ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

3D Scanner

Team #1

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1 Introduction

1.1 Problem

3D scanning is an innovative technology that allows the collection of physical object data to construct highly accurate digital 3D models [1]–[3]. This technology has vast applications across many industries, from manufacturing to healthcare [4], [5],where the ability to capture detailed 3D models is becoming increasingly indispensable. One of the limitations of traditional 3D scanners is their size and portability, making them less accessible to people who do not have access to these tools.

Embedding 3D scanning technology into mobile phones could revolutionize the way people approach 3D scanning. With smartphones becoming more prevalent and widely adopted, incorporating 3D scanners into mobile devices could popularize 3D scanning technology, making it accessible to individuals, businesses, and organizations of all sizes. This could potentially transform the way people use 3D scanning in their everyday lives and work.

One of the major issues with traditional 3D scanners is the time it takes to process and render a 3D model. For larger or more complex objects, this can be a significant challenge. However, designing applications that can process data more quickly could improve user experience and increase the practical applications of 3D scanning on mobile devices. By developing more efficient and user-friendly applications, 3D scanning can become a more accessible and powerful tool.

Another challenge with traditional 3D scanners is the complexity of the scanning process. Some techniques require specific settings or lighting conditions to work correctly, which can be frustrating for new users. Designing a more intuitive and user-friendly 3D scanner could help make 3D scanning more accessible to a wider audience. By simplifying the scanning process and removing barriers to entry, more people can begin to explore the possibilities of 3D scanning.

In conclusion, 3D scanning is a rapidly evolving technology with numerous applications across many industries. Embedding 3D scanning technology into mobile phones could popularize this technology and make it accessible to a wider audience [3]. However, there are still challenges to overcome, such as the processing time and complexity of the scanning process. By addressing these issues and creating more user-friendly applications, 3D scanning could become a ubiquitous tool that transforms the way we approach design, manufacturing, healthcare, and many other fields.

1.2 Solution

Our proposed solution involves designing an autonomous system that utilizes a mobile phone's camera to capture multiple-angled photos. These photos are then used to generate 3D models from various 2D images taken at different positions. Additionally, a remote-controlled mechanical device will be implemented, which will allow the mobile phone to rotate 360 degrees and move the object up and down on the platform. The system will enable the user to scan objects within a specific range of volume using their phone's camera, and generate highly accurate digital 3D models in a short period. Regarding the software component of our proposed solution, our plan is to create a program that will enable the camera on a mobile phone to capture images at predetermined intervals and subsequently transmit them wirelessly to a designated server. On the server side, we intend to develop an algorithm with the capability of transforming the 2D images captured by the mobile phone into digital 3D models. By doing so, our solution aims to provide a user-friendly and accessible means of creating 3D models for individuals who do not have access to traditional 3D scanning equipment. In terms of the hardware component, we plan to design and construct a mechanical device that consists of a platform with height adjustment capabilities and a phone holder that is adjustable and equipped with wheels at the bottom.

The phone holder can rotate around the platform via remote-controlled motors, while the platform can be raised or lowered to adjust the height of the object being scanned. Through these mechanical functions, our solution aims to provide users with a versatile and adaptable means of capturing 3D images using their mobile phones. The technology has the potential to be used in various fields, including product design, manufacturing, healthcare, and cultural heritage preservation [4]. With the increasing accessibility and affordability of mobile phone technology, our proposed solution provides a promising alternative to traditional 3D scanning equipment.

1.3 Visual Aid

Figure 1: Visual Aid of 3D Scanner

1.4 High-level Requirements List

- ✔ The 3D scanner should be able to capture data from a wide range of object sizes, from small objects to large structures, and be able to scan objects in 360 degrees.
- ✔ The 3D scanner should be user-friendly and easy to operate, requiring less than 30 minutes of training.

- ✔ The mechanical device should take the phone and the holder to rotate 360 degrees continuously. One rotation takes 10 seconds on average.

