

Smartphone Hemocytometer

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Abstract

Smartphone Hemocytometer is a portable integrated system that aids doctors to perform blood cell counting for point of care blood tests. This smartphone microscope system captures images of the blood smear sample the doctor prepared and stained, and displays a panoramic image for the doctor to perform blood tests. Since the field of view of a single image is not enough for blood cell count, we developed an automatic linear motion stage to move the blood smear slide, so that the smartphone scans through the surface area of the slide and captures continuous frames of images. These images are then stitched into one panoramic image for doctors to perform blood cell count at the point of care. This report describes the design and development processes of the smartphone hemocytometer.

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1 Introduction

1.1 Problem and Solution Overview

White blood cell counts and classification are critical measurements in medical settings as it alerts doctors to autoimmune diseases, immune deficiencies, and blood disorders and helps monitor the effectiveness of chemotherapy and radiation therapy for cancer. Most doctors use hemocytometers with microscopes to differentiate and count the number of white blood cells in a counting chamber, which is both bulky and inconvenient. This traditional method of cell counting is not suitable for point of care diagnostics, particularly in areas with poor medical resource settings. Very few portable cell counting products are designed for rapid documentation at the point of care. Bills et al. provides a smartphone and paper-based solution for blood cell counting by integrating microscope attachment, LED and optical filter together with the smartphone camera. However, their product requires external device to operate the image processing algorithms and their blood cell image is only within one frame[1]. Our project offers an integrated solution that allows doctors to diagnose disease from the blood sample without any external devices needed.

In our project, we design and build a portable smartphone hemocytometer that enables testing and documentation at the point of care. Our project creates an automatic platform for taking panoramic microscopic images of the blood smear sample. It also provides a foundation for future development so that eventually doctors can run a machine learning identification algorithm on the smartphone hemocytometer to differentiate the five different types of white blood cells and complete said important item from blood test that would have taken hours.

2 Design

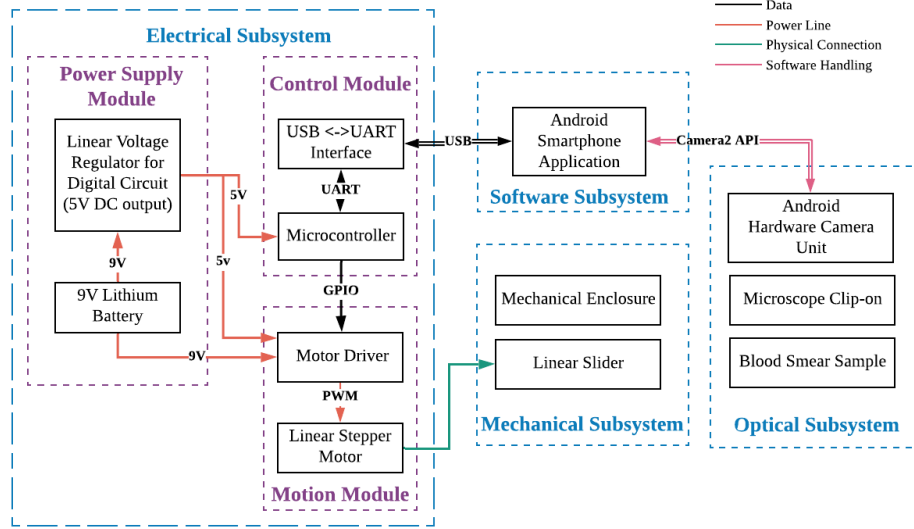


Figure 1: Block Diagram

To create an automatic platform that utilizes the smartphone camera for taking microscopic images, we decided to divide the project into four subsystems: **Mechanical Subsystem**, **Optical Subsystem**, **Electrical Subsystem**, and **Software Subsystem**.

In **Mechanical Subsystem**, since we wanted to have a flat bottom and well-controlled illumination conditions, we first proposed to make a box that contains all the parts using 3D printing. Later, after doing experiments with the microscope clip-on and communicating with ECE Machine Shop, we decided to remove the enclosure and use a metal bottom plate. A sample holder is mounted on top of the linear slider, and the external screw of the motor is directly connected to the linear slider.

In **Optical Subsystem**, we first proposed to use the PNNL Smartphone Microscope[2], which is an inexpensive and simple ball lens microscope. But later we figured out that its design did not support illumination using the smartphone flashlight and provide the required image quality since the ball lens distorted the view. Then we switched to the microscope clip-on from Nurugo, which has all the features we want.

In **Electrical Subsystem**, it consists of a power supply module that provides power for all devices in the circuit, a motion module of a high precision linear stepper motor and the corresponding motor driver, and a control module that contains a microcontroller and a USB-UART IC that controls the motor and serves as a bridge between the smartphone and the control circuit. In power supply module, our original design had two different linear voltage regulators, one for the digital control circuit, and another one for the motor. We removed the second regulator since it would cost large power consumption and it is also unnecessary for the motor driver. In control module, we decided the microcontroller between two options, one is stm32, and the other one is ATmega328P. We chose ATmega328p because it fulfills all our requirements and it is simpler and compatible with Arduino IDE.

In **Software Subsystem**, an Android application is devised to communicate with the microcontroller soft-

ware and to take photos. The images are processed by a python program for image stitching.

2.1 Mechanical Subsystem

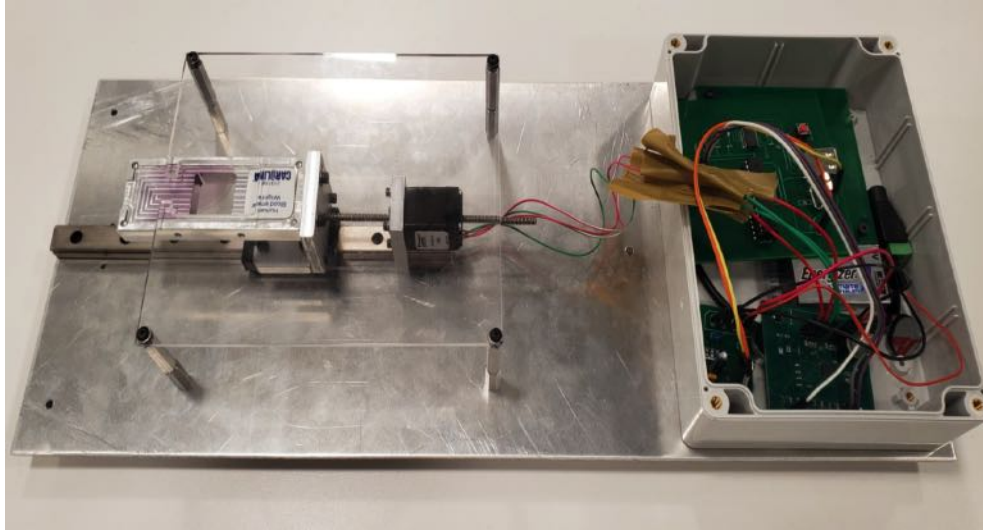


Figure 2: Mechanical Design

2.1.1 Linear Slider

The linear slider is a one dimensional ball bearing slider manufactured by Usongshine. It has the advantages of low friction coefficients and small size. The external screw of the linear stepper actuator is attached to the slider and pushes the slider to move the blood smear sample laterally. This practice of linear actuator acting on a ball bearing slide is widely adopted by the industry.

