ECE445 / ME470
Design Document

Smartphone Microscope

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Part 1: Introduction

1.1 Problem and Solution Overview

Microscopy technology is an important tool especially in the bio-chemistry and healthcare industries. From detecting the presence of microorganisms to understanding molecular structure and behaviour, microscopes are highly useful to us because they help us overcome our visual limitations as human beings. However, conventional microscopes that are most widely used are benchtop microscopes that sit in scientific laboratories. These benchtop microscopes come with several limitations: they are bulky and therefore inconvenient to move around, and they are also built up of sensitive and highly expensive optical instruments.

Due to the limitations mentioned above, benchtop microscopes are often inaccessible to a wider population, who sometimes are actually the people who need these apparatus the most. For instance, communities living in rural, underdeveloped areas who struggle to access clean sanitation and fight against viral diseases every day.

By realizing the robust development of smartphone cameras and how accessible smartphones are today, we propose a single-lens microscope design that utilizes smartphones' cameras and an objective lens. We aim for our design to achieve magnification and resolution that are at least sufficient for us to observe basic plant tissue samples, microorganisms such as *C. Elegans* (roundworm). We also aim to integrate the usage of light-emitting diodes (LED) in our design for fluorescence microscopy (FM).

1.2 Clarifications on Design Starting Point

Prior to listing out our high level requirements, there are two clarifications that we think is worth-mentioning given the nature of our project.

The first reason is that we have limited knowledge and access on what target samples we will be able to use for our microscope. This leads us to being realistic when we consider what our end goal can be, such that we can properly quantify and analyse our results.

The second reason is the calculations behind optics are heavily hindered by our lack of access to the specifications of optic elements, as well as multiple sources of uncertainties inherent within a low-cost setup. This leads us to having a two-pronged approach when setting up our prototype. We have to go through some thoughtful trial-and-error process with a relatively simple mathematical setup.

We are informed by our project instructor that Zhejiang-University of Edinburgh Institute (ZJE) laboratory has *C. Elegans* samples that we can acquire. Therefore, we will be using observing *C. Elegans* as our end goal to quantify our microscope parameters. An adult *C. Elegans* worm is approximately 1mm long and has a diameter of roughly 50 microns.

As a starting point for the smartphone model used in our design, we will be using the HUAWEI P30 model. For brevity purposes, we will not list down the specifications of the P30's components since they are accessible, verifiable information.

1.3 High-level Requirements List

The necessary components to build our FM system include: an objective lens, a LED illumination source, a sample stage, emission filter and an external casing to hold the microscope system.

We narrow down three key requirements in determining the success of our design prototype into:

1. The magnification of our smartphone microscope to be able to observe target sample.

   As mentioned in section 1.3, our target sample is set as *C. Elegans.* As such, the most important milestone we need to fulfil is to be able to see the image of roundworms being captured on our smartphone camera when using our microscope device.

2. The stability, durability and flexibility of our mechanical design for microscope system.

   Our current design blueprint for the smartphone microscope looks similar to a mini bookshelf, as shown in Figure 1. We expect the external casing to be first of all, stable and durable. We also expect the components that are supposed to be stationary remain fixed in position. The components that we expect to not move are: the stage for objective lens, the stage for emission filter, and the illumination module attached at the base of the casing.