2 Design

2.1 Block Diagram

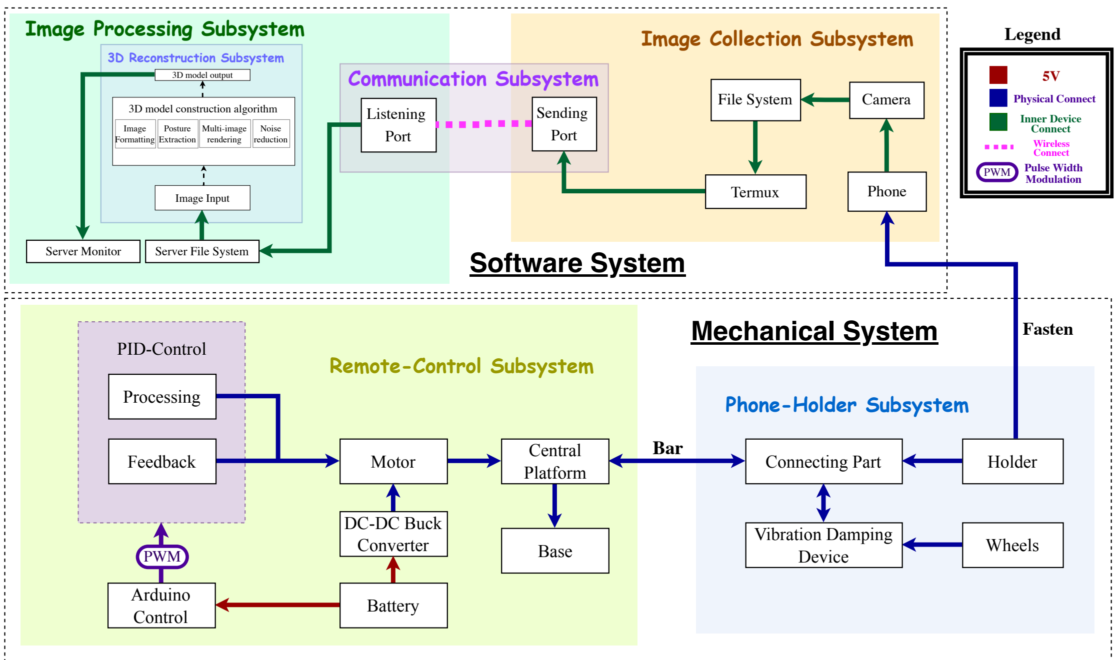

Figure 2: Block Diagram of 3D Scanner

2.2 Physical Design

As shown in figure 3 and 5, a phone can be put into the phone holder. The phone holder, the universal wheel and the central ring are all connected together to the adapting piece with 3 bars. The central ring is tightly connected to the belt, while the belt is connected to 2 bevel gears, which are driven by the DC motor through a shaft. Since we plan to install wheels under the central ring and the one end of the bar is attached to a universal wheel, the phone holder and the central ring are both able to rotate smoothly in contact with the ground. In our design, the central ring should have a fixed center, while the central ring, the DC motor and the belt roller should be fixed on the ground without rotation.

2.3 Subsystem Overview

1. **Image collection subsystem**. Image collection subsystem is composed of a mobile phone and a specialized software application. The application will allow for the precise control of a camera's settings and enable it to capture images at predetermined

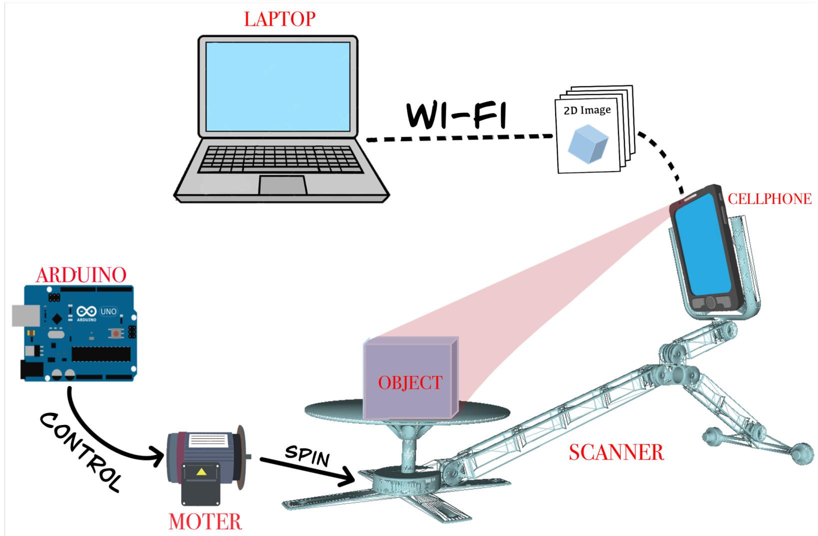

Figure 3: Physical design

time intervals. Through the wireless communication protocols, these images will be sent to a designated server in real-time. This program will provide a convenient and efficient way to remotely collect and transfer 2D images at different angles.

For the type of cell phone, we chose the Android phone with a richer open source ecosystem. Due to the limitation of the computing power of mobile devices, we decided to separate the image conversion system into two parts. The image collection subsystem corresponds to the client part. The client part communicates (transferring images) with the server part through wireless communication, such as TCP connection. Our experimental machine is iQOO Neo3, it has Android 10.0. We chose Termux and QPython to be the development platform, which are available in the Google Play. For Termux Version 0.118.0, it requires Android 7.0 or newer. For QPython 3L, it requires Android 4.0 or newer.

Requirements:

- ✔ It should be built based on software platform Termux 0.118.0 and QPython 3L so that the software has both the compatibility with Android 4.0 mobile operating system and upward compatibility.
- ✔ All photos taken can be found in the local path of the Android phone, and the time interval between photos is in accordance with the program's settings.

Verification:

- ❍ The compatibility can be checked in our experimental Android phone.
- ❍ The number of photos and the interval of capturing time are checked according to the storage path, and the interval of capturing time should match the programmed time interval ($\pm 10\%$).

