3D-Printed Microscope Accessory:

Affordable Technology for Efficient Diagnostics

Nicholas Addy-Tayie

Degree Thesis

Materials Processing Technology

2019

DEGREE THESIS	
Arcada	
Degree Programme:	Materials Processing Technology
Identification number:	17816
Author:	Nicholas Addy-Tayie
Title:	3D-Printed Microscope Accessory: Affordable Technology for Efficient Diagnostics
Supervisor (Arcada):	Stewart Makkonen-Craig
Commissioned by:	Stewart Makkonen-Craig

Abstract:

3D-printing technology has evolved over the years to accommodate devise application areas. With 3D-printing, accessories for enhancing the efficient operation of microscope in studying and diagnosing diseases such as malaria is made possible.

Malaria is prevalent in the Sub-Saharan countries and parts of Asia due to the suitability of mosquito breeding grounds. It is a killer disease that has children as its major victims. Malaria can be effectively treated after a timely and efficient diagnosis. The standard means of diagnostics is a microscopy test; because of the detailed results it provides, which then influences the effectiveness and efficiency of treatment.

Incidentally, acquiring a standard microscope for timely diagnosis is an expensive venture for some low resourced health facilities in the country-sides of Ghana.

This project seeks to develop the possibility and produce microscope accessory with 3D-printing technology; which would utilize the imaging capabilities of smartphones; to serve as an affordable microscope for diagnostics.

Keywords:	Efficient, Accessory, RDT, Diagnosis, MOPID, Affordable
Number of pages:	57
Language:	English
Date of acceptance:	3rd June 2019

Table of Contents

1 INTRODUCTION 5
1.1 Aim 5
1.2 Thesis Objectives 5
1.3 Thesis Structure 5
1.4 Global Perspective on Malaria 5

2 MALARIA IN GHANA 7
2.1 Definition and Statistics 7
2.2 Parasite Life Cycle 7
2.3 Healthcare Needs 8
2.3.1 Awareness 8
2.3.2 Diagnosis 8
2.4 Current Practices in Malaria Diagnosis 9
2.4.1 Research Methodology 9
2.4.2 Limitations 12
2.5 Justification for Microscopy 13
2.6 Requirements for Microscopy Diagnosis and Implementation 15
2.6.1 Light Microscope 15
2.6.2 Quality Management System Requirement 15
2.6.3 Microscopy Specification for Malaria Diagnosis 16
2.6.4 Recording Malaria Microscopy Results 17

3 REVIEW OF OPTICS, 3D-PRINTING AND SMARTPHONES 17
3.1 Optics 17
3.1.1 Lens Parameters 17
3.1.2 Components of a Microscope 19
3.1.3 Microscope Objectives 21
3.2 3D-Printing 23
3.2.1 Introduction 23
3.2.2 Complementary Processes Involved for 3D printing 23
3.2.3 Types of 3D printing Technology 25
3.2.4 Contemplation for Choosing a Process 26
3.2.5 Applications of 3D-Printing 27
3.2.6 Cost Savings 28
3.3 Smartphones Availability 29

4 REVIEW OF 3D-PRINTED MICROSCOPY ADAPTERS FOR SMARTPHONE 30
4.1 Clip-on 31
4.1.1 Advantages 31
4.1.2 Limitation 31
4.2 3D-printed parts of full microscope 32
4.2.1 Advantage 32
4.2.2 Limitations 33
4.3 3D-printed Lenses (On-lens) 33
4.3.1 Advantages 33
4.3.2 Limitation 33
4.4 MOPID 34
4.4.1 Advantages 34
4.4.2 Limitations 35

5 EXPERIMENTAL DESIGN, FABRICATION AND TESTING 35
5.1 Project Choice 35

5.1.1 Parts and Functions 36
5.1.2 Justification for Project Choice 36
5.2 Printing Material and 3D-Printing Type 38
5.3 Project Cycle Chart 39
5.4 Design and Production 39
5.4.1 Project Design 1 40
5.4.2 Improvements 42
5.4.3 Project Design 2 47
6 CONCLUSION 52
7 BIBLIOGRAPHY 53
8 APPENDICES 57