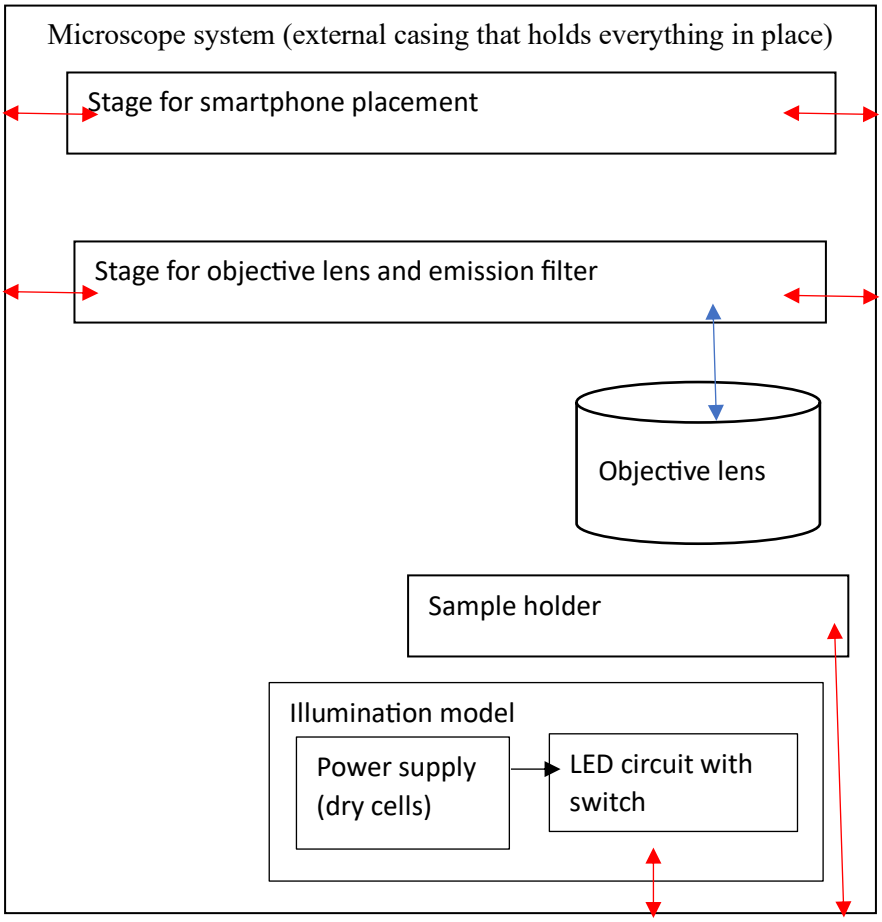
   There are also components within our design that we expect some flexibility in adjusting their positions, which are the stage for the smartphone holder and the sample holder.

3. A functioning fluorescence microscope model

   The optical path for our transillumination model should work as expected when coupled with excitation and emission filter. For example, if we use an excitation filter of 485nm (blue light) and emission filter of 515nm (green light) [2], with a tissue/blood sample stained with carboxyfluorescein diacetate, succinimidyl ester (CFSE), we expect to see green dots on our image, because that is the range where CFSE fluoresces when it interacts with the amine groups in live cells [3].

Part 2: Design

2.1 Block Diagram



indicates the connected block components are firmly attached

indicates the connected block components can be adjusted

Figure 1 shows the block diagram of our smartphone microscope with the legend for the arrows.