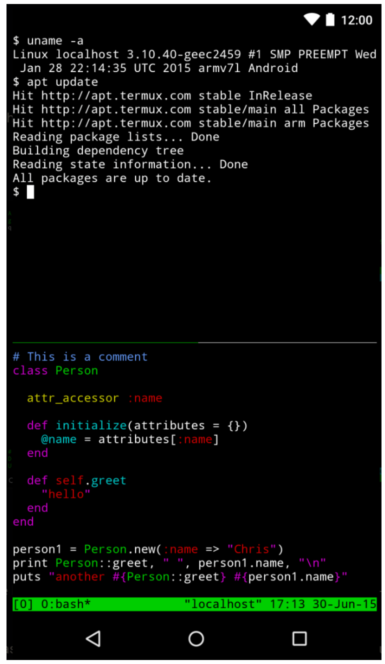

Figure 4: Termux development interface

2. **Communication subsystem**. This subsystem is designed to facilitate seamless image transmission between mobile phones and leptops using the TCP wireless transmission system. By leveraging the robust and reliable nature of TCP, this subsystem ensures accurate and uninterrupted transfer of image data across devices. We provide pseudo-code for sock network programming in python, including sending data 1 and receiving data 2, respectively.

Algorithm 1: Socket sending data

Input : server_address, server_port, data_to_send
Output: None

sock ← `create_socket()`
`connect`(*sock*, *(server_address, server_port)*)
for *data in data_to_send* **do**
  `send_data`(*sock*, *data_to_send*)
end
`close`(*sock*)

Algorithm 2: Socket receiving data

Input : server_address, server_port, buffer_size
Output: client_data

```
server_socket ← create_socket()
bind(server_socket, (server_address, server_port))
listen(server_socket, 1)
while Connection Set do
    client_socket, client_address ← accept(server_socket)
    client_data ← receive_data(client_socket, buffer_size)
end
close(client_socket)
close(server_socket)
```

Requirements:

✔ The vast majority of images collected by mobile devices can be transmitted quickly and reliably to the server-side.

Verification:

❍ The transmission rate of images should not be lower than one image per second, and the rate of transmission failure should not exceed 10%.

3. **Image processing subsystem**. Image processing subsystem is a key component in the development of a autonomous system that can transform multiple 2D images into a high-quality 3D model. This subsystem takes the images collected by the image collection subsystem as input and uses advanced algorithms to analyze and process them. The 3D reconstruction algorithms primarily involves the following steps. Feature extraction: detecting feature points in the input images. Feature matching: finding corresponding feature points between different images. Structure from Motion (SfM): estimating the camera poses and the positions of feature points in the 3D space. Multi-View Stereo (MVS): generating a dense 3D model based on the known camera poses and 3D point cloud. 3D mesh generation: creating a 3D mesh model from the dense point cloud. Texture generation: projecting the colors from the input images onto the 3D mesh, generating textures. The detailed algorithms are shown in appendix A.

Requirements:

✔ The generated 3D model should bear a resemblance to the scanned object when viewed by the human eye.

✔ The chamfer distance (CD) and earth mover's distance (EMD) between the generated point cloud and the ground truth[1] point cloud should be minimized to the greatest extent possible.

[1] As we do not possess the true 3D model of the object, we adopt the reconstruction results of the current state-of-the-art 3D reconstruction model as the ground truth.

Verification:

❍ Human evaluators should be employed to assess the quality of the generated model, with the vast majority of evaluators concluding that the generated 3D model bears a resemblance to the scanned object.

❍ The value of chamfer distance (CD) should be below 5e-3, while the value of earth mover's distance (EMD) should be below 0.2.

4. **Phone-holder subsystem**. As shown in figure 5, the phone-holder subsystem, which supports the image collection system, is a physical device containing several mechanical parts, such as the DC motor, belt, wheels, gears and bar. The object that needs to be scanned should be placed on the round plate at the center. When the mechanical system works, the DC motor firstly receives signals from the remote-control subsystem and starts to rotate a horizontal shaft, which is connected to one side of a bevel gear. With the help of 2 bevel gears, then the rotational momentum is passed to a belt roller that is in close contact with a belt. After that, the belt can drive the ring at the center to rotate. Since the phone holder is connected to the central ring on one end and a universal wheel on the other end with bars, at last the phone holder is able to rotate a complete circle around the central plate. The remote-control subsystem controls the speed of the motor by sending signals.

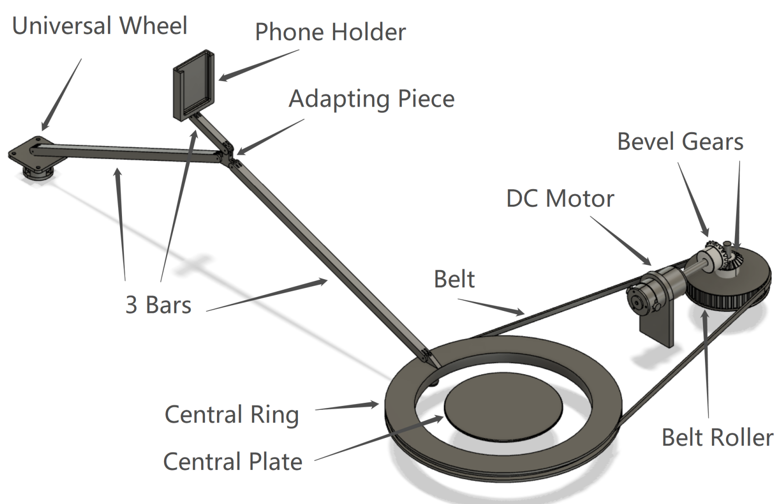

Figure 5: Phone-holder CAD model

Requirements:

✔ The phone should be able to move and take pictures of an object from many angles.