TABLE OF FIGURES

FIGURE 1: ILLUSTRATED PARTS OF RDT (WHO, 2015) 9
FIGURE 2: TYPES OF MALARIA PARASITES AND THEIR DEVELOPMENT STAGES. (MALARIA SITE, 2015). ..14
FIGURE 3: ILLUSTRATION OF FOCAL POINT OF A LENS. (PANASONIC, NA) 18
FIGURE 4: ILLUSTRATIVE OUTLOOK OF OPTICS WITHIN A MICROSCOPE. (EDMUND OPTICS , 2018) 20
FIGURE 5: ILLUSTRATIVE DESIGN OF FINITE CONJUGATE OBJECTIVE. (EDMUND OPTICS , 2018) 21
FIGURE 6: ILLUSTRATIVE DESIGN OF INFINITY CORRECTED OBJECTIVE. (EDMUND OPTICS , 2018) 22
FIGURE 7: A 3D-PRINTED CLIP-ON ATTACHED TO A SMARTPHONE. (ENGLAND, 2018) 31
FIGURE 8: A 3D-PRINTED PLATFORM FOR PHONE ATTACHMENT. (KWALUS, 2013). 32
FIGURE 9: 3D-PRINTED LENSES (FORMLABS 3D PRINTER, 2016) 33
FIGURE 10: THE MOPID SYSTEM - 3D-PRINTED HOLDERS. (GARCIA, 2015) 34
FIGURE 11: PARTS OF THE MOPID SYSTEM (PIRNSTILL & COTÉ, 2015) 35
FIGURE 12: POLARIZER-LESS IMAGING: COMPARISON OF STANDARD MICROSCOPE AND MOPID. (PIRNSTILL & COTÉ, 2015) 37
FIGURE 13: POLARIZED STANDARD MICROSCOPE IMAGING VS MOPID IMAGING. (PIRNSTILL & COTÉ, 2015). 37
FIGURE 14: OUTLOOK OF THE MOPID IN USE – OBTAINED FROM VIDEO (GARCIA, 2015). 40
FIGURE 15: PROJECT DESIGN 1 40
FIGURE 16: PHONE PLATFORM 41
FIGURE 17: LENS 1 41
FIGURE 18:LENS STACKER 43
FIGURE 19: LENS HOLDER 1 43
FIGURE 20: LENS HOLDER 1A 44
FIGURE 21: LENS HOLDER 1B 44
FIGURE 22: LENS 2 44
FIGURE 23: LENS 3 45
FIGURE 24: PROJECT DESIGN 47
FIGURE 25: SIDE VIEWS OF PROJECT DESIGN 2 48
FIGURE 26: LAMP HOLDER 49
FIGURE 27: LENS HOLDERS 49
FIGURE 28: THE ASSEMBLED OUTLOOK OF THE PROJECT OUTPUT 50
FIGURE 29: IMAGE OF A MAGNIFIED 70 μM HUMAN HAIR 51

LIST OF TABLES

TABLE 1: THE SIX KILLER DISEASES OF CHILDREN OF 2015 6
TABLE 2: RESPONSES FROM THE QUESTIONNAIRE 12
TABLE 3: PROPERTIES OF PLA 38
TABLE 4: RESULTS OF LENS STACKING ANALYSIS 46

1 INTRODUCTION

1.1 Aim

This project is aimed at harnessing the capabilities of 3D-printing technology to produce a microscope accessory; and rely on the imaging capabilities of smartphones, in order to assemble an affordable microscope for the efficient diagnostics of malaria.

1.2 Thesis Objectives

In order to achieve the stated aim, it will be necessary to understand the principle involved with the composition of a light microscope as well as the concept of microscopy diagnostics. Also, the applications areas of 3D-printing will be explored to ascertain its effective usage for the production of parts needed for this project.

1.3 Thesis Structure

The outline of this Thesis would be as follows:

1. A literature review on the theme of the Thesis. This would be followed by
2. A review of some of the existing 3D-printed microscopy adapters for and smartphone.
3. The next section would be focused on the project output from this Thesis: the experimental design, fabrication and testing of the product from this project.

1.4 Global Perspective on Malaria

Malaria is a disease usually associated in the tropical regions like Sub-Saharan Africa and parts of Asia. A bite from an infected mosquito is the means of transmission – the female anopheles mosquito is usually the vector.

Some symptoms of the disease include high body temperature, sweat chills, vomiting, headaches, muscle pains as well as diarrhoea. (The Guardian Labs, 2017).

