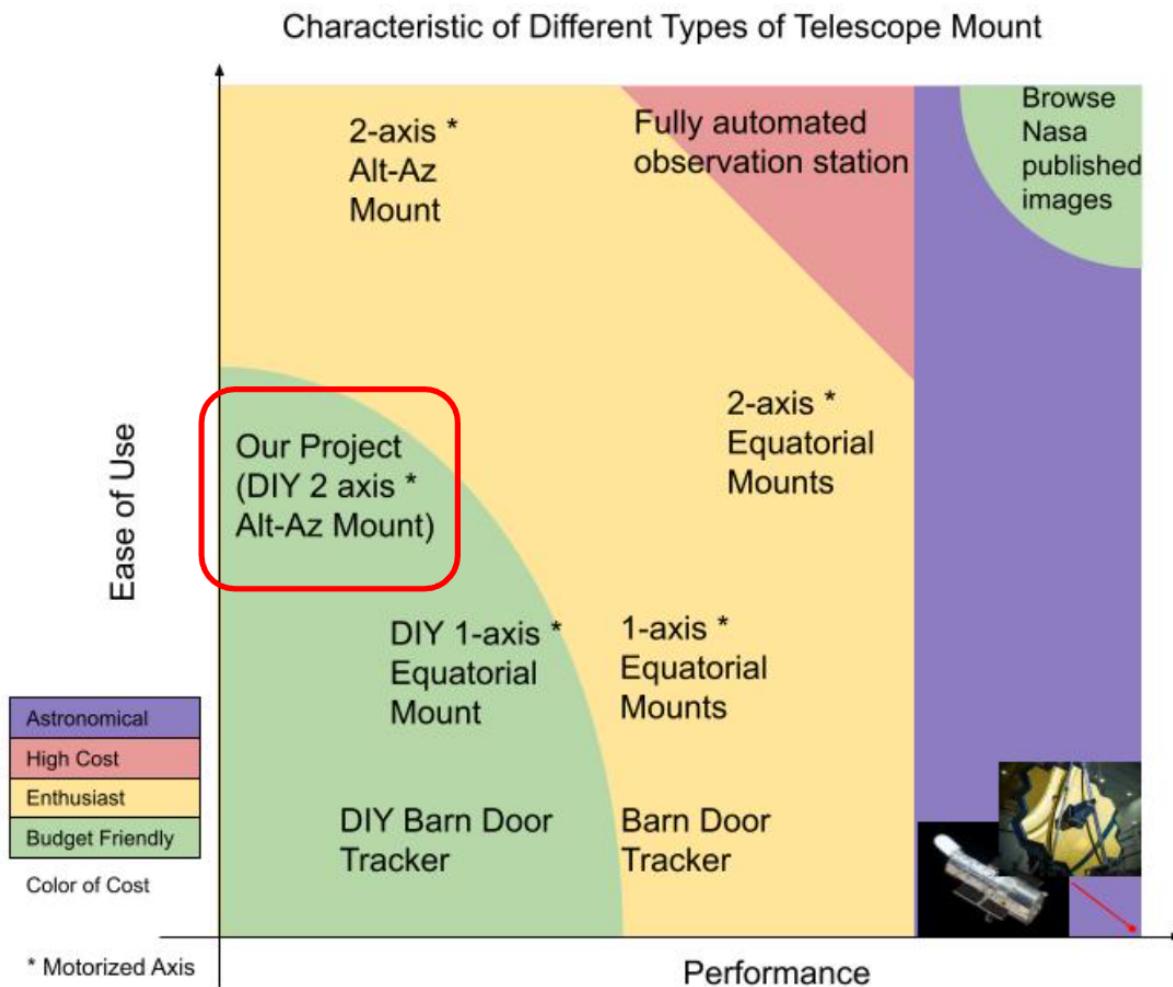


Fig. 2. market position for our star tracker project in relation to other products

Lastly for people where money is not an obstacle, I (Sing) personally recommend purchasing one of the telescopes used in space by NASA, which is mounted on some form of satellite orientating system with altitude boosters. I believe it can take pretty nice images, if any of this paper's readers have purchased one of those, please invite me over for a star party. :)