✔ The mechanical device should be able to stand the weight of a typical smart phone without any damage.

Verification:

❍ The phone holder can rotate at least 360° around the center without hitting any other parts (the belt, the belt roller, etc). The distance between the universal wheel of the phone holder and the center of the plate should be larger than 544 mm, which is the distance between the furthest end of the belt and the center of the plate.

❍ The whole mechanical system should be able to work normally when a load of 300 g (a weight of 240 g for the heaviest iPhone plus another 60 g of tolerance) is applied on the holder.

5. **Remote-control subsystem**. Remote-control subsystem should control the motor's rotating speed to control the horizontal shaft, connected to one side of the gear. This subsystem can drive the central plate to rotate where the object is placed. This will help the phone to take photos for the object in a clear and convenient way. The motor is controlled by sending a series of pulses through the signal line. The frequency of the control signal should be 50 Hz and pulse every 20 ms. The pulse width determines the angular position of the motor, and these types of motors can usually rotate 180 degrees. Moreover, the remote-control subsystem should also have solid connections with the phone-holder subsystem by a bar and its joints need to tolerate at least a torque of 1 N · m. Figure 6 is the circuit diagram of the subsystem. We use a stepper motor to simulate, and the PWM can control the signal of the motor. When the load torque is 0, we simulate the circuit and the result is shown in 7.

Requirement:

✔ The scanning process takes 10 seconds on average to complete one round.

Verification:

❍ The angular velocity of the central ring is 0.628 rad/s (±10%). The angular velocity of the belt roller is 1.743 rad/s (± 10%). The rotation speed of the DC motor should be 16 rpm (±1).