2.2 Physical Design

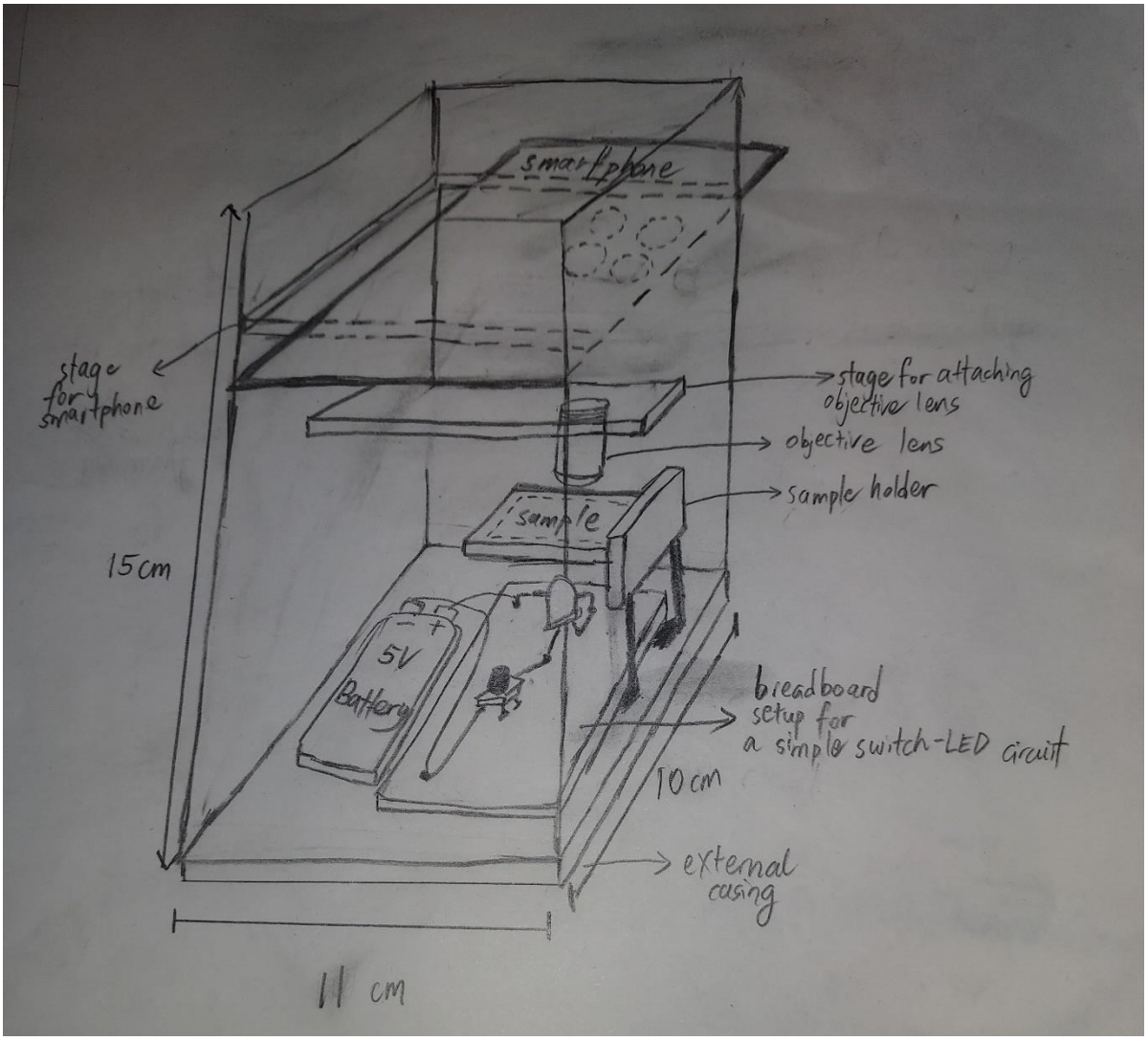


Figure 2 shows a sketch of the physical design of our smartphone microscope.

The height of the casing is determined by the vertical distance between the components that form our optical path.

In the bottom-up direction:

i. Distance between the circuit and the bottom of the sample holder is 4cm.
ii. Distance between the top of the sample holder and the objective lens is determined by the working distance, which is 0.53mm and 3.1mm depending on which objective. We set it to be 1 cm for flexibility.
iii. Distance from the bottom of the objective to the stage is 4cm. This is mainly determined by the height of the objective lens.
iv. Distance between the objective lens stage and the smartphone stage is 5cm. The final distance of this parameter is still yet to be determined because we still need to collect more data on how the distance affects the resolution and magnification of the imaging.

Combining the vertical distances between the components, we get that the height of the casing must at least be:

$$4 + 1 + 4 + 5 = 14cm$$

To account for limitations in 3D-printing and some extra room between the components, we set the height of the casing to be $15 \pm 1cm$.

2.3 Subsystem Description

a. Illumination module

The illumination module acts as the fluorescence light source for our microscope. We will be using a rechargeable 5V battery as our power supply to a circuit we constructed on a breadboard. The circuit diagram for the simple circuit that we construct is as shown:

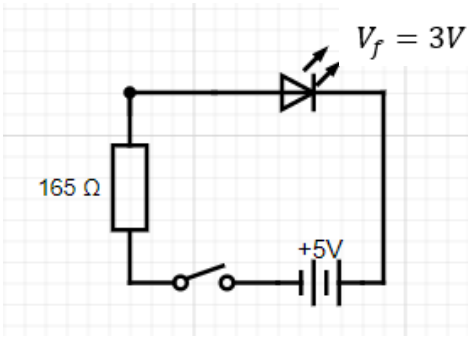


Figure 3 shows our LED circuit setup using toggle switch, a resistor, a LED with 3V forward voltage and 5V dry cells.

By Kirchoff's Voltage Law, we can calculate the resistor will have a voltage drop of 2V when the switch is closed. This means the total current of the circuit is 12mA (which is sufficient for most LEDs), giving its output power to be 3.6mW. If we want to increase the current, we can simply connect two 165 Ohm resistors in parallel to reduce the effective resistance. The forward voltage of the LED is provided on the datasheet of the LED we used.