2.1.2 Mechanical Platform

The mechanical platform includes the bottom plate, box for PCBs, and the smartphone platform. The linear slider and linear actuator are mounted on the bottom to avoid vibration of the system. The smartphone is positioned on top of the platform. And there are four standoff spacer screws for adjusting the height of the platform, which determines the distance between the smartphone camera and the blood sample in order to adjust it right on the camera's focus. Micro-vibrations of the environment is neglected as we found that micro-vibrations do not affect the image quality.

2.2 Optical Subsystem

2.2.1 Hardware Camera Unit

In this unit, smartphone camera hardware parameters are modified for capturing a clear image in which cells can be clearly seen. The first condition that the smartphone camera needs to satisfy is the luminance condition. This is accomplished by having flashlight on during the whole capture session. In order to be able to recognize cells, we cropped the image region to a smaller area for seeing more details and for allowing the smartphone camera to adjust the focus parameters accordingly. For the sake of capturing non-blurry images, our smartphone is set to perform auto-focus each time before capturing an image.

An alternative way to adjust the camera auto-focus parameter is to utilize the continuous-auto-focus mode. This mode allows the camera to only do auto-focus at the first time rather than auto-focus on every image. However, we didn't choose to use this mode because every motor movement causes minor difference on the focus condition of the camera. In order to have a good focus, the focus parameters have to be adjusted each time the motor moves, and this is the reason that we choose to have the camera perform auto-focus each time before capturing an image.

2.2.2 Nurugo Microscope Clip-on

The microscope attached to the rear facing camera is Nurugo Micro Smartphone Microscope Clip-on. It provides 40x-400x magnification and integrated illumination using the camera flashlight. It has the advantages of small size, light weight and compatibilities with all smartphones.[3]



Figure 3: Nurugo Microscope Clip-on [3]

2.2.3 Blood Smear Slide

Blood smear slides contains human blood cells stained with Wright's stain method which labels the red blood cells and the white bloods cells with different colors. They are all prepared by Carolina Biological Supply Company. We could potentially choose the buffered Wright Giemsa stain to stain different white blood cells in different color, but it requires more chemical solutions and procedures involved in preparing the blood sample and is not necessary for the purpose of counting. Yet this will be a viable solution when we move on to differentiating white blood cells.



Figure 4: Blood Smear Slide

2.3 Electrical Subsystem

2.3.1 Power Supply Module

The Power Supply Module(PSM) provides load power to the motor and 5V DC power to the motor driver and microcontroller. The PSM contains a 9V lithium battery and a power regulator board. We connect the motor directly to the load voltage for maximum power efficiency and use a linear low-dropout(LDO) regulator to power the digital circuit because its current is consistent and small. Figure 5 shows the circuit schematic of this module.

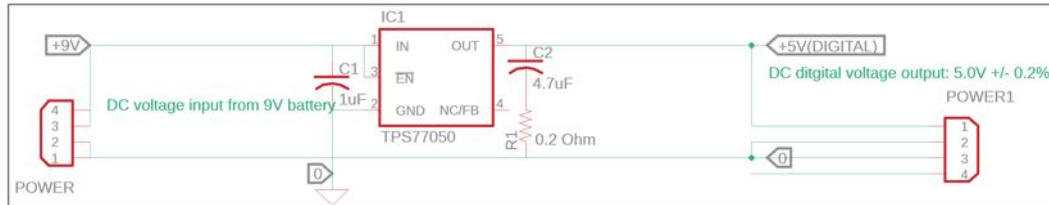


Figure 5: Power Supply Module Schematic

Power Output: 9V Load Voltage, 5V DC voltage for digital circuit.

TPS76950 5 Volt Linear Regulator by Texas Instrument

This component is chosen because it is power efficient. As the side effect, it has a low maximum current (<100 mA). But our microcontroller's working current is significantly less than the threshold, therefore it does not affect our design.

Battrey

The battery is a ENERGIZER L522 9V Lithium Battery, which has 750mAh rated capacity under normal operating conditions. 9V battery is commonly found and has enough battery life for 350 operations, therefore is the ideal power source of our design.

Power Consumption

Idle Mode:

0.75 uA - ATmega328p microcontroller [4]

70 uA - FT232R USB UART IC

7000 uA - A3982 driver

Total current consumption at Idle Mode:

$$0.75 + 70 + 7000uA = 7070.75uA = 7.07mA \quad (1)$$

Working Mode:

14 mA - ATMega328p microcontroller [4]

15 mA - FT232R USB UART IC

12 mA - A3982 Driver

700mA - Hayden 43F4R-5-800 Linear Actuator

Total current consumption at Working Mode:

$$14 + 15 + 12 + 700mA = 741mA \quad (2)$$

Battery Lifetime:

Based on the datasheet of ENERGIZER L522 9V Lithium Battery, the typical capacity is 750mAh.

We keep our assumption that the device will need to go through 10 frames per sample and spend 2.5s for each frame, 0.5s for linear movement and 2s for taking photo, and it also needs 5s for returning to starting

position. We will need to consume totally

$$(10 * (2 * 7.07 + 0.5 * 741) + 5 * 741) / 3600mAh = 2.10mAh \quad (3)$$

Therefore, our battery can finish approximately

$$750 / 2.1 = 357.14 \quad (4)$$

operations. Therefore, we can make a conservative estimation that our battery can guarantee supporting the device for 350 operations, and we take 10 images for each operation.

2.3.2 Control Module

The Control Module contains a microcontroller responsible for controlling the Motion Module and a USB-UART IC responsible for building up a bidirectional bridge between the microcontroller and smartphone software. The module is powered by 5V DC from the voltage regulator in the power supply module. The signals will be converted to UART through this interface and send to the microcontroller. For the other direction, the UART signals sent out from the microcontroller are also converted to USB to send to the smartphone. Figure 6 shows the PCB of the Control Module, and figure 7 is the circuit schematic.

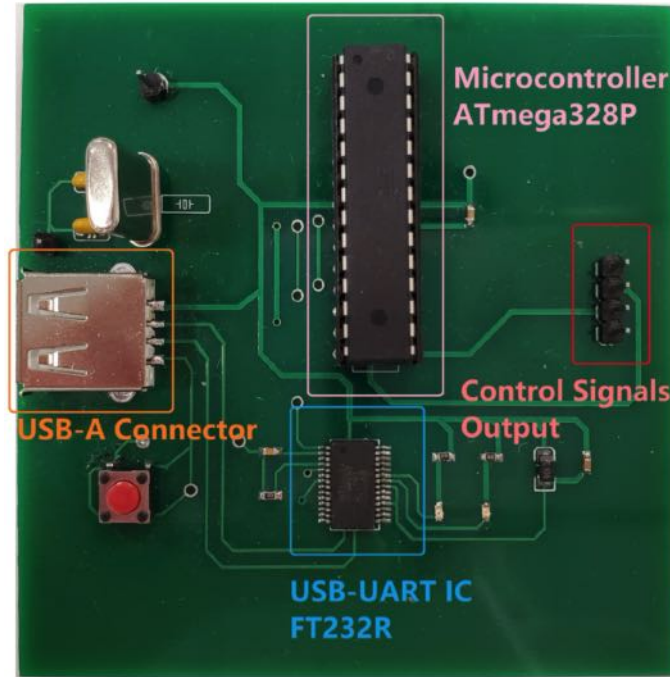


Figure 6: Control Module PCB

ATmega328P Microcontroller

Power Input:

5V DC, operating range (1.8V - 5.5V)

Data Input:

UART RX signals from the USB-UART interface in the communication module.