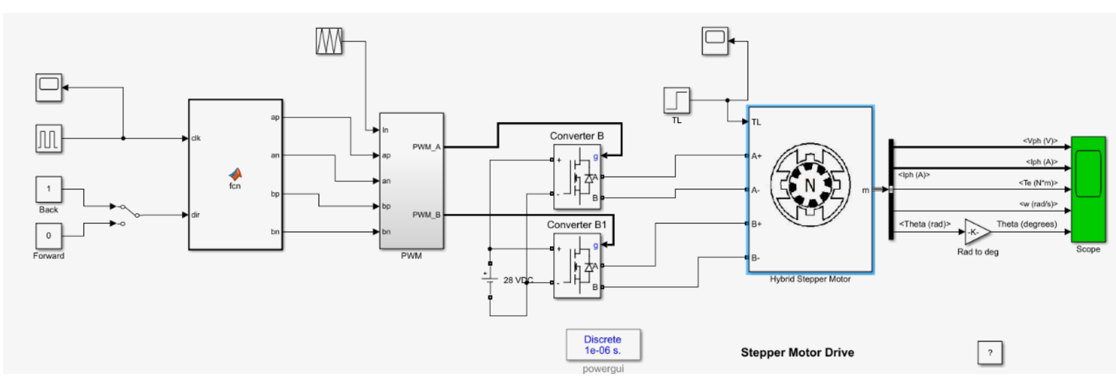

Figure 6: Circuit diagram of the remote-control subsystem

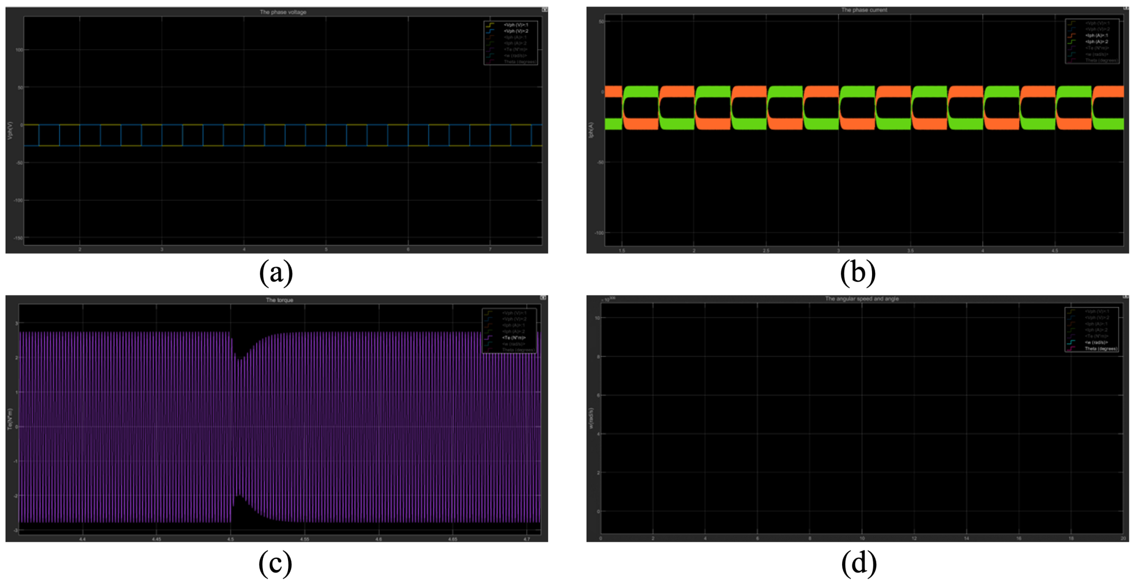

Figure 7: Simulation waveform of the motor when the load torque is 0. (a) represents the phase voltage. (b) represents the phase current. (c) represents the torque. (d) represents the angular speed.

2.4 Tolerance Analysis

1. **Failure of Wireless transmission**. Wireless communication between the image acquisition and processing subsystems may lead to occasional interruptions, causing the image processing subsystem to miss some 2D images. Therefore, it is crucial for the image processing algorithms to achieve high-quality reconstructions in such cases. Robust algorithms capable of handling missing data effectively can be incorporated into the subsystem to address this issue. One possible solution is to employ interpolation techniques based on spatial or temporal consistency. Another approach is to use deep learning to generate missing data based on available images. Additionally, appropriate error handling and recovery mechanisms, such as TCP retransmission protocols, should be incorporated to prevent wireless transmission failures and ensure successful transmission and reception of all images.

2. **Remote-control: out of range**. Various factors may cause the motors be out of control range of the remote control. For example, the environment in which the motor is located may affect the transmission and reception of signals, such as buildings, obstacles, or interference from other electronic devices. In addition, the functionality and capabilities of the motor itself may also affect its distance from the remote control's operating range. For example, if the motor requires higher power output or higher sensitivity to perform specific tasks, it may need a closer operating range to achieve a precise control.

3. **Unstable Motor Speed Failure.** The electromagnetic torque generated by the stepper motor is equal to the sum of the torque generated by the interaction between

the phase current and the magnetic flux generated by the magnet and the braking torque generated by the salient pole of the rotor.

$$e_a(\theta) = -\psi_m \sin(p\theta) \frac{\mathrm{d}t}{\mathrm{d}\theta} \tag{1}$$

When the load torque is large, from the simulation waveform, we can see that the voltage and torque are not stable. This will cause the speed of motor not stable, which will also influence the angle of photos the phone takes. Figure 8 is the result of simulated circuit under the conditional of the load torque is 8 $N \cdot m$.

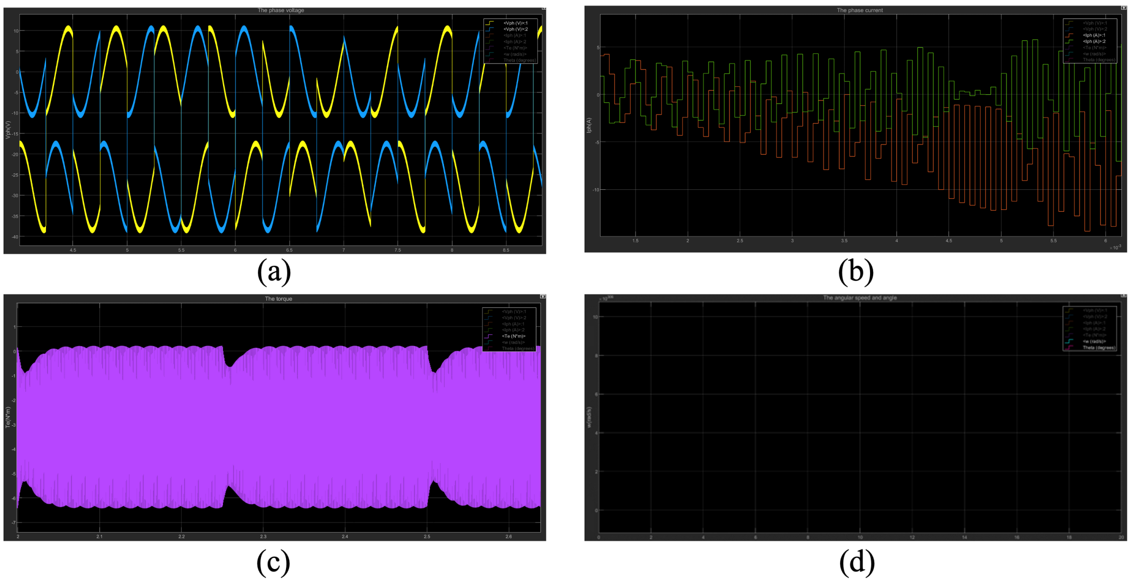

Figure 8: Simulation waveform of the motor when the load torque is 8 $N \cdot m$. (a) represents the phase voltage. (b) represents the phase current. (c) represents the torque. (d) represents the angular speed.