In the space of 15 years between 2000 and 2015, malaria mortality rate has declined by some 60%, while the number of recorded malaria cases dropped by 37% worldwide. This resulted in saving lives of up to 6.2 million – including some 5.7 million, 92%,

being children under the age of 5 years. (UNICEF , 2016). According to (The Guardian Labs, 2017) malaria fell into 3rd place for being among the six killer diseases of children under 5 years in 2015, in a table that follows:

Table 1: The Six Killer Diseases of Children of 2015

6 Killer Diseases	Number of Death of Children Under 5 in 2015
Pneumonia	920,000
Diarrhoea	526,000
Malaria	306,000
Meningitis	116,000
HIV	87, 000
Measles	74,000

The World Health Organization (WHO) reports that there were up to 216 million reports of malaria cases worldwide in the year 2016 – out of which 445 000 deaths occurred. With an investment meant for the control and subsequent eradication of this endemic hovering around US$ 2.7 billion in the year 2016, it could be noted that the damning statistics about malaria "has not gone done well with world powers". (World Health Organization, 2017).

Malaria is curable once efficient and timely diagnostics have been undertaken. There are two main practices currently involved with malaria diagnostics, namely; the standard microscope test and Rapid Diagnostics Test otherwise called RDT.

Whereas the standard microscope is the most preferred choice for diagnostics; because of the detailed results it provides, which then influences the effectiveness and efficiency of treatment; the microscope facility requires some level of cost to acquire. This cost involvement has influenced the low availability of the microscope in developing countries and communities.

2 MALARIA IN GHANA

2.1 Definition and Statistics

Malaria could be termed as an endemic disease in Ghana. This is so, generally because of the prevalence of suitable breeding grounds for mosquitoes – as Ghana happens to be among the tropical regions of Sub-Saharan Africa. Influencing factors include the existence of open gutters and stagnated waters. Also, there are farming communities with irrigational projects as well as stagnated dams. The risk of contracting malaria is higher for occupants of settlements in and around the above stated areas. In a matching order, awareness level of malaria being a major health setback is universal among such residents. (Attu & Adjei, 2018).

Records from (Ghana Health Service, 2017, p. 2) indicate that the first three months of 2017 recorded 2.3 million cases being the number of suspected malaria cases in Ghana. That is 24,885 cases in a day. Relative to same period in 2016, this figure shows a 1.18% increase. Out of the number of the said suspected cases, about 70,000 people were admitted and 143 deaths occurred. Children under 5 years were the majority among the dead – recording 74 deaths or 52%.

In causes of all death of under 5 year olds, UNICEF indicates that 11.1% of those causes of death in Ghana in 2017 were as a result of malaria (UNICEF, 2018).

2.2 Parasite Life Cycle

Some of the characteristics of the life cycle of malaria parasite include:

- Human beings serve as the intermediate host, whereas mosquito remains the final host
- Infective stage is the sporozoite
- Liver and red blood cells (RBCs) are the parasitic positions
- The transmitted is gametocytes
- Transmission is through mosquito bite of human skin. (Dr Rao, 2012).

2.3 Healthcare Needs

2.3.1 Awareness

Information and education regarding causes and symptoms of any disease is crucial for enhancing prevention or efficient treatment. To this regard, Ghana Health Service undertakes an awareness programme with mass media campaign on TV and radio (Ghana Health Service, 2017, p. 3). Consequent to awareness programmes like these, the article (Attu & Adjei, 2018) made mention of the fact that the awareness level of malaria being a major health setback is universal among residents residing in the prone areas.

However, the nature of the population and wealth distribution in Ghana is such a way that basic communication facilities are not evenly distributed, and a reasonable number of the population residing in the countryside could be missing out on certain critical privilege (Dagadu, 2017). Therefore, the Ghana Health Service through partners adopts other means such as community mobilization, durbars, partaking in religious meetings and one-on-one engagement among other means to try and create adequate awareness in every community (Ghana Health Service, 2017).

2.3.2 Diagnosis

It is recommended for "rapid, accurate and accessible detection of the malaria parasites" before the issuance of any medication for some perceived symptoms of malaria (UNICEF, 2016). As stated in (UNICEF , 2016) – "since not all fevers are due to malaria, parasitological confirmation by light microscopy or RDTs is recommended in all patients before antimalarial treatment is started". In Ghana, sensitization through public awareness creation has caused patients to accept or demand diagnosis before any form of antimalarial prescription is issued (Senoo, 2017). This enhances prevention and treatment of malaria effectively. As in Ethiopia, a fellow African country, there are a number of parasite types that cause malaria; two of them include plasmodium falciparum and plasmodium vivax which are sympatric in Ghana, and have different regimens for treatment (Abreha et al, 2014).