For fluorescence microscope, we are actually most concerned about the light intensity of the LED and the specificity of the emitted wavelength, rather than its output power. Light intensity is measured in lumens, and our LED datasheet provides the intensity range to be 8000-10000 lumens. We also chosen our LED to be blue colour, which emits light in the 460-465 nm wavelength range.

Requirement	Verification
We want our LEDs to release intense light within our target wavelength (460-465nm) so that the light has enough energy to excite the target fluorophores. These parameters are readily provided on the LED datasheets when we purchase the LEDs.	The verification of whether the light emitted by the LED is correct will require specific stains to act as our sample. Some stains that fluoresces when excited within 460-465nm wavelengths are *Acridine Orange* and *Auramine O.* These stains excite and emit wavelength in the range of 500-600nm (yellowish-green). Our smartphone camera should be able to capture photons of these colours as a verification.

Table 1 shows the requirement and verification needed for our illumination circuit.

b. Sample Holder

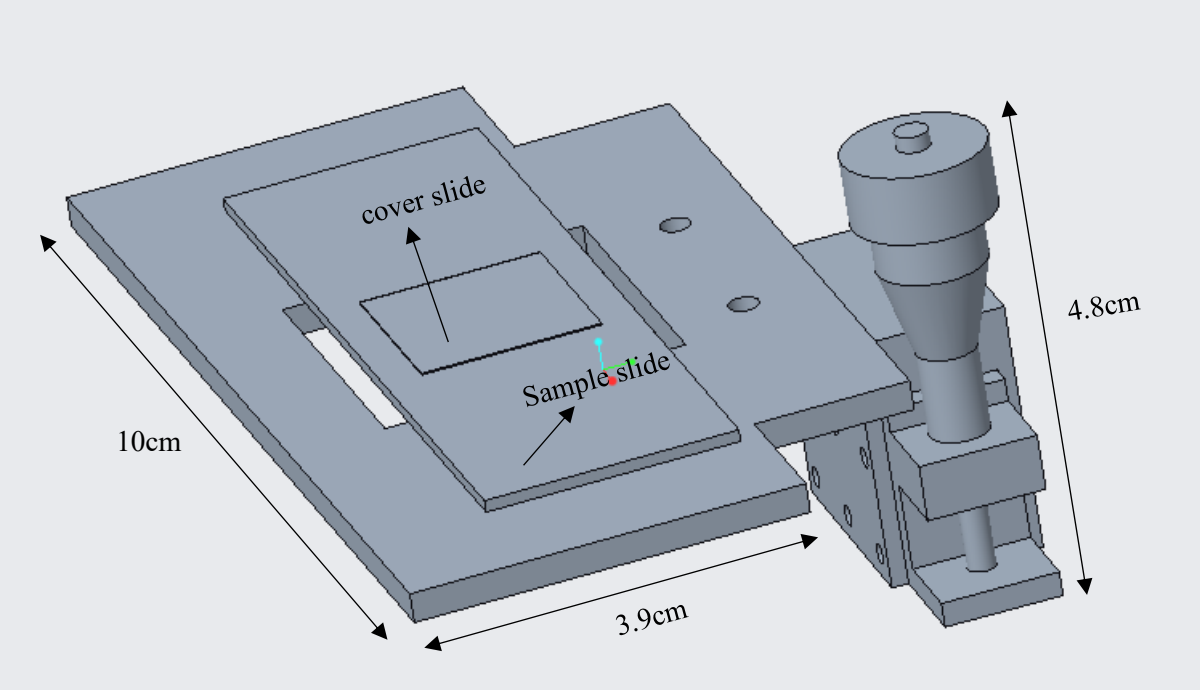


Figure 4 shows the dimensions of the sample holder we design using computer-aid design (CAD) software.

The dimensions of our sample holder design takes into consideration the measurements of the our sample slide and cover slide, which are 7.62cm × 2.54 cm and 1.8cm × 1.8cm respectively. We design a 3cm × 3cm opening at the bottom of the holder for light to pass through from beneath our sample. The side of the sample holder is an optical translational stage in the vertical direction.