4. **Failure of the Mechanical Structure.** As there are many parts made of different materials in the mechanical system, energy transmission may lead to failures on the structure. To avoid problems such as broken linkages and fatigue, we should carefully estimate the load on our component. To analyze the tolerance in a more efficient way, we chose the most fragile part, the longest bar, as our object of study.

   With proper assumptions, we performed a basic statics analysis on the bar at first. Given the approximate density of PLA (the material of the bar), we can calculate the mass of the longest bar as shown in equation 2. With the assumption for the load on the phone holder 3, we then can get the normal force on the side connecting to the universal wheel 4 using the equilibrium equation in statics. The material of the universal wheel that contacts the ground is steel, and in most cases, the coefficient of kinetic friction is less than 0.5, so in our analysis we can assume that the coefficient is 0.5. Therefore, we can use 5 to calculate the frictional force exerted on the universal wheel.

$$m_b = V \times \rho = 0.5m \times 0.015m \times 0.015m \times 1240kg/m^3 = 0.1385kg \tag{2}$$

$$m_p = 0.3kg \tag{3}$$

$$N_w = (m_p + 2 \times m_b) \times g/2 \approx 2.83N \tag{4}$$

$$f = \mu \times N_w = 1.415N \tag{5}$$

With the approximate values of forces on the bar, we ran a static stress simulation on Fusion. The result in figure 9 shows that under all potential forces and certain constraints, the safety factor is within a very safe region, so the bar would not break. Additionally, we found that the maximum stress occurs on one joint, which is connected to the universal wheel, as shown in figure 10. This may largely due to the location of the frictional force and the thin material at the connection point. Therefore, we should pay more attention to the joints in further manufacture.