### 3.2 Minimum Viable Product

Our MVP will be a 3D printed worm gear driven Alt-azimuth mount that holds and rotates a raspberry pi and its camera. The mount should be capable of pointing to some famous celestial object, specifically all 110 messier objects ([https://en.wikipedia.org/wiki/Messier\\_object](https://en.wikipedia.org/wiki/Messier_object)). Then automatically track the object and keep it in the frame for 20 mins, assuming the object is centered originally. Then the device should be able to display a long

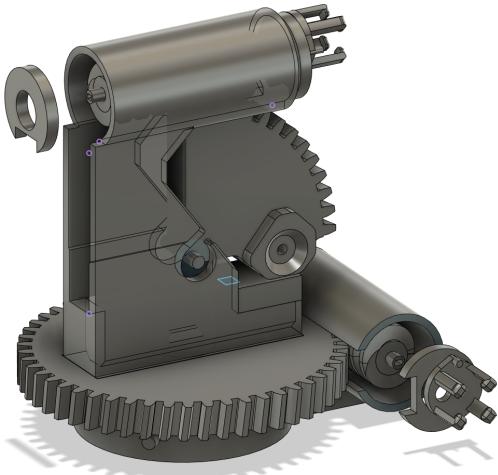


Fig. 3. 3D Design

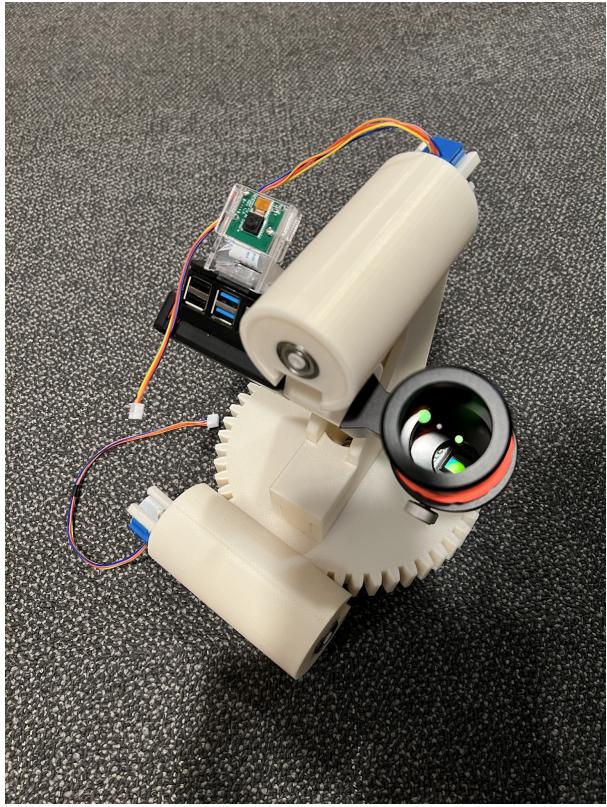


Fig. 4. Assembled Model

exposure image of the object, so the user will get a photo of the starry night sky and the celestial object without noticeable star trails.

## 4 OUR STAR TRACKER

### 4.1 Hardware

The main focus of the hardware portion is the manufacturing of our tracker. Since large off-the-shelf gears are expensive, we have chosen to go with 3D printed gears and structures. Then purchased some other low cost hardware like bearings and screws.

**4.1.1 3D Design.** We used Fusion 360 [6] to work on our design, and the photo on the right is the tracker that we've designed. During our design process, we went through many iterations due to concerns about printability, accuracy, and interfacing with other components. Our 3D design star tracker consists of the base, base gear with worm gear holder, stand with worm gear holder, top quarter gear, caps, caps with stepper motor holder, and worm gear. Total of 7 different components and 9 total items need to be printed, where 2 components need 2 of each. We have designed our gears to be as big as possible to increase part strength and reduce the difficulty of printing small gear, especially the worm gear. Also, the mounting solution, assembly process, and clearance for Pi, stepper motor, guiding camera, and imaging Camera are all considered during the design process. Additionally,

rotating parts are designed to have a bearing in mind and the base has additional bearings as support for the base gear for a smooth operation. Our design has turned out great and we have avoided the need for any reprints. The image of the complete 3D design is attached, with finalized files available in our GitHub repository.