Requirement	Verification
1. The base dimensions for the sample holder must be greater than the base dimensions for our sample slides to provide stability. The height of the stand from the base of the stand to the base of the sample stage must be at least 4 cm to allow the LED circuit to place directly beneath the sample 2. The support stand for the sample stage must be able to adjust the vertical height of the sample stage to a sensitivity of $\pm 1mm$ to match the sensitivity of the working distance for microscope objectives.	1. The component design of the sample stage is done through CAD, where we can determine its dimensions. After 3D printing out the component, we can manually measure the dimensions with a ruler. 2. We will be using off-the-shelf product for the optical translation stage, with a provided limitation of $\pm 1mm$ in adjusting the heights.

Table 2 shows the requirement and verification needed for the sample holder.

c. Objective lens

We will be using off-the-shelf objective lens that we acquire online as testing apparatus. However, the provided magnifications of the purchased objectives are useless to us because those parameters assume that those objectives are coupled to standard benchtop microscopes.

The purchased objectives are useful to us in a sense that the optical elements are held together within the objective casing, and the working distance is provided. The objectives also use the Royal Microscope Society (RMS) thread, which can help us determine the design parameters for the objective stage (see (d)).

Requirement	Verification
The optical elements within the purchased objectives must provide magnification (20X and 40X as provided by their specs) when coupled with standard microscopes. This is because we purchased these low-cost components online and cannot be sure about their reliability.	Bring our microscopes to ZJE laboratories where we have access to standard microscopes and record the observations we see through the eyepiece when we use our objectives.

Table 3 shows the requirement and verification needed for objective.

d. Stage for Objective Lens and Emission Filter

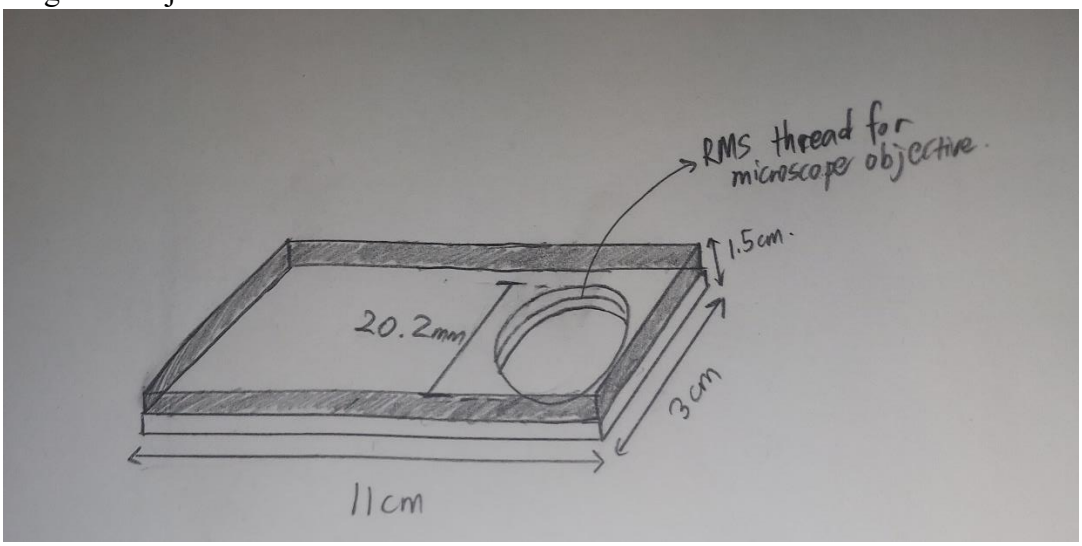


Figure 5 shows the 3D sketch for the stage to attach our microscope objective and emission filter.

Our design idea is a stage that serves two purposes – to mount the objective lens as well as placing an emission filter on the observing end of the objective. The reason to combine these two functionalities into one component is for simplicity, as there is no distance requirements for the emission filter. The emission filter does not affect the optical train.

The dimensions of the stage take into consideration the dimensions and thread standard of the objective lens, as well as the dimensions of the emission filter.