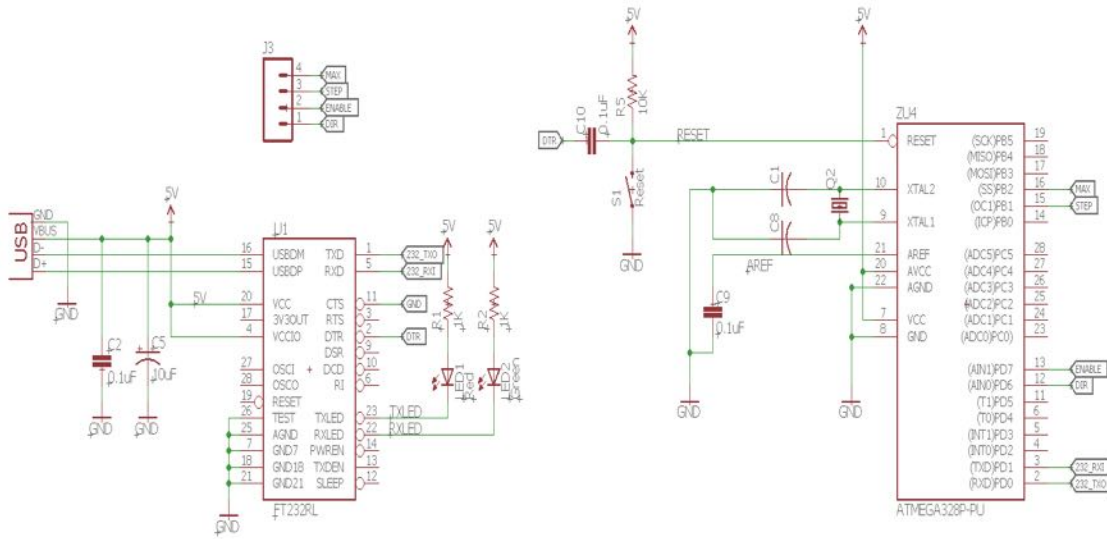


Figure 7: Control Module Schematic

Data Outputs:

Digital control signals (DIR, STEP, ENABLE) to the motor driver in motion module.

Signals(TXLED, RXLED) to the LEDs to show device status.

UART TX signals to the USB-UART IC..

The ATmega328P is a low power, CMOS 8-bit microcontrollers based on the AVR enhanced RISC architecture. It has frequency up to 20MHz, and contains 32KB ISP flash memory with read-while-write capabilities, 1024B EEPROM and 2KB SRAM. It has a total of 32 pins, 23 general purpose I/O lines, 32 general purpose working registers, three flexible timer/counters with compare modes. It also supports serial programmable USART. [4]

For our design, we will use a 5V output voltage regulator combined with the battery unit to supply power to the microcontroller. It can control the linear stepper motor driver using its high-speed digital outputs, communicate with the software in smartphone module through the USB-UART interface, and drive the LEDs to show device status.

FT232R USB UART IC

Power Input:

5V DC, operating range(1.8V - 5.5V)

Data Input/Output:

UART interface with microcontroller:

UART TX/RX (Transmitter/Receiver) signals from and to the microcontroller.

USB interface with smartphone:

USB signals received from the smartphone, and USB signals converted from UART TX signals to the

smartphone.

This chip is a highly-integrated solution for USB - UART conversion that has USB transceiver, oscillator, and Universal Asynchronous Receiver/Transmitter (UART) in packages. This IC supports 5V operating supply voltage and high data transfer rate, and compatible with USB 2.0 full speed. [5]

2.3.3 Motion Module

The Motion Module receives the digital control signals from Control Module and drives the motor. As shown in figure 8, the motion module schematic, input and output jumpers are labeled on the left.

Power Inputs:

5V DC digital circuit power input(Vcc), and 8V-35V DC load supply power input from battery (VC+).

Inputs:

Digital control signals (DIR, STEP, ENABLE).

Outputs:

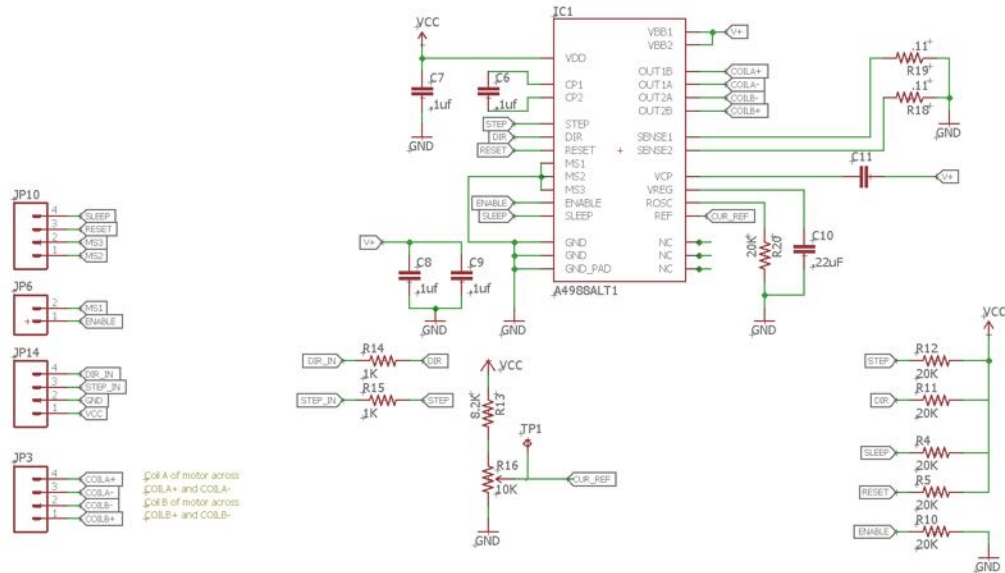
4 pin bipolar Motor control sequence labelled as A+,A-,B+,B-.

A4988 Bipolar Motor Driver with DMOS logic

This component is chosen because it has low power consumption when idle and quick response to the control signal so we can minimize the delay.

Dual Motion 21F4AC-2.5 Linear Stepper Actuators by Haydon Kerk Motion Solution

This component is chosen because of its high precision. We need to have motor step size in tenth of micrometers and this motor has a unit step size of $9.906\mu\text{m}$. We conducted a verification and concluded that this motor is sufficient for our design.



2.3.4 Software Subsystem

Our software subsystem consists of three applications - a high-level application on a smartphone, a low-level application on a microcontroller and a python program that stitches continuous images together into a panoramic image. The Android application exchanges signals with the microcontroller software to notify each others when to trigger the motor motion and when to take a photo. The microcontroller software controls the motor movement, and the smartphone takes a series of photos of different regions on the blood sample. After images are captured, The image stitching python program takes these images as input, and outputs the panoramic image to a specified directory so that doctors could perform the cell examination. The Finite State Machine(FSM) is shown in figure 9.