There two main means of malaria diagnosis in Ghana are:

- Rapid Diagnostics Tests (RDT) kit: RDT is used in "primary health facilities in resource-limited settings where weak resources limit the use of microscopy". It

is a relatively cheaper, quicker and easier to operate as compared to the microscopy diagnosis (Boadu, et al., 2016). It is also effective in diagnosing the prominent malaria parasite type, which is the plasmodium falciparum. Furthermore, the Kit is capable of determining only the parasite type of falciparum; and not the amount of parasite within the victim.

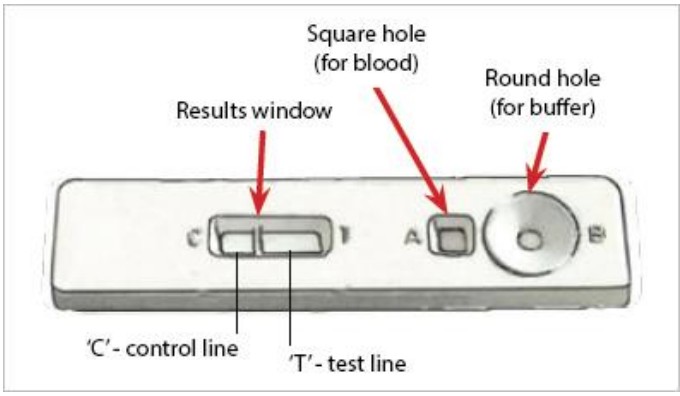

Figure 1: Illustrated parts of RDT (WHO, 2015)

- Microscopy Test: Microscopy is a more advanced means of diagnosing the malaria disease. According to (Boadu, et al., 2016), the microscopy is considered "quality assured and gold standard for diagnosing malaria". With the microscope, the parasite type and the amount of parasite within the blood sample of the patients could be established. Microscopy diagnosis usually take place within the bigger health facilities like the hospitals; and receive referrals when the kit has failed to diagnose adequately due to the possibility of existing parasite type other than falciparum.

2.4 Current Practices in Malaria Diagnosis

2.4.1 Research Methodology

In a bid to get a better understanding of the practices in dealing with malaria within the health care facilities in Ghana, a qualitative research was undertaken. The research included interviews with health workers within different levels of capacity-resourced

health facilities. The difference in levels of health care facilities selection was to accumulate varying health delivery solutions to the diagnosis and treatment of malaria. The theme of the interview was to determine whether RDT kits or microscopy test were used for diagnosis and how often. A questionnaire was designed for the said health workers at the different facilities

2.4.1.1 Questionnaire

1. *What equipment do you use for malaria diagnosis?*
2. *How much time is required for a diagnose with the equipment?*
3. *Could the equipment be suitable for malaria diagnosis in all medical situations like:*
    - *emergency*
    - *mild illness or*
    - *severe illness?*
4. *In your estimation, is the equipment reliable?*
5. *What's the level of know-how and technique required for operating the equipment?*
6. *What type of malaria parasite is usually found?*
7. *Are you able to quantify the amount of parasite in the blood with the equipment?*

2.4.1.2 Responses

Eikwe Hospital

Eikwe hospital happens to be the main referral hospital within the Ellembelle District of the Western region of Ghana. It is the biggest health facility within the said area. The interview was conducted with two health workers – a Registered Nurse who has worked with the facility for over 4 years, and a laboratory technician.

Menzezor Clinic

A private clinic located in a small town of Menzezor within the Ellembelle District. They operate both OPD and In-patients services for mild degree of illness; they also

provide maternity services, and have a functioning laboratory as well. Interviewee was a laboratory technician.

Aiyinasi Health Centre

This is a basic health care facility located in the town of Aiyinasi in the Ellembelle District. They operate Out Patients Department (OPD) and provide In-Patients services for very mild illnesses; they also provide maternity services. They do not have a functioning laboratory. Interviewee was a Community nurse at the facility.

Whindo Health Centre

This is another basic health care facility in the suburb of the capital city of the Western region. They operate Out Patients Department (OPD) and also provide maternity services. They also do not have a functioning laboratory and thus, make referrals to Kwesimintim Hospital which is a much bigger facility. Interviewee was a Community health nurse at the facility.