Requirement	Verification
1. The length of the stage must match the length of the external casing, which we set to be 11cm. 2. The opening of the stage to mount the objective lens should follow the RMS thread standard for microscopes. 3. The depth of the stage must consider the depth of the objective threads and the thickness (4mm) of the emission filter (1.1mm), which in total are ~5mm. 4. The width of the stage must consider the diameter of the objective and emission filter.	1. The design of the casing and the stage will be done through CAD, which enables us to determine the dimension of the component. 2. The design of the objective opening on CAD must have a 20.32mm diameter, 36 thread per inch (TPI) Whitworth thread. 3. The depth of the stage should be within 1.5cm range to serve as a barrier for the emission filter and the objective screw threads. 4. The emission filter has a larger diameter: 25mm, so during CAD design the width of the stage has to be at least 3cm.

Table 4 shows the requirement and verification needed for objective stage.

e. External Casing

We plan to use CAD and 3D printing for the external casing of the microscope. For convenience of operating the system while not sacrificing stability, we decide upon a cubic casing with an ‘open-able’ front surface. Such design allows operation of the

LED-switch circuit at the base (user needs to press on switch to turn LED on), as well as attaching the objective lens to the stage.

The key aspects of the casing include the dimensions of the casing. The base area of the casing is determined by the dimension of the circuit and the phone model we are using.

Dimensions of the breadboard circuit including the dry cells:

Length = 8cm, Width = 9cm, Height = 3.5cm (mainly because of LED)

Dimensions of HUAWEI P30:

7.1cm wide, 14.9cm long

The height of the casing is determined by the distance between components in our optical train.

Requirement	Verification
1. The base dimensions for our casing should be 11cm wide and 10cm long. This is to accommodate for the circuitry and to be able to reasonably place a HUAWEI P30 on the smartphone stage. 2. The height of the casing should be at least 15cm per the explanation in section 2.2.	The design dimensions of the external casing will be done via CAD and printed out with acrylic board and the 3D printing materials available in ZJUI laboratories. We can use ruler to measure the 3D printed prototype.

Table 5 shows the requirement and verification needed for external casing.

2.4 Tolerance Analysis

During the process of setting up our testing model, we came across a fundamental concept that we did not consider in the earlier stages of our design. This leads us to a different exploration compared to our initial goal and proposed design. The fundamental concept that we realized this time is the different kinds of optical system that we should determine *before* constructing our optical path.

There are two fundamental optical models in microscope optics: the finite conjugate and the infinite conjugate system, as shown in figure 4:

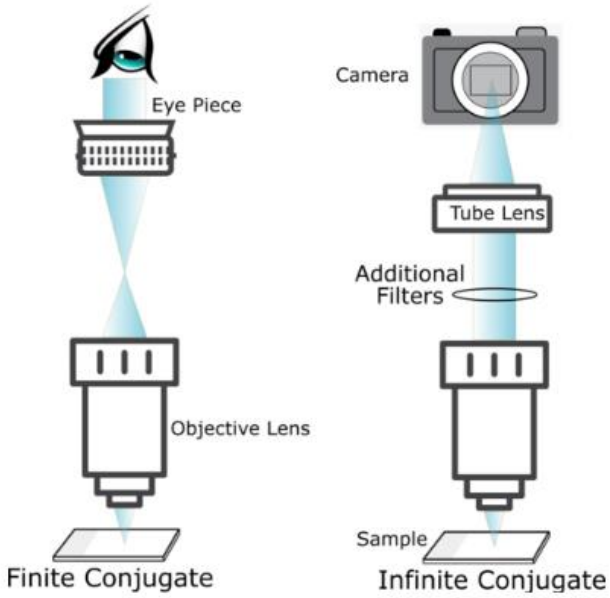


Figure 6 shows a side-by-side comparison of the two different conjugate systems of a microscope.

Our initial design took the assumption of the infinite conjugate optic model, where we attempt use the lens of our smartphone camera to replace the role of tube lens (see figure above). The infinite conjugate system was initially chosen because it is the most commonly used system in microscopes today as it allows multiple optical correction/enhancing elements to be placed between the objective and the camera without losing the focused image.

In an infinite conjugate system, the effective magnification of the microscope can be calculated by:

$$M = \frac{f_{tubelens}}{f_{objective}}$$

Where $f = focal\ length\ of\ the\ lens$.

Since our initial plan was to use HUAWEI P30 as our smartphone model, and P30's camera lens to act as the tube lens, we get that the focal length of P30 is $\sim 6mm$. Using the information provided by the merchant from which we purchased our objective, we also know that the focal length of our objective lens is $4mm$.