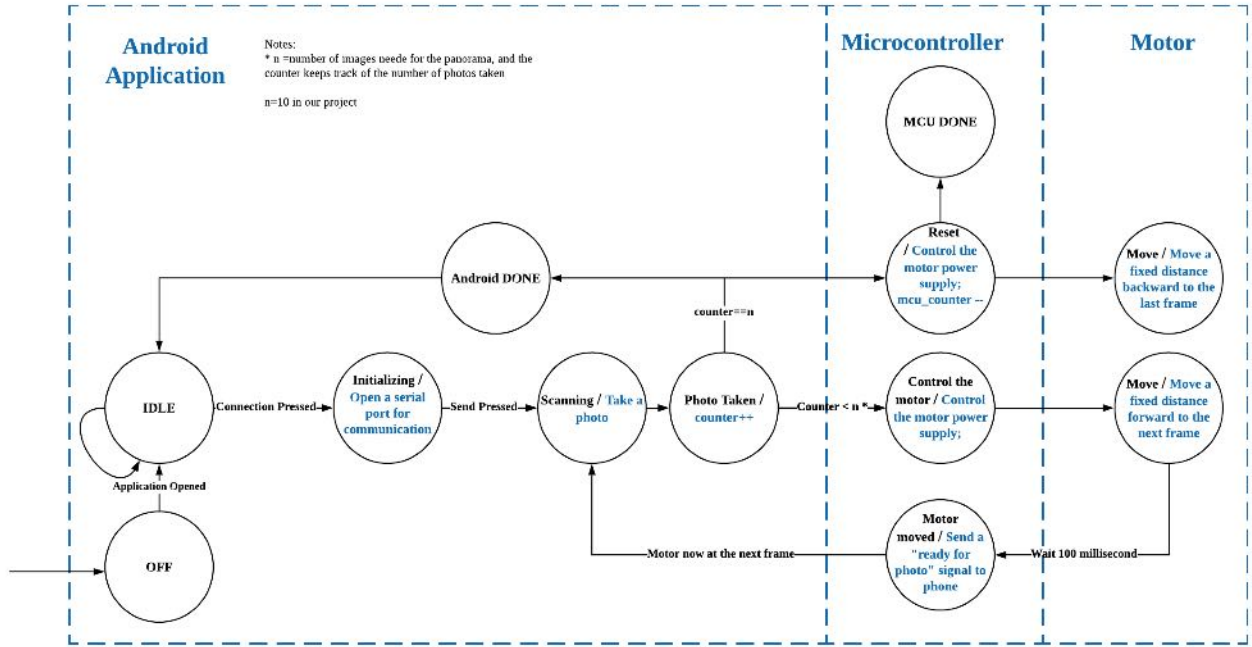


Figure 9: FSM of Software Operation

Android Application

A snapshot of the application is shown in figure 10. Once the user opens the application, the FSM goes to the idle state and waits for the user to click “connect”. After “connect” button is clicked, the mobile application initiates the communication with the microcontroller via communication unit. After the connection is built, the application waits for the user to click “send” button. It starts the image capturing process after “send” button is clicked, as per described by the flowchart in figure 11. The application takes the first photo and sends a “next frame” signal to the microcontroller. The application takes the next photo upon receiving the feedback signal from the microcontroller, and sends another “next frame” signal to the microcontroller. This process repeats until a required number of photos are taken, and the application sends an ending signal to the microcontroller to complete the process. Besides the image capturing process, this application also provides users “forward” and “backward” buttons to manually adjust the position of the motor.

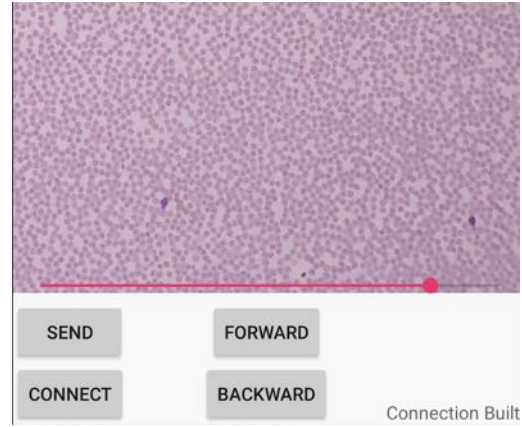


Figure 10: Android UI

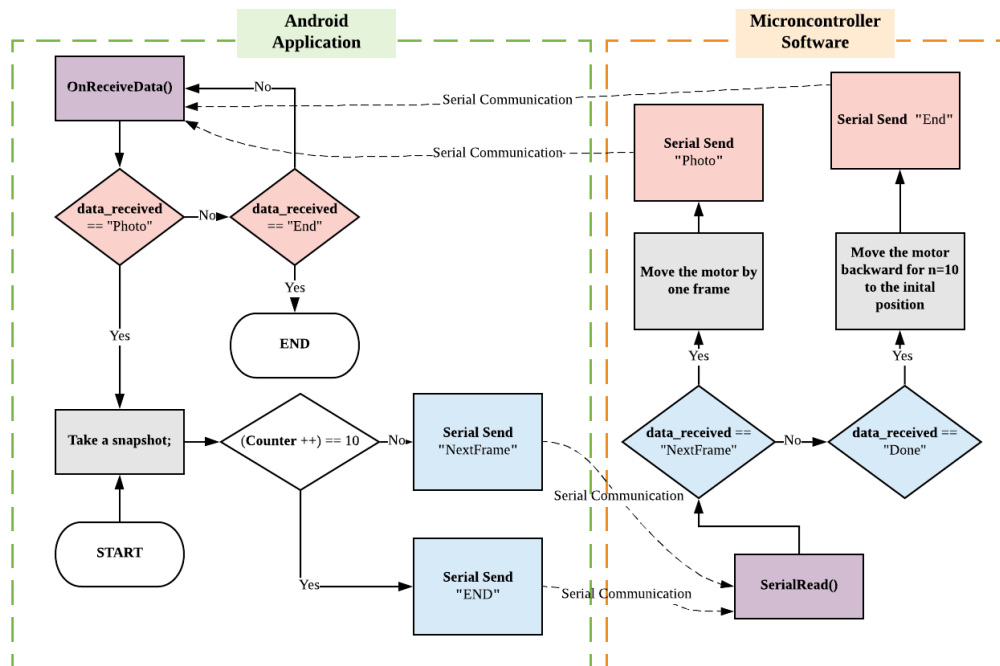


Figure 11: Software Logic Flowchart

1. Communication Unit:

In order to communicate with the microcontroller, we used android.hardware.usb API and UsbSerial Library by felHR85[6], and the designed flowchart is shown in figure 12.