**4.1.2 Cameras.** The whole imaging system consists of a ZWO ASI 120mm mini camera [1] and a svbony mini scope, which are easily purchasable and will be providing all the beautiful images you will be seeing in the following sections. The mini camera also comes with the software and the driver for ASI camera control, imaging, guiding and processing [5].

**4.1.3 Additional Hardware.** Besides the mentioned hardware, we also used the half-inch screws for connecting parts, and the bearings. We have a bearing for the axis of each moving parts, which are the base gear, the vertical gear, the base worm, and the vertical worm. Additionally, we have 4 extra bearings at the edge of the base. These are to support the base gear as well as the other components attached to it. So the horizontal base gear will not touch the base and thus no extra friction will be added to the base motor. Finally, we used limit switches and some aluminum foil to automatically determine where the zero positions of our gears lie. While this would be included in the hardware a user would have to purchase, we were unable to acquire them in time.

**4.1.4 3D Print and Assemble.** Digital fabrication technology is one of the most fast- emerging technologies in the 21st century [11]. The 3D printing is handled by an engineer in SeaLab, Nathan Hui, and we'd like to give him a special thanks for handling all the 3D printing process. The 3D printing took about 4 days and it turned out pretty nice, with some simple clean and assembly, the tracker is assembled under an hour and functions nicely.

## 4.2 Hardware Software Interface

In order to interface the motors and the cameras to the raspberry pi, several jobs need to be done. First, we need to test our cameras and ensure they function properly with the long exposure mode. Sing has completed this part by setting up a tripod and all cameras in a parking lot at night to take photos of a couple of bright stars, including Sirius and Polaris, and got good images of the target using both the pi camera and the mini-guide camera with star trail, so we have a baseline to compare to. Next for the motor control, we need to connect the pins correctly, this includes the power pins and the signal pins. Also, we need to write the code based on the pins we use. Each of the stepper motors has 4 signal inputs and 8 different states [3]. We need to iterate through the states in order to make it work. James has completed that part since he can provide videos of the motors spinning. He has also tested the stepper motors, which have found a potential issue with heat. To track the stars accurately, we need to rotate our assembly at certain degrees per second. In order to be able to do that accurately, we need to know the zero positions of our gears and, by extension, our stepper motors. To this end, we need to create a calibration system that will rotate the gears to the correct starting (zero) position every time the star tracker is restarted. For our MVP, we will have the user manually rotate the gears until a beep is heard, meaning the gear has been calibrated. Later, we would like to have this as an automatic homing process every time the system is turned on. To this end, we will use two separate systems. We will use a limit switch for the vertical quarter gear since this gear does have a stopping point. For the base gear, however, we will be using conductive pads made of aluminum foil on both the base and the gear, and when these pads are touching, therefore completing the circuit, we will know we have reached the zero position. Initially, we were planning on having this feature implemented in our original MVP. We were not able to order the components soon enough to get this done on time. However, since the system we were planning on using is nothing but two switches (the aluminum foil contact pads also act like a switch since they are opening/closing the circuit), we wrote and published the code for the calibration on our GitHub.