Table 2: Responses from the Questionnaire

	Equipment Type for Malaria diagnosis?	*Time Required for Diagnosis*	*Case Suitability*	*Equipment Reliability*	*Skill and know-how Required*	*Parasite Type*	*Parasites Quantifying possibilities*
Eikwe Hospital	Microscopy and RDT kit	About 30 and 15 minutes respectively	Microscopy for severe illness. RDT for all cases	Reliability for both equipment high	Higher skills and basic skills respectively	Plasmodium falciparum with both, microscopy detects others	Microscopy quantifies; kit does not
Menzezor Clinic	Microscopy and RDT kit	Between 25 – 30 minutes; and 20 minutes respectively	Microscopy for severe illness. RDT for all cases	Dependent on expected results; both high	Higher skills and basic skills respectively	Plasmodium falciparum with both, microscopy detects others	Microscopy quantifies; kit does not
Aiyinasi Health Centre	RDT kit	From 10 to 20 minutes	For all cases	Reliability is high	Easy to operate	Plasmodium falciparum	Cannot determine parasite quantity
Whindo Health Centre	RDT kit	About 20 minutes	For all cases	Reliability is high	Easy to operate	Plasmodium falciparum	Cannot determine parasite quantity

2.4.2 Limitations

Apparently, data gathering in the institutions in Ghana is not very common. As a result, pursuing a quantitative research for actual data figures on "how often" a particular equipment, whether the RDT kit or microscope, was specifically requested to be used

did not yield fruition. Also, the number of times or a percentage of how often any other parasite apart from the falciparum parasite did not yield any figures.
The general assumption with all the interviewees was that there is a very high possibility that it is either the falciparum parasite causing the prevailing symptoms of malaria or the symptoms cannot be attributed to malaria infection. In other words, the other malaria causing parasites like vivax and others are not common in the country.

2.5 Justification for Microscopy

The RDTs were produced targeted at providing malaria diagnosing capacities to health facilities that were previously unable to access good quality microscopes for the same purpose. In other words, microscopy is the standard or the method of choice for the investigation of malaria cases. Emphasising this tag are:

- The microscope has the ability to identify the malaria-causing parasites, namely:
    1. Plasmodium vivax: usually comes with milder health symptoms, and generally not fatal. This parasite forms the widest geographical distribution in the global world.
    2. Plasmodium malariae: this parasite could stay in the patient's blood for decades; and generally not fatal.
    3. Plasmodium ovale: also comes with milder health symptoms, and generally not fatal. This parasite is said to have a liver stage and could remain in the body for years without causing symptoms of sickness.
    4. Plasmodium falciparum: it is the only parasite identifiable by the RDT kit in sub-Saharan Africa including Ghana. It is the deadliest parasite among the list. (Malaria Site, 2015)

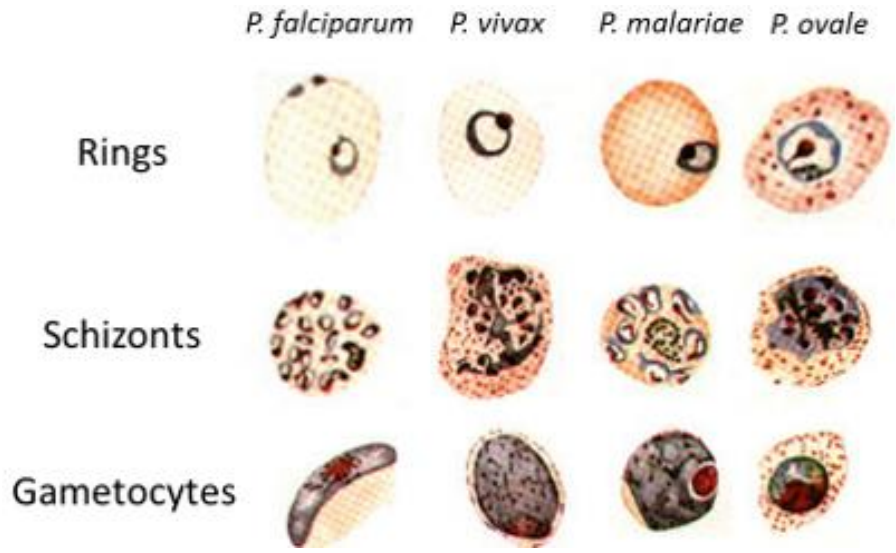

Figure 2: Types of malaria parasites and their development stages. (Malaria Site, 2015).