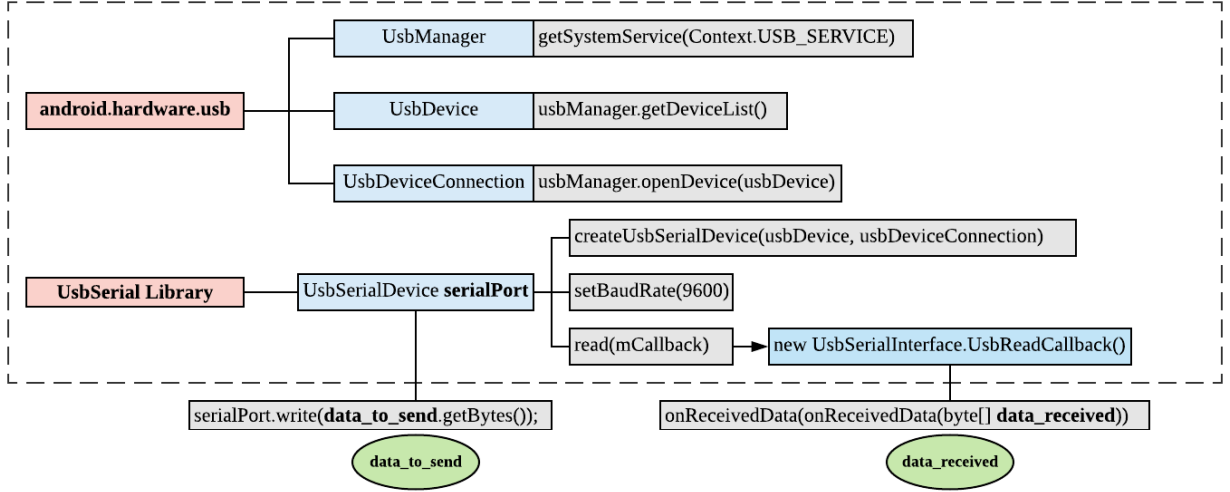


Figure 12: Communication Flowchart

2. Camera Unit: The input of this unit comes from the communication unit. Once received the “photo” signal, the application would initialize the process of image capturing. As described in the optical system, some of the parameters on the camera hardware like flashlight_always_on need to be modified in order to meet the optical requirements prior the capture session. The application then utilizes the android.hardware.camera2 API to capture an image on a thread. The application first initializes a CameraDevice, and creates a CaptureSession. During the CaptureSession, the system sends capture request to the camera, and the camera returns CameraMetadata. After the process completes, the Android application sends the “next frame” signal to the microcontroller. The designed image capture process flowchart is described in figure 13.

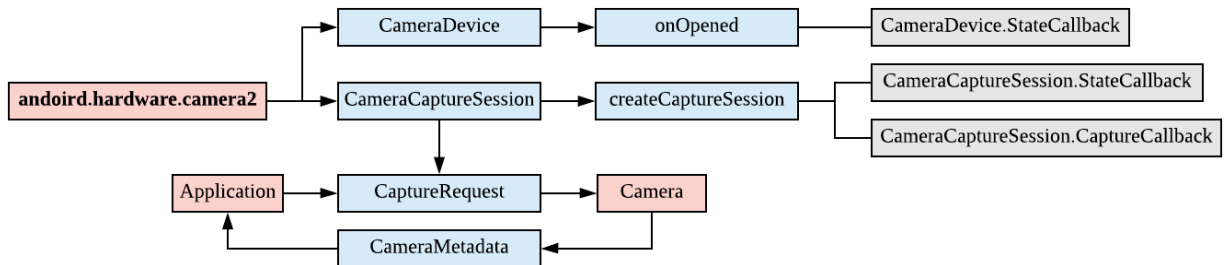


Figure 13: Camera Unit Flowchart

Microcontroller Software

The microcontroller software sends control signals to the motor driver to drive the linear stepper motor to travel a fixed distance, and table 1 shows the four operating modes for controlling the motor. Upon receiving the “next frame” signal from the Android application, the microcontroller controls the motor to move forward for 45 steps, which is one image frame. The microcontroller software will wait 100 milliseconds after the control signal terminates, and it will return the “ready for photo” signal after the motor completes its action. When the image capturing process is done, the microcontroller receives “done” signal from the Android application. The microcontroller controls the motor driver to move the motor backwards to reset the position. Operating modes MoveForward and MoveBackward allow users to manually move the motor forward and backward for 10 steps for adjusting position of the motor.

Operating Modes	Functions
FrameForward	Moving forward for one image frame (45 steps)
FrameBackward	Moving Backward for ten image frame (45*10 steps)
MoveForward	Moving forward for 10 steps
MoveBackward	Moving backward for 10 steps

Table 1: Microcontroller Operating Mode

Image Stitching Python Program After all images are captured, we designed a python program that performs image stitching on images to form a panoramic image. The program applies sharpening kernel on the images to enhance edges. Then, this python program utilizes opencv package to match features of these images, find homography matrix, and warp the perspectives to stitch these images together. A stitched image of 10 frames is shown in figure 14.

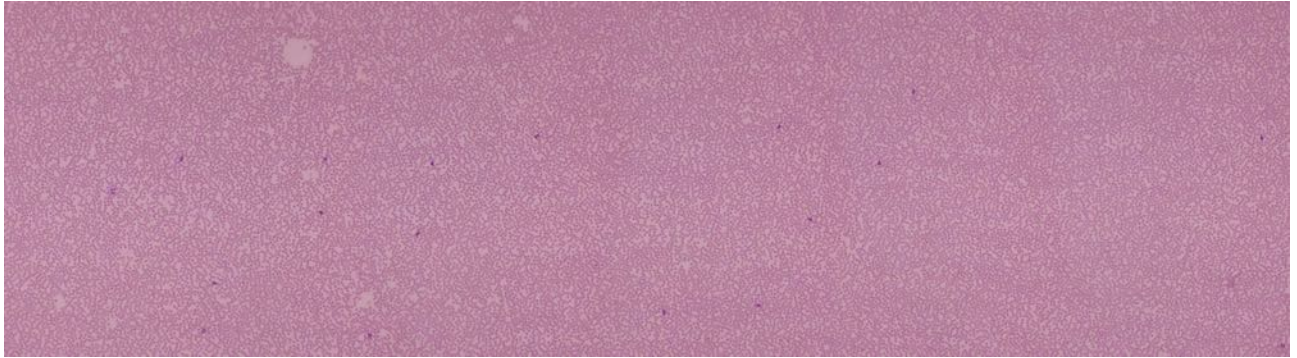


Figure 14: Stitched Image

3 Design Verification

3.1 Optical Subsystem

3.1.1 Visual Quality Assessment

One of the important goals of our project is to have blood cell images of high visual quality such that different blood cells can be identified correctly. In order to assess the image quality of the photos taken from our system, we referred to a blood cell images dataset on kaggle as the golden sample dataset images. The designed convolutional neural networks on the blood images dataset can achieve as high as 97% accuracy on the validation set.[7] To compare images taken from our system with the golden sample dataset, we asked human identifiers with medical background to determine the cell types from both the golden sample dataset and the image dataset from our system. We verified our image quality by confirming that our system can achieve more than 90% of the correctness comparing to the golden sample dataset.

3.1.2 Digital Zoom in

Although digital zoom is not mentioned in the original RV tables, we found its importance during the design procedure as we need to be able to see each single blood cell. Therefore on top of the optical zoom, we implemented the digital zoom to focus on part of the image. In order to examine our design's maximum magnification in digital zoom, we used the Camera2 API's function in getting and setting the zoom in factor. The original camera frame size is 4032pi * 3024pi and the maximum zoom in frame we could get without losing focus is 718pi * 560pi. This factor is $\sqrt{\frac{4032*3024}{718*560}} = 5.5$. For the convenience of the user, we also quantified the zoom in scrollbar from 0 to 100% of the maximum zoom in factor set by the smartphone. The optimal percentage is at 90% of the maximum. Figure 15 and 16 compare the original and the zoomed image.

3.1.3 Sample Size

According to the research done by Chung et al.[8], hemocytometer need to gather blood cell count from at least 5 mm² to have sufficient data sample for estimation of the blood cell distribution. To verify that our project took more than 5 mm² of sample, we measured the field of view of the camera with a ruler. Without digital zoom, the camera has a field of view of 6.67mm * 5.00mm. When we zoomed in to the optimal factor, the field of view is 1.19mm * 0.93mm. After stitching 10 images together with 48% overlap in between, theoretically, we should have a image size of $(0.93 + (1 - 0.48) * 0.93 * 9)mm * 1.19mm = 6.286mm^2 > 5mm^2$. In practice, we get $(0.93 + 0.45 * 9)mm * 1.19mm = 5.93mm^2 > 5mm^2$ as demonstrated in figure 17.