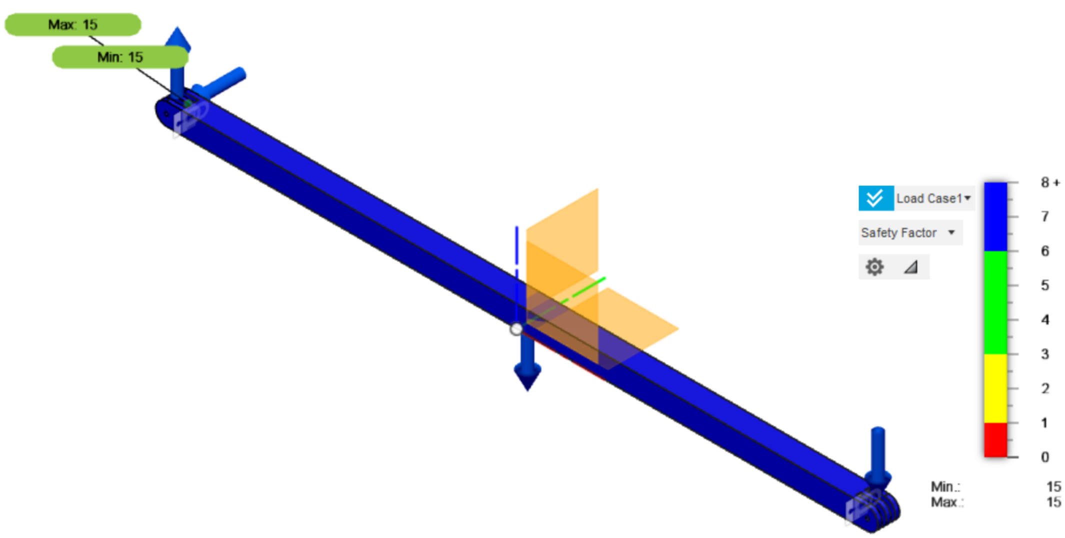

Figure 9: Simulation for the safety factor

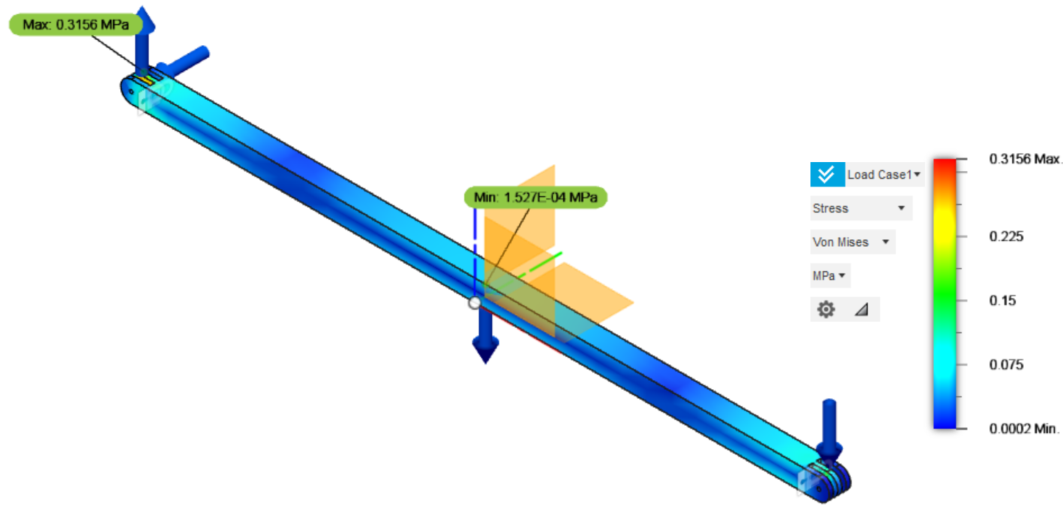

Figure 10: Simulation for the stress

3 Cost and Schedule

3.1 Cost Analysis

Labor: The labor cost for our project is shown below. We estimate the salary to be ¥100 per hour per person, which follows the standard of the graduate students in Zhejiang University. Our team is expected to work 14 hours per week according to our complexity of project. Moreover, the project lasts for 10 weeks. With the data above, we can calculate the labor cost: 2.5×4 people × 100/hr × 14 hr/week × 10 week=¥140,000. This is only the expected labor cost, and the actual cost changes due to the changes of our time of work and progress. So the actual labor cost varies from ¥120,000 to ¥160,000. The prices of other materials are displayed in table 1.

Name	Description	Manufacturer	Part	Quantity	Price	Cost
DC Motor	DC 24V rpm: 31	ZHENGK	ZGB37RH	1	¥56	¥56
Belt Roller	20 Teeth, 6 mm Width, 4 Holes	Deliqin	S3M	1	¥15	¥15
Belt	73.15 mm	MCGRADY	HTD 8M-800	1	¥20	¥20
Universal Wheel	360°	MARIE	Black7545	3	¥5	¥15
Bolts & Nuts	d = 4mm, l = 6 mm, 50 pairs	Jinchao	304DIN933 M6	1	¥9.15	¥9.15
Bevel Gears	R = 26 mm, r = 11.3 mm	Hanyu	1:1 25 Bevel Gear	2	¥13	¥26
3D Printer	Filament PLA, d = 1.750.02 mm	Lan Bo	PLA+1.75 Black 1KG	1	¥56.8	¥56.8
Smartphone	Android phone 5G	vivo	vivo iQOO Neo3	1	¥2598	¥0

Table 1: Cost table

3.2 Schedule

Please refer to appendix A.

4 Ethics and Safety

4.1 Ethics

Our project is aimed at designing an autonomous system that uses a mobile phone to generate 3D models from multiple 2D images taken from various angles and positions. Using 3D scanners, 3D models of human bodies, objects, and environments can be easily scanned and reconstructed, which can violate the privacy of others. For example, using a 3D scanner to scan someone's face, body and personal belongings may reveal someone's personal information. Therefore, privacy is of great importance to our project.

In the IEEE Code of Ethics, term 1: "To hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment" [6]. Also, in the ACM code of Ethics, 1.6, it talks to respect privacy. "Computing professionals should only use personal information for legitimate ends and without violating the rights of individuals and groups." [7] So for our project, we need to carefully collect the information we get and make sure the information is not leaked to others and made to other uses.

The 3D scanner also has intellectual property issues: 3D models of items can be easily scanned and reconstructed using 3D scanners, which could violate intellectual property rights. Using a 3D scanner to scan copyrighted artwork or design drawings, for example, could violate Copyrights and trade secrets.

In the ACM code of Ethics 1.5, "Respect the work required to produce new ideas, inventions, creative works, and computing artifacts." [8] For the objects that has intellectual property, we need to respect all the objects, and we should not upload what we scanned on the internet. In the process of manufacturing and using 3D scanners, relevant laws, regulations and ethical guidelines should be complied with to ensure that they do not violate the intellectual property rights and privacy of others. Security, privacy and intellectual property issues should be taken into account, and corresponding technologies and measures should be taken to minimize the risk of violating others' privacy and intellectual property rights.

4.2 Safety

- ! Electrical Safety: Since the 3D scanner involves electronics and electrical components, there is a potential risk of electrical shock. It is important to ensure that all electrical components are properly insulated and grounded, and that appropriate safety protocols are followed when working with electricity.

- ! Mechanical Safety: The 3D scanner may include moving parts that could pose a risk of injury. It is important to ensure that all moving parts are properly enclosed and that appropriate safety protocols are followed when working with these parts.
- ! Environmental Safety: The 3D scanner uses materials like lithium battery that can be harmful to the environment, which contains toxic chemicals or heavy metals, it is important to ensure that appropriate measures are in place to prevent contamination and to dispose of these materials properly.
- ! Data Privacy: The 3D scanner may capture and store sensitive data, such as personal or confidential information. It is important to ensure that appropriate security measures are in place to protect this data from unauthorized access or theft [8].
- ! User Training: To prevent accidents and injuries, it is essential that all personnel involved in the project are properly trained on the safe operation of the 3D scanner and understand the potential hazards and safety protocols.