This leads us to having a significant limitation, because our magnification is now a set number, instead of an adjustable parameter as we initially thought. More precisely, our magnification is fixed at:

$$M = \frac{6mm}{4mm} = 1.5X$$

Therefore we are currently at an important junction where we have to determine whether we shift the focus of our microscope to set the magnification factor at around unit magnification (in other words M = 1X), and focus on the realizing the fluorescence aspect of our design. This is because the concept of fluorescence microscopy is more about detecting the emitted photons that were excited by specific wavelengths and capturing those photons (if present) rather than observing cell structures.

If fluorescence microscopy becomes the new main focus of our model, then image post-processing in terms of pixels, the preparation of the samples as well as the resolution of our images will be the key parameters we need to be measuring.

The other alternative if we decide to still work on realizing a practical and useful magnification, we will have to seriously reconsider the optical model for our microscope design. One of the ways to do so is that we will construct a compound microscope lens setup, employing another eyepiece. If we choose this option, the tolerance analysis then is to determine the distance between the eyepiece and our smartphone camera lens, and we will most likely need to change our “box-like” design of our microscope to a “tube-like” design because of the length.

Part 3: Cost and Schedule

3.1 Cost Analysis

Labour:

We expect approximately 5 hours of work per week for each team member. By allocating 50 RMB per work hour for each member, since there are four of us and we will be working on this course for roughly 16 weeks:

$$Total\ cost = 8 \times 50 \times 16 \times 4 = 25{,}600\ RMB$$

Parts:

Component	Unit	Cost (RMB)
Objective Lens (for testing purposes)	2	100.00
500nm Emission Filter	1	120.00
Full Retort Stand Setup (clamps, support)	1	67.50
5V battery	1	34.00
Circuitry components (breadboard, LED, switches, resistors, wires)	1	30.00
Crossed-roller bearing linear translational stage	1	210.00
Glass slides for Microscope Samples	1	15.00
Diffuser (optic component)	1	10.00
Mechanic toolkit (screwdrivers, bolts etc.)	1	150.00
3D printing material	1	150.00
Acrylic board	1	100.00
Higher quality optic components for assembling/refining final prototype	1	500.00
	Total	1486.50 (approx. 1500.00)

Table 6 shows the cost breakdown for purchasing the components needed to assemble our prototype.

Combining the labour cost the expenses needed for purchasing components, we estimate we will need a final expenditure of 27,100 RMB for our entire project, maxing out the budget provided by the course for purchasing. Some of the expenses listed on the table above are tentative and could scale up/down as our project progresses into the later stages.