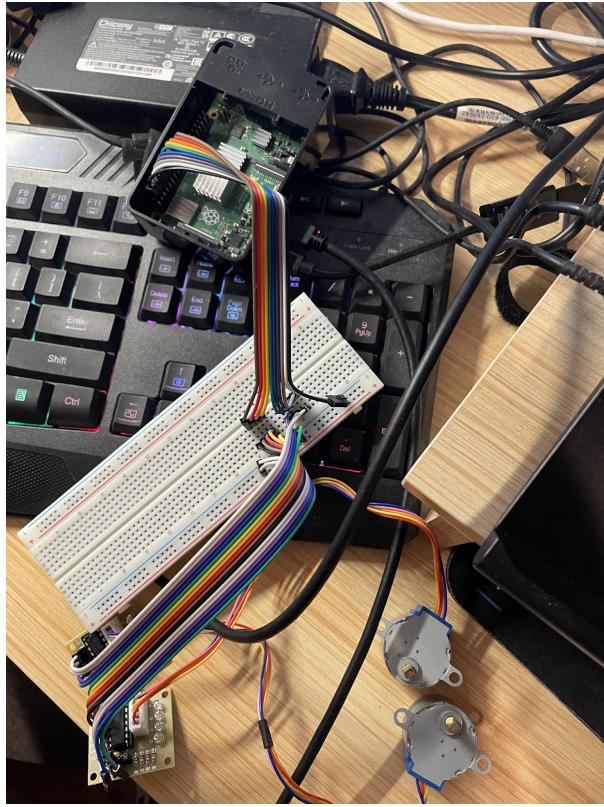


Fig. 5. Wiring of the motors

**4.2.1 mount operation.** There are some mount operations implemented for easier tracker control. First, James implemented continuous move with the keys "WASD", which can let the gears move continuously in the desired direction. "W" sets the vertical gear to rise, "S" sets the vertical gear to decrease, "A" sets the horizontal gear to turn left, "D" sets the horizontal gear to turn right. Second, we have the precise control with the keys "IJKL", which allows the gears move only when the correspond key is pressed and held. Then, James implemented the "set displacement" mode, which allows the user to enter the displacement in the horizontal direction and the vertical direction, in this step, negative inputs will be automatically translated to displacement in the negative direction. Finally, there is the "set speed" mode, which allows the user to enter the speed for the gears, and let the gears move continuously. As the "set displacement" mode, negative inputs will be translated to be a speed in the negative direction. Both modes can be used in the code for the software part. With all these functionalities, the star tracker can be manipulated freely by both the user and/or the software algorithm.

**4.2.2 camera operation.** We are using the provided camera operation software from the company, ZWO, which also provides a live stacking feature, where stars are used to correct for minor errors in shift and rotation. Which means that our mount now just needed to be able to point to a rough position and doesn't need to be perfect on tracking.

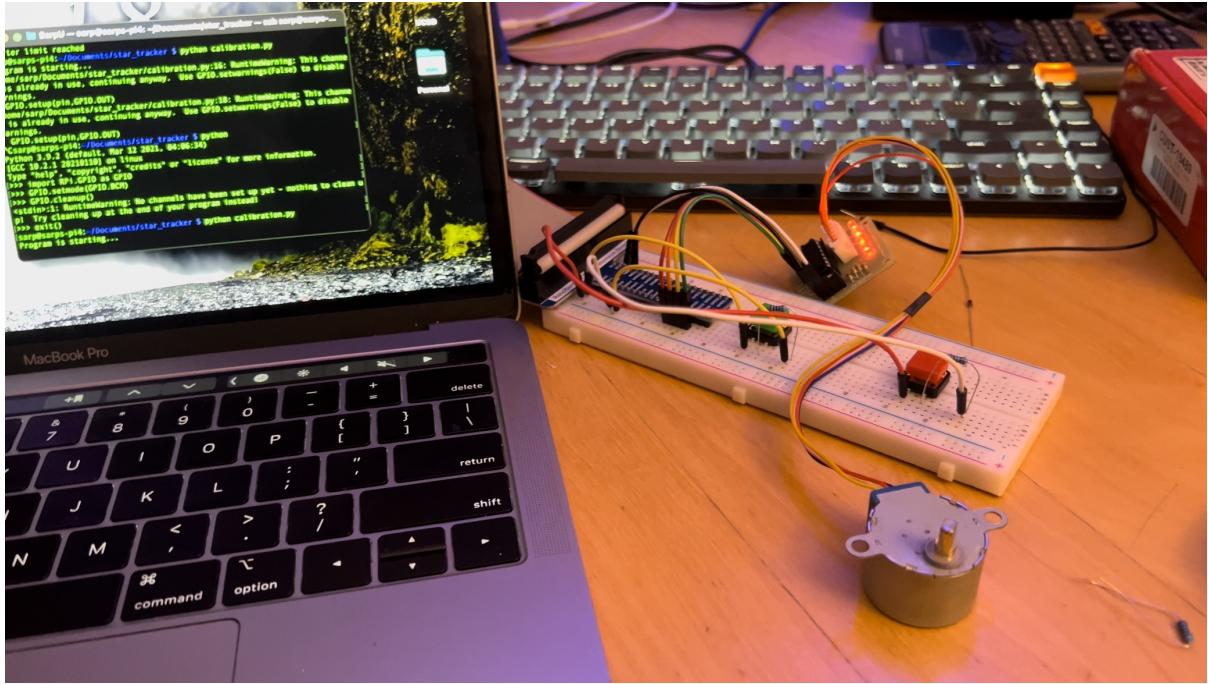


Fig. 6. Calibration code testing setup (we would use limit switches and aluminum foils instead of push buttons)