References

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[4] M. Javaid, A. Haleem, R. P. Singh, and R. Suman, "Industrial perspectives of 3d scanning: Features, roles and it's analytical applications," *Sensors International*, vol. 2, p. 100 114, 2021.

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Appendix A Schedule

Week	Task	Member
03/20/2023	Design a complete 3D model in Fusion 360.	Chenchen Yu
	Read relevant essays and buy motors, belt and other components.	Jiayi Luo
	Research algorithms and papers related to 3D reconstruction.	Peiyuan Liu
	Read blogs about the automation of Android phone	Yifei Song
03/27/2023	Purchase and make all parts of the mechanical system, and try assembly.	Chenchen Yu
	Assemble the motors with the belt.	Jiayi Luo
	Select some classic 3D reconstruction methods for testing and investigate wireless transmission.	Peiyuan Liu
	Design the code framework to control the phone to take pictures	Yifei Song
04/03/2023	Test the basic functions of the device.	Chenchen Yu
	Test the function of the remote-control subsystem.	Jiayi Luo
	Designing the code framework for 3D reconstruction.	Peiyuan Liu
	Designing the code framework for photo transfer.	Yifei Song
04/10/2023	Complete the first version of the phone-holder subsystem.	Chenchen Yu
	Combine the remote-control device with the central platform.	Jiayi Luo
	Test the reconstruction accuracy and integrate with Yifei's part.	Peiyuan Liu
	Implement the code roughly and debug it on the Android phone	Yifei Song
04/17/2023	Connect the remote-control device into the phone-holder subsystem.	Chenchen Yu
	Connect the remote-control device and the phone holder.	Jiayi Luo
	Design a server that can automatically receive images and perform reconstruction.	Peiyuan Liu
	Try to interact with Ardiuno part and make the time interval between photos more regular	Yifei Song
04/24/2023	Make adjustments and improvements.	Chenchen Yu
	Operate the function of the mechenical system.	Jiayi Luo
	Finish the sever design.	Peiyuan Liu
	Optimize the efficiency and stability of mobile-to-server transfer	Yifei Song
05/01/2023	Test the final version of the mechanical system and try to make the whole product work together.	Chenchen Yu
	Test the function of the mechenical system to operate properly.	Jiayi Luo
	Integrate with Yifei's Part and completing the overall design.	Peiyuan Liu
	Connect with the server side and completing the overall design.	Yifei Song
05/08/2023	Prepare for the presentation.	Chenchen Yu
	Prepare for the presentation.	Jiayi Luo
	Prepare for the presentation.	Peiyuan Liu
	Prepare for the presentation.	Yifei Song

Appendix B 3D Reconstruction Algorithm

Algorithm 3: Detailed 3D reconstruction algorithm

```
Input  : image_set
Output: 3D_model
Step 1: Feature Extraction
foreach image in image_set do
    keypoints ← detect_keypoints(image);
    descriptors ← compute_descriptors(image, keypoints);
    Add keypoints and descriptors to the dataset;
end
Step 2: Feature Matching
foreach image_pair in image_set do
    matches ← match_descriptors(descriptors_1, descriptors_2);
    Add matches to the dataset;
end
Step 3: Structure from Motion (SfM)
foreach image_pair with matches do
    relativ_pose ← estimate_relative_pose(keypoints, matches);
    Add relative_pose to the dataset;
end
sparse_point_cloud ← triangulate_points(relative_poses)
camera_poses, sparse_point_cloud ← bundle_adjustment(relative_poses, sparse_point_cloud);
Step 4: Multi-View Stereo (MVS)
depth_maps ← compute_depth_maps(camera_poses, sparse_point_cloud, image_set);
dense_point_cloud ← depth_maps_to_fused_point_cloud(depth_maps);
Step 5: Point Cloud Filtering
filtered_point_cloud ← fuse_point_clouds(dense_point_cloud);
Step 6: Mesh Generation
mesh ← poisson_surface_reconstruction(filtered_point_cloud);
Step 7: Mesh Refinement
Refine mesh to improve the accuracy and quality of the reconstruction;
3D_model ← Combine mesh and final texture;
```

Appendix C Point Summary

Module name	High level requirement	Points
Image collection subsystem	The number of images should be the same as specified by the user. The time interval between each picture taken should be of equal length.	10
Communication subsystem	The successful transfer rate of photos should be higher than 80%.	10
Image processing subsystem	The generated 3D model should bear a resemblance to the scanned object when viewed by the human eye. The value of chamfer distance (CD) should be below 5e-3, while the value of earth mover's distance (EMD) should be below 0.2.	10
Phone-holder subsystem	The phone holder can rotate at least 360° around the center without hitting any other parts. The whole mechanical system should be able to work normally when a load of 300 g (a weight of 240 g for the heaviest iPhone plus another 60 g of tolerance) is applied on the holder.	10
Remote-control subsystem	The remote-control subsystem should control the position and angle of the central platform, which can successfully help the phone to take photos from different angles.	10
Total		50

Table 2: Point summary table