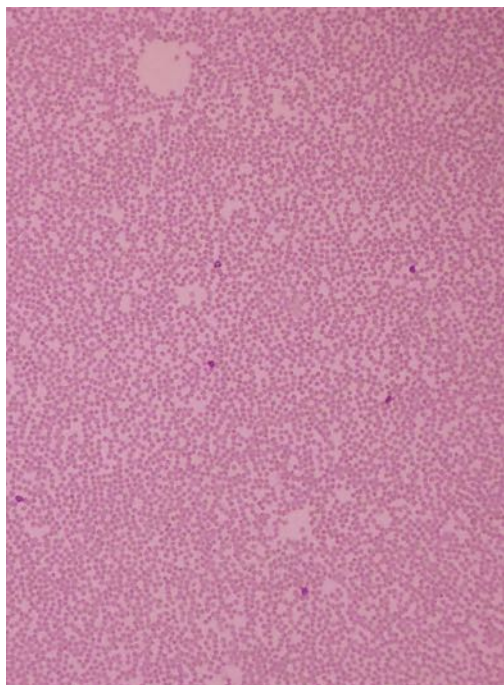


Figure 15: Zoomed-in Image of Blood Sample

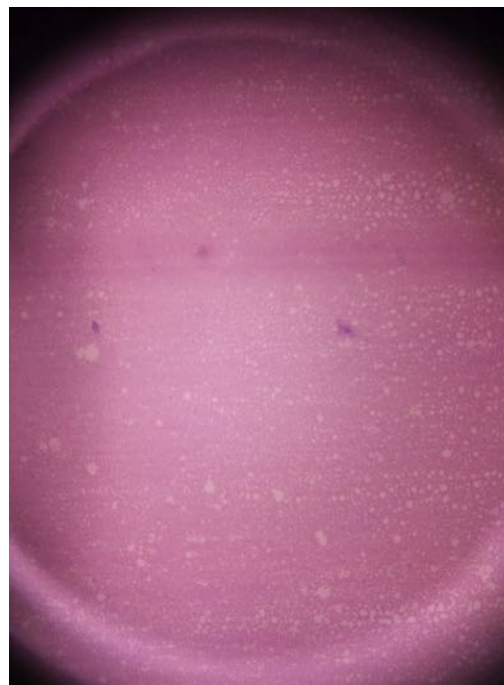


Figure 16: Image of Blood Sample in Original Frame

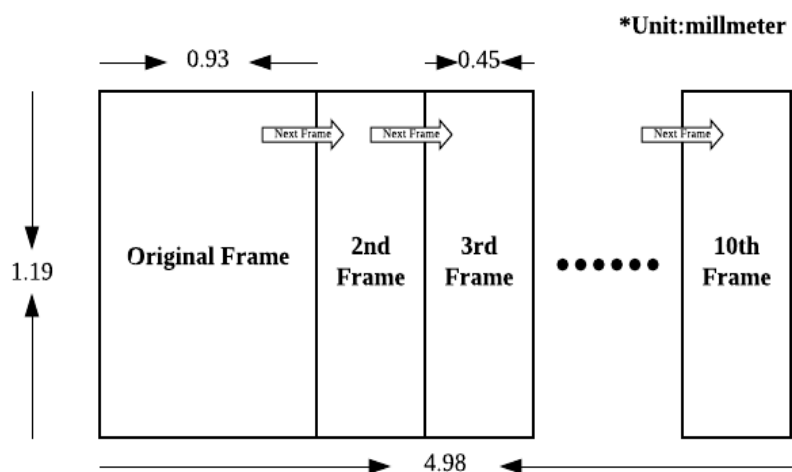


Figure 17: Final Image Stitched from Frames of Image

3.2 Electrical Subsystem

3.2.1 Power Supply Module

The voltage input output curve essentially depicts the characteristics of the Power Supply Module. We measured the open circuit output voltage with different input voltage.

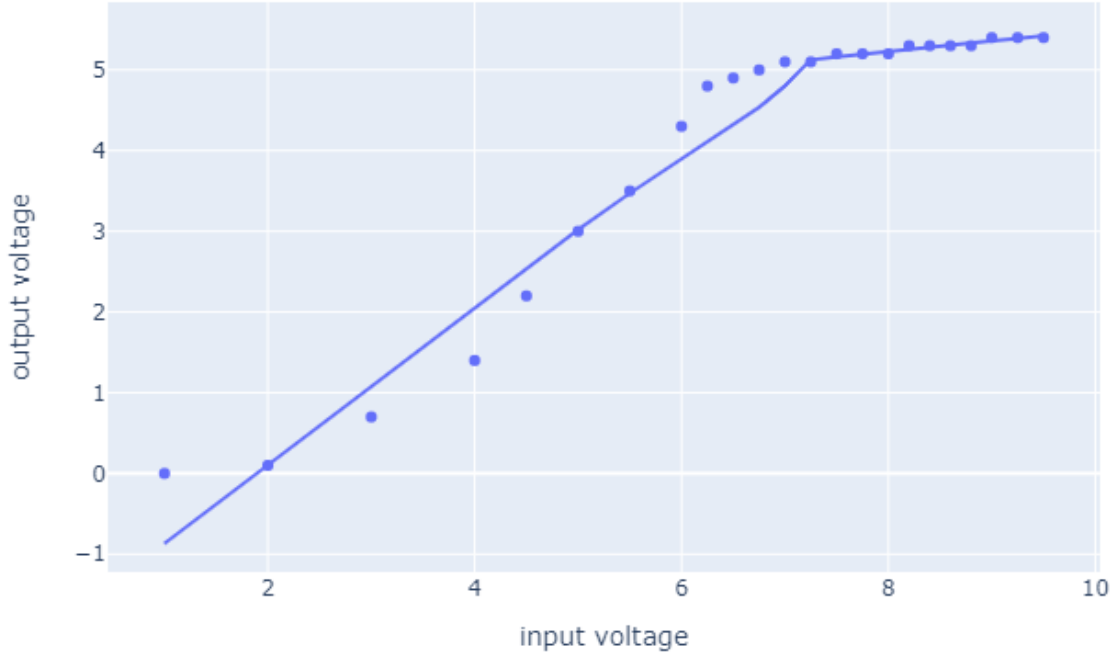


Figure 18: Input Voltage vs Output Voltage for Power Supply Module

As shown in figure 18, the Power Supply Module reaches its target voltage when input reached around 6V. The typical operating range of input voltage is from 8.7V to 9.2V which is well above 6V. At our operating range, the output voltage is at 5.2V with less than 0.1V difference between maximum and minimum, which satisfies the requirement for stable power supply.

3.2.2 Control Module

In order to check if the microcontroller is able to be programmed through Arduino IDE, we first built an Arduino standalone circuit on breadboard and boot-loaded the ATmega328P. Then we put the ATmega chip onto Arduino Uno and verified that it could be recognized and programmed through Arduino IDE.

For verifying the functionality of the USB-UART IC FT232R, we used the breakout board from Sparkfun to program the microcontroller without Arduino Uno.

After we soldered the control module PCB, we first verified the soldering and the device status by LEDs, and then we connected the PCB with a laptop and uploaded the microcontroller software. We also verified the successful communication with smartphone by doing an echo test in the Android App. We verified the

digital output signals using an oscilloscope.