### 4.3 Software

**4.3.1 Go-to Feature.** For go-to features, we will need to ask the user for some information, including time, GPS location, and point the mount to a known star. From there we can infer the mount's orientation [10], inferred from the one bright star we ask the user to point to, which here we completed the code for inferring the mount's location. Then, to move the mount to any other target, we would need to know the coordination of the object, which we would need to have a list of, and they are usually stored in Ra-Dec coordinates, which our mount uses the Alt-Az coordinate system. The correct Alt-Az coordinate can be calculated from Ra-Dec with GPS and time information. for this coordinate system conversion, we used a library, astropy, for the task. After we have the Alt-Az coordinates, we can point our mount to it and some math is completed to calculate the mount angle and the rotation needed by the stepper motor.

**4.3.2 Tracking Feature.** For the tracking feature, we decided to use a continuous go-to way to complete the tracking feature [9], the computer will constantly recalculate the coordinate in Alt-Az coordinate and move to the location where the celestial object will be heading slowly, it would achieve a tracking feature without too many additional codes.

## 5 MILESTONE

Hardware	Hardware Software Interfacing	Software
Tracker 3D design	Motor control	Go-To feature
All additional hardware purchased	Position calibration	Tracking feature
Tracker 3D printing and Assembly		Camera assisted tracking

so for the mount to function, we need to work on hardware, software and integrating of both. For hardware we first need to 3D design the main structure, purchase additional hardware like bearings and screws then assembled it, which is listed as a miles stone each. We have completed all of the milestone in hardware and are very proud of it. Then on the hardware software interfacing, we need to control the motor and need to track and control how many times the motor spins, so we can calculate the angle of where the scope is pointed at, which we have completed. For the software part, we have completed both the go-to feature and the tracking feature, where the tracking is implemented by doing go-to continuously and recalculating the new location. and the coordinate system converts celestial object's Ra-Dec coordinate to the Alt-Az in degrees which can be then converted into stepper motor step counts. then the mount can rotate accordingly.

The milestone what we haven't completed is position calibration in hardware software integration and camera assisted tracking in software. While we were unable to mount the calibration hardware on the actual assembly due to not having the hardware in time, we have demonstrated that the calibration does work as intended using push buttons. The code for this can be found on our GitHub as well as a demonstration on the final video. On the other-hand, camera assisted tracking required a good camera integration with the code, but we have found out the pi is not very usable for tracking, as the delay of obtaining images are too long at 25 seconds after optimizing, and our main imaging camera are complicated with use by python code. so we've deemed it too complicated to complete in the time-frame we have. However, both can be consider a good to have feature, not a must have feature.

### 5.1 Problems

We had two kinds of problems. The first is about not having enough man power. We are a relatively small team compared with other teams, and not all of our team member were working as they are supposed to. We solved this problem through better team communication and kept a good team dynamic. The second came from a more technical part, because we upgraded our imaging system from 26 mm (full frame equivalent) to larger than 800 mm (full frame equivalent), the vision of the camera became much narrower, which made the star tracks visually more obvious and thus added difficulties to the project. The problem with long focal length is a really good feature for astrophotography, so we've decided to make the mount micro adjustable by the user, so it can point to anything accurately with some help from the user. When we field tested our system, the system shows that it worked well when pointing to the moon after some minor adjustments.

## 6 LIMITATION

There are some fields of astronomy that are impossible to observe with our setup. Namely, anything that's outside of infrared and the visible spectrum. Some researchers and hard-core enthusiasts observe radio waves or even high frequencies like gamma-rays. Our setup only focuses on the visible light spectrum with some IR spectrum as our main imagined camera has a clear filter instead of the usual UV/IR cut filter.