3.2 Schedule

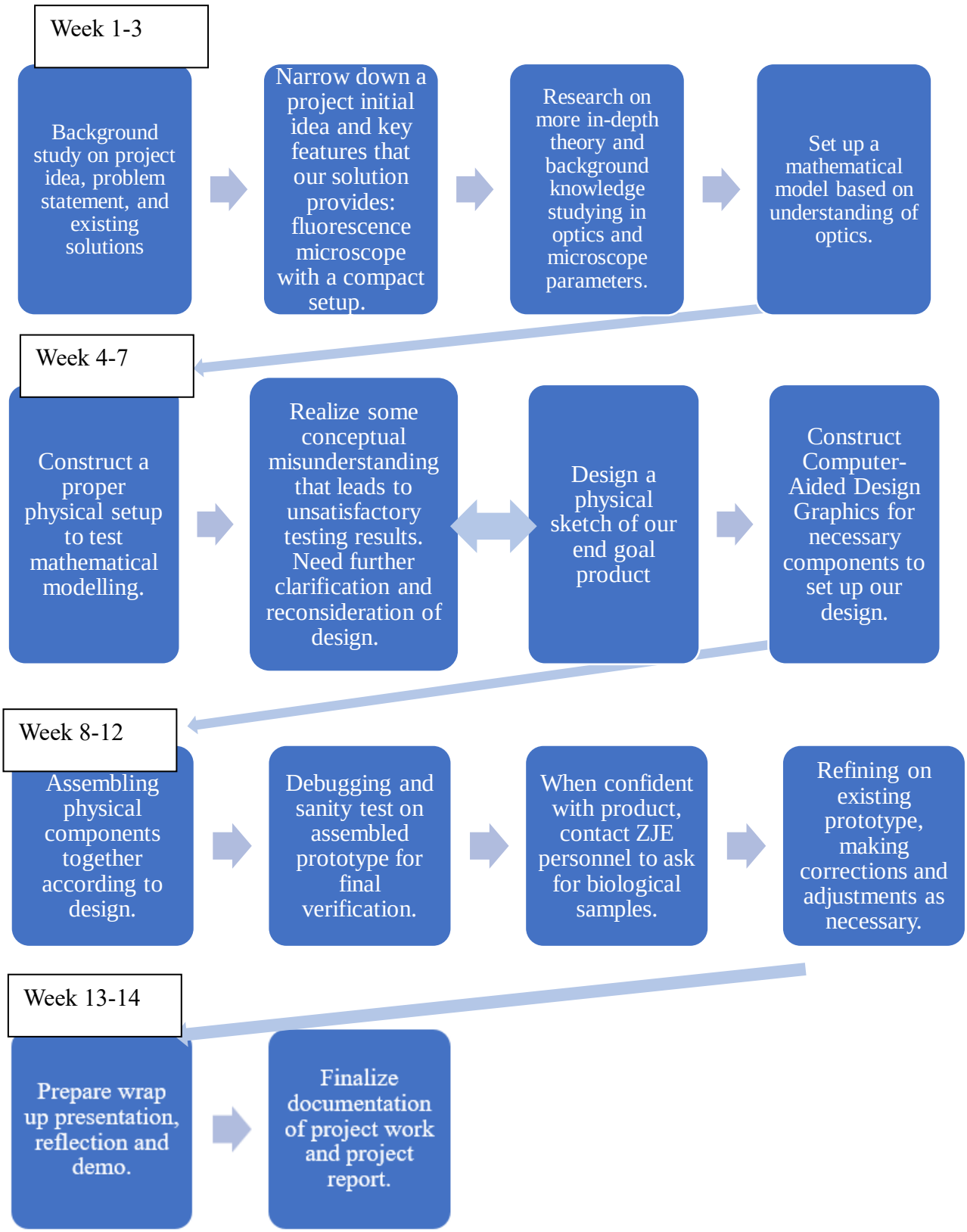


Figure 6 shows the flowchart diagram for our planned schedule, we are currently on the box 2-3 on the second row.

Part 4: Discussion of Ethics and Safety

Throughout the design and creating the prototype of our smartphone microscope, there are code of ethics and professionalism that our team must adhere to. Some of these codes are in alignment with the IEEE Code of Ethics and ACM Code of Ethics. We will choose to expand the most relevant ones in this section.

The code of ethics that align with IEEE Code of Ethics are:

i. "to hold paramount, the safety, health and welfare of the public, …"

This is related to the healthcare applications potential of our microscope, particularly the fluorescence aspect. This is because fluorescence microscope is a highly cost efficient tool to detect pathogens like *Tuberculosis Mycobacterium* and sickle cells.

ii. "to seek, accept and offer honest criticism of technical work, … and realistic in stating claims… and to credit properly the contributions of others"

This code of ethics is important to us because the field that we are exploring is a field that many has contributed excellent working ideas on. Given that we are very unfamiliar and new in terms of the theories, applications and design ideas, we will have to be careful that we proceed with realistic goals, and always be humble to ask questions and credit all sources that offered us insights.

iii. "…to undertake technological tasks for others only if qualified by training or experience…"

In the later stages of our projects, some of our work will involve biological samples and chemical substance for fluorescence stains. Since none of the team members are experts in biology and chemistry as per our majors, it is important that we always confirm with the lab personnel and our project instructor before getting into contact with potentially harmful and dangerous substances.

The code of ethics that align with ACM Code of Ethics and Professional Conduct are:

1. Contribute to society and to human well-being, acknowledging that all people are stakeholders in computing.
2. Respect the work required to produce new ideas, inventions, creative works, and computing artifacts.
3. Perform work only in areas of competence.

These three codes have significant overlap with the points we mentioned above in the code of ethics for IEEE. We have also elaborated on them in detail in our project proposal. For the sake of brevity, we will not further expand again.

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