3.2.3 Motion Module

Step size is critical to evaluate the precision of the motor. The field of view is fixed for our design = $1.19\text{mm} * 0.93\text{mm}$ and we need at least 30% overlap between images for image stitching, therefore the distance between frames need to be smaller than 70% of the length = $0.93\text{mm} * 70\% = 0.651\text{mm}$, but we also need to move more than 40% of the length = $0.93\text{mm} * 40\% = 0.372\text{mm}$. We also need the step size to be much smaller than the frame displacement so that we can reconfigure the motor to move more or less between frames base on the output image quality. If we allow 30 steps in a frame, the step size is between $0.372\text{mm}/30 = 12.4\mu\text{m}$ and $0.651\text{mm}/30 = 21.7\mu\text{m}$. Based on this criteria, we found our motor from Haydon Kerk which claimed to have motor step size of $0.00039\text{inch} = 9.906\mu\text{m}$. Previously when we tested motor performance with another motor, we found that the most significant factor is the number of steps per frame. The unit step size when taking 10 steps at a time can be 1.5 times larger than that when taking 100 steps at a time. We suspected that the motor acceleration and deacceleration might play a role in the difference in unit step size difference. Therefore we conducted the same experiment on Haydon Kerk's motor.

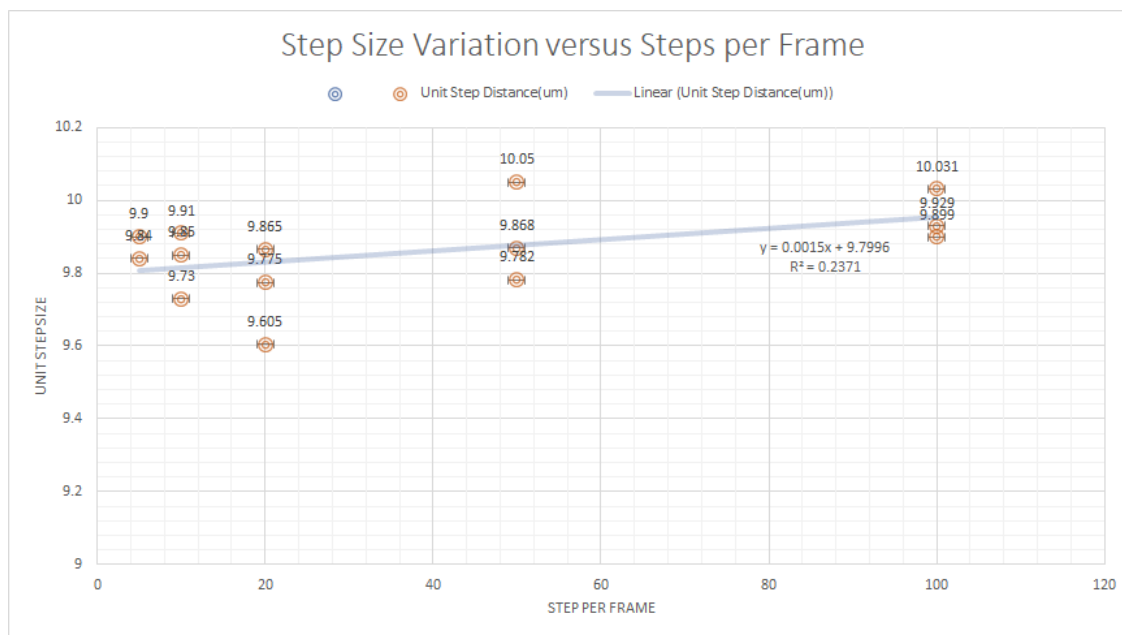


Figure 19: Step Size vs Steps per Frame

From the result, it's clear to see that the unit step sizes are fairly consistent across the whole range. The linear trend line shows an R-square value of 0.23 meaning that the model can explain less than 10% of the relationship. Suggesting that there's not linear correlation between step per frame versus unit step size. The standard deviation of the unit step size is $0.1148\mu\text{m}$, which means the step sizes are very consistent. The average unit step size is $9.86\mu\text{m}$ which is a little bit smaller than advertised, and is advantageous for our project.

4 Cost

4.1 Parts

Description	Vendor	Manufacturer	Part number	Quantity	Cost (prototype)	Cost (bulk)
Linear Ball Bearing Slider	Amazon	Usongshine	MGN12H	1	\$15.99	\$15.99
Nurugo Micro Smartphone Microscope	Amazon	Nurugo	B077V2JN8B	1	\$64.99	\$64.99
5V linear regulator for motor	Digi-Key	Analog Devices	LT1086CT-5	1	\$0.87	\$0.50
9V Lithium Battery	Digi-Key	Energizer	L522	1	\$12.47	\$8.11
Microcontroller	Digi-Key	Microchip	atmega328p	1	\$2.14	\$1.78
FTDI USB-UART Converter	Digi-Key	FTDI	FT232R	1	\$4.5	\$4.5
Linear Motor	Haydon Kerk	Haydon Kerk	21L4(X)-V	1	\$109.08	\$109.08
Motor driver	Digi-Key	Allegro	A4988	1	\$4.5	\$2.83
Assorted resistors, capacitors, LEDs, connectors	SparkFun Electronics			1	\$20	\$10
Total Cost					\$234.54	\$227.78

Table 2: Costs

4.2 Labor

We estimate the labor cost to be \$30 cost per hour, 10 hours/week for three people. The duration of the project is 15 weeks, so the labor cost is calculated as below:

$$3 * \$30 * 10 * 15 * 2.5 = \$33750 \quad (5)$$

5 Conclusion

5.1 Accomplishments

We are able to design a functioning system that controls the motion of the blood smear sample and take microscopic images of the blood sample. With a press of the “send” button, the system will automatically complete the process of taking sample images for blood analysis. Moreover, we performed various modular tests on all the subsystems and therefore we can pinpoint and debug any problem if it comes up in the future. We can also easily replace them with other functional units for future development.

5.2 Uncertainties

Since this prototype is currently being handled by people with professional knowledge, many of the error handling features for users are not yet implemented because we assume that the users are going to operate the device properly and with instruction. Later we can implement some features to avoid the machine being malfunctioned when users accidentally touch multiple send commands or touch buttons during operation.

Another uncertainty we encounter is the staining method of our blood smear sample. Currently our design can count the number of white blood cells but can not differentiate different types of white blood cells. For future development, we are considering a different type of staining method to our blood smear slides, which is Wright Giemsa stain, that can assign different colors to different types of white blood cells. We can also improve the optical magnification of our clip-on so that we can generate clearer images at higher magnification. In this way, we can use also differentiate white blood cells based on the cell morphologies. Comparing these two methods, we think changing the staining method will be more practical and easy to implement.

5.3 Ethical considerations

The objective of our project is to simplify the process of blood cell differentiated counting such that doctors could perform blood test within a couple minutes, and this aligns with the IEEE Code of Ethics, #5 “to improve the understanding of technology, its appropriate application. . .” [9].

There are several concerns regarding the safety and ethics of our project. The main safety hazard comes from the possibility of virus spreading via human blood sample. Doing experiments with human blood involves dealing with biology safety level 2 hazard. To mitigate the hazard, every individual involved in the project is required to complete a safety level 2 training and to pass the safety quiz. In such way, people will be taught to appropriately dealing with blood sample, significantly reducing the possibility of getting virus, following the IEEE Code of Ethics, #9 “to avoid injuring others, their property. . .” [9]. Another safety concern comes from the power supply, and we will be responsible for ensuring the voltage and current fed into different electronic modules won’t exceed their standard thresholds so the project is safe to use. The linear actuator could also be a safety hazard if someone tries to touch it while it is moving. Therefore the mechanical enclosure covers the motor from top so that the possibility of contact during motion is minimized.