Secondly, with our current setup, without additional filters or equipment upgrades, there are some observations that are very hard to be done. Namely Solar observation and planetary observation. First, for solar observation, the Sun is incredibly bright and would require solar filters (only allow 0.4% light through) for observing without damaging the imaging sensor. On the other hand, planetary observation is possible but will not obtain awesome results due to the wide focal length our lens has ( 100mm; wide in astronomy terms), whereas normally planetary

observation recommends a focal length > 1500mm. As a result, we expect all the planets will look like a single dot of light, just like a star.

Lastly, we have relied heavily on 3D printed parts and budget hardware, which will result in less accuracy with more gear backlash compared to all commercially available products that use higher precision metal gears. However, we believe that our target audience will not mind lesser performance in tracking accuracy and gear backlash due to the price point we offer and the more general public-facing market instead of the enthusiast crowds.

## 7 RESULTS

### 7.1 Field Test Setup

from figure 7, We do not have the best result due to the consistent cloudy nights that we have for about 2.5 weeks. In this 2.5 weeks Only less than 5 hours of cloud-less dark sky are available to conduct field test. It is very rare such condition happens in San Diego. We've done our best to provide celestial images.

and from figure 8, we can see the system overall is able to function in the expected environment, where no external power and internet connection are available. Everything is powered by the laptop battery and the software is capable of functioning offline.



Fig. 7. weather where final field test is conducted, moon is visible behind some clouds

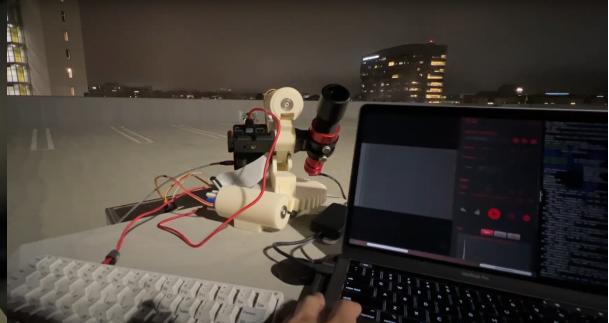


Fig. 8. final field test set up

## 7.2 Final Results



Fig. 9. 5 sec image with mount



Fig. 10. 60 sec image without mount

For both 10 and 9, this 2 images are taken before the final field test, separated from the moon image below, as the clouds haze would completely cover up stars, making it impossible for taking photos of stars.

From figure 10, This is the baseline 60 seconds image that's taken before-hand. We can see that the star trail is very long. and it's an issue when imaging other celestial objects

From figure 9. After the using the mount and the live stacking feature provided by the camera software, we can see that for 5 seconds it's able to capture pin-point sharp stars. Additionally we can see the length for the star trail is shorter than 1/12 of the 60 seconds image, showing that the live stacking are able to correct for the field rotation and the jitters in the mount, and the mount are able to point the camera to a roughly accurate position.

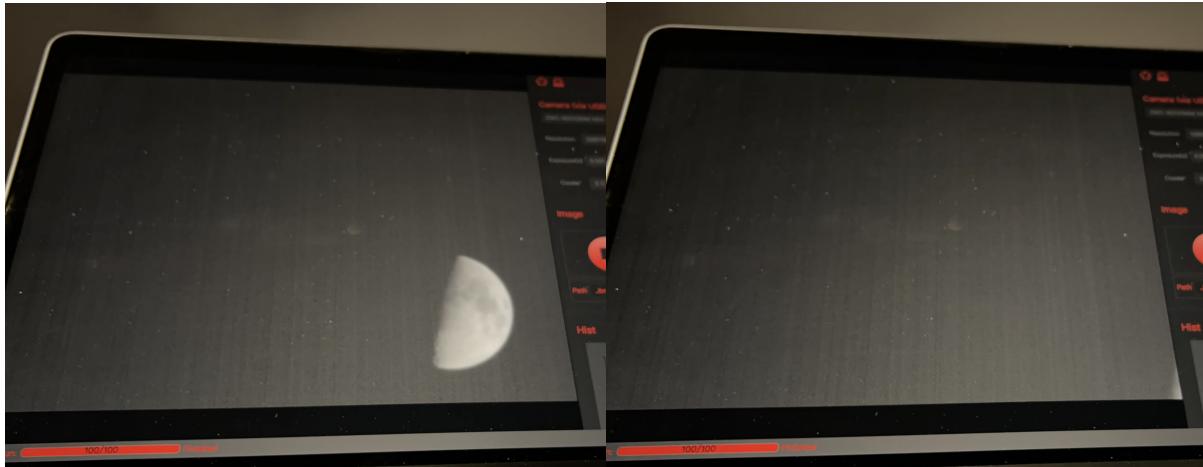


Fig. 11. initial

Fig. 12. after 3 minutes

Fig. 13. position change of celestial object for 3 minutes without the mount

from figure 11, with the moon as reference we can see that with how small patch of sky the mini scope are seeing. both image are not cropped in at all. With this level of magnification, the sky's rotation becomes a serious challenge, as the moon can move away from the from after a couple minutes, as seen in figure 11.

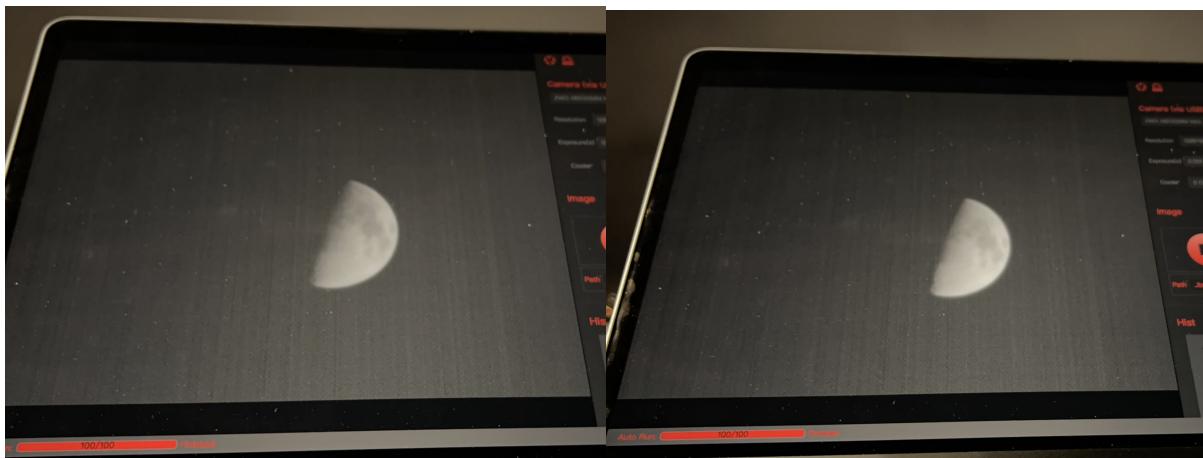


Fig. 14. initial

Fig. 15. after 3 minutes

Fig. 16. position change of celestial object for 3 minutes with the mount

from figure 14 and 15, we can see that the position stayed roughly at the same spot. Each step in stepper motor along with it's 1:50 worm gear reduction, it should have only be a change of 0.1 degree. However, though-out the tracking, the position of the moon actually jumps around quite a bit, as gear have some roughness to it and the

level of gear reduction aren't enough, making a single step of change in the stepper motor translated to a jump in moon's position and it's noticeable when viewing the screen. Overall the mount is capable of correcting some of earth's rotation while being quite simple to setup.



Fig. 17. raw image of moon taken by our imaging system with tracker in less then ideal condition with clouds and Bortle 7 light pollution zone

Figure 17, this is the raw image that's captured in the final field test, which both of us are incrediblily proud of and it's the definitive result of our project and the result of us conquering and adapting to the hardship with technical and weather difficulties.

## 8 CONCLUSION

Astronomy has been an difficult and expensive hobby for most of the population, therefore we are working on implementing our own 3D printable alt-az type star tracking system, which is low-cost for everyone who is interested in astronomy. Even though it has resulted in a much more challenging project than we expected. After working through numerous software and hardware hurdles, we were able to produce a working minimum

viable product that can get us half decent images. Even though this product is far from market ready, we are very pleased with the promising initial results. Moving forward, we would like to implement the self calibration and some image processing to clean up the images.

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