5.4 Future work

We can combine the power supply and the motor controller on the same PCB. There are multiple accidents where the motor driver board was damaged because the motor output pins or pins on the motor driver board

are touching by accident and caused short circuit. In the future, we should integrate the PCBs to one PCB to hide all the connections and prevent short circuit from happening.

There could be lots of deduction on the cost if we replace the motor with cheaper alternative motors with lower precision, as we found that we can relax on the motor precision and use microstepping instead. We have researched other motors with around 100 to 500 μm of accuracy and cost around 15 dollars. Using those can reduce around 80 dollars, which is 35.2% of the cost. We can also use self-designed lens. We originally planned to use a 3D printed microscope clip-on designed by Pacific Northwest National Lab(PNNL), which could be 3D printed at home and cost less than \$1 each. If we could improve on the PNNL lens or use other self designed lens, we can cut the \$64.99 Nurugo lens out, which is 28.54% of the cost.

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Appendix A Requirement and Verification Table

Table 3: System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
<p>Mechanical Subsystem</p> <ol style="list-style-type: none"> 1. The blood smear sample can be installed on a pocket which was placed on the slider. The linear slider is connected with the external screw and able to provide smooth linear movement with low friction. 2. The mechanical enclosure should provide a flat bottom (± 0.5 degree tolerance). 	<ol style="list-style-type: none"> 1. (a) Use the mechanical connector from machine shop to stitch the slider with one end of the external screw. (b) Apply little step movement on the slider using the linear actuator, and check there is no vibration. 2. (a) Check spacer screws and use Caliper to check the tilt degree. 	<ol style="list-style-type: none"> 1. Y 2. Y
<p>Optical Subsystem</p> <ol style="list-style-type: none"> 1. The images taken from our system should high image quality such that human identifiers are able to identify white blood cells, and should be able to achieve 85% of the correctness comparing to the golden dataset images from kaggle. 2. Able to provide 40X ($\pm 5\%$) magnification. 3. Able to provide good illumination with the camera flashlight. 4. The camera should be able to continuously take snapshots without having to auto-focus every time when it takes a photo. 	<ol style="list-style-type: none"> 1. (a) Human identifiers identified the cells on the image dataset on kaggle and also on the image taken from our system, Our image quality is considered good if the percentage of correctness is greater than 85%. 2. (a) Attach the clip on to the smartphone camera. Then use the smartphone software to turn on the Nurugo App and set the magnification of the camera to the reset condition. (b) Check the size bar and magnification parameters on the app. 3. (a) Use the Nurugo App to turn on flashlight and check if the illumination is good enough to see and identify blood cells. (b) Write a function in the Android App that always keep the flashlight on and test if it works properly both in preview mode and image taking mode. 4. (a) Write a function that utilizes the continuous auto focus mode from the Android API. 	<ol style="list-style-type: none"> 1. Y 2. Y 3. Y 4. N, <p>We choose to do auto-focus for each frame, and this guarantees better image quality.</p>
Continued on next page		

Table 3 – continued from previous page

Requirement	Verification	Verification status (Y or N)
<p>Electrical Subsystem-Power Supply Module</p> <ol style="list-style-type: none"> 1. Able to convert voltage ranging from 8.7V to 9.2V to $5 \pm 0.3V$. 2. Able to provide a max of 100 mA current to power the digital circuits. 3. Able to provide a max of 1.5 A current to power the motor. 	<p>Electrical Subsystem-Power Supply Module</p> <ol style="list-style-type: none"> 1. (a) Provide 9V input voltage from DC power supply to the component. (b) Use digital multimeter to measure the output voltage. The output voltage should be $5 \pm 0.3V$. 2. (a) Use a clamp-on amp meter to measure the current consumption of the digital circuit when the device is working. The maximum current should be below 100mA. 3. (a) Use a clamp-on amp meter to measure the current consumption on digital circuit power line and motor power line when the device is working. The maximum current should be below 1.5A. 	<ol style="list-style-type: none"> 1. Y 2. Y 3. Y
Continued on next page		

Table 3 – continued from previous page

Requirement	Verification	Verification status (Y or N)
<p>Electrical Subsystem-Control Module</p> <ol style="list-style-type: none"> 1. Microcontroller is able to output 1MHz ($\pm 0.1\%$) frequency GPIO signals and correct digital control signals to the stepper motor driver. 2. Microcontroller is able to both receive and transmit over UART. 3. Microcontroller is able to use the digital output pins to drive LEDs for showing device status. 4. USB UART IC is able to convert USB to UART data and vice versa, and support data transfer rates from 300 baud to 3M baud. 5. USB UART IC has driver support for USB communication with Android. 	<p>Electrical Subsystem-Control Module</p> <ol style="list-style-type: none"> 1. (a) Connect the GPIO pins to an oscilloscope and check the duty cycle and frequency of the waveform. (b) check if the digital outputs' voltage levels match with what we specify in the microcontroller software. 2. (a) Connect the UART communication pins with a SparkFun FTDI Basic Breakout board. (b) Connect the board to a PC terminal via USB cables. (c) Use the Arduino software to check if we can both receive and transmit UART signals. 3. (a) Connect the specific digital output pins to digital multimeter and check the voltage output levels. 4. (a) Check datasheet and try different baud rates at 300 baud rate, 30000 baud rate and 3M baud when testing with the SparkFun FTDI Basic Breakout board with microcontroller and PC terminal. (b) Verify the data transmission accuracy. 5. (a) Check Datasheet and install the specific Android driver from FTDI's website. (b) Try sending and receiving back small data packages. 	<ol style="list-style-type: none"> 1. Y 2. Y 3. Y 4. Y 5. Y
Continued on next page		

Table 3 – continued from previous page

Requirement	Verification	Verification status (Y or N)
<p>Electrical Subsystem-Motion Module</p> <ol style="list-style-type: none"> 1. The DMOS full bridge motor outputs are able to drive motor and supply 0 to 1.3A of current. 2. The motor drives 45 steps between frames and makes the slide to travel $450 \pm 10\mu\text{m}$. 3. Shut off load power supply in less than 1us to ensure precision. 	<p>Electrical Subsystem-Motion Module</p> <ol style="list-style-type: none"> 1. (a) Use clamp-on Amp Meter and Volt Meter to determine the operating point. 2. (a) Use Smartphone Microscope Camera to pick a reference point before travel. (b) After 45 steps, measure how many pixels the reference point has travelled. (c) Calculate how far physically the slide has travelled by converting pixels travelled to length travelled. 3. (a) Use Oscilloscope to track the shut off transition time. 	<ol style="list-style-type: none"> 1. Y 2. Y 3. Y
<p>Software Subsystem</p> <ol style="list-style-type: none"> 1. the microcontroller should be able to control the motor driver to make the motor move a fixed distance 2. Once the microcontroller is connected to the Android phone, the Android application should be able to find the microcontroller device, and to send and receive messages 	<ol style="list-style-type: none"> 1. we will write a function on the microcontroller that controls the motor driver to move the motor to a fixed distance. 2. we will write a function in the Android application that identifies the microcontroller from the device list, requests permission from the user, and initializes the transfer channel. Then we will test the function by “buckTransfer” a data segment to the microcontroller, and at the same time we’ll write a function on the micro-controller to send back a data segment to the Android application if it receives the data from Android. 	<ol style="list-style-type: none"> 1. Y 2. Y