- Identifying the different stages of parasites, gametocytes inclusive. Thus, the capability to efficiently produce a definite result in a second test, when a first test by the kits has yielded an invalid result.
- Capability of quantifying the parasite density. The quantification of parasites enhances effective delivery services in drug prescriptions and monitoring (World Health Organization, 2018).
- Also, the technique provides higher sensitivity threshold. This is due to the fact that whereas microscopy detects parasitemia associated with as little as 5-10 parasites in 1 μl of blood sample, RDT has a threshold of 100 parasites per 1 μl. (Pirnstill & Coté, 2015, p. 2).
- While a microscope is a stationary and a reusable facility, the RDTs kits are unrenewable consumables, and supply could be limited at times (Boadu, et al., 2016). Therefore, the availability of a microscope is a guarantee for diagnosis before treatment.
- With a national health insurance in place – where government is supposed to reimburse health service providers periodically, delayed reimbursement of used kits jeopardises the running of the facility. Therefore, providers prefer to use microscope for diagnosis so as to limit cost. (Boadu, et al., 2016)

2.6 Requirements for Microscopy Diagnosis and Implementation

2.6.1 Light Microscope

The standard microscope type for malaria diagnosis is light microscope. This forms the basis or benchmark with which other diagnostics have been compared. Light microscope involves the visualization of malaria parasite in either a thin or thick smear of a patient's blood. (World Health Organization, 2018). Thick blood smears tests are done to mostly provide either a positive or negative malaria screening outcome to a particular blood sample; while thin blood smears are undertaken to determine the particular species of infection (Pirnstill & Coté, 2015, p. 1).

2.6.1.1 Accessories

Some equipment that are needed to facilitate efficient and effective microscopy include timers, centrifuges, refrigerators and pipettes. Others are spare bulbs for the microscope's light, slide, staining racks, beakers and flasks. (Abreha et al, 2014).

2.6.1.2 Laboratory Consumables

The classical stain used for the malaria microscopy is the Giemsa stain. (World Health Organization, 2018). Other necessary consumables are microscopic slides, PH paper, buffer, lens tissue and cleansing solution, biohazard container, immerse on oil, lancets, bleach, filter paper and alcohol among others. (Abreha et al, 2014)

2.6.2 Quality Management System Requirement

According to WHO (World Health Organization, 2018), the acceptable microscopy service is that which are both cost-effective and provides results that are always accurate and time efficient in having a direct influence on the treatment. To achieve these, a particular quality assurance programme ought to be comprehensive and functioning. The list of such programme include:

- Central coordinator to implement and monitor quality assurance
- A reference group of microscopy experts, aided by quality assurance programme, and with competence in training and slide validation

- Adequate training systems “based on competency relevant to clinical settings”
- Regular retraining and assessment or grading of competency, being aided by a validated reference slide set
- A sustainable means of slide validation systems, so as to check inadequacies with an effective feed-back and a system to address such inadequacies.
- Adequate supervision at all levels of the hierarchy
- Potent supply management as well as maintenance of microscopes
- Clarity in standard operating procedures (SOPs)
- Sufficient capital budget for malaria case management. (World Health Organization, 2018).

2.6.3 Microscopy Specification for Malaria Diagnosis

Certain specifications are necessary to effectively enhance the realisation of set parameters for diagnosis of malaria parasites in blood smears (WHO, 2016). Some of such specifications are listed below;

2.6.3.1 Competence in Microscopy

Performance in microscopy diagnosis is a measure of the accuracy of output of microscope technicians in their routine operations, whereas the competence in microscopy is the ability of the user to examine a blood film accurately, as well as accurately report the findings.

2.6.3.2 Size of Malaria Parasite

The size of the malaria parasites being sought after in a smeared blood ranges from 1 – 2 microns, equivalent to 0.001 – 0.002 mm for asexual form which is usually of a ring shape; and between 7 – 14 microns for sexual forms or gametocytes of the falciparum parasites. The size for the ring stage parasite for the plasmodium vivax is about 2.5 microns or 0.0025 mm. (Dr Rao, 2012).

With regards to estimation of the malaria parasite density by looking at a monolayer of a thin smear of red blood cells (RBCs), it is recommended that there would the use of oil immersion objective of 100x and 10x eyepiece – resulting in a 1000x magnification

(WHO, 2016). Consequently, 1 micron of parasite as in the case of the falciparum would be magnified to:

$$\text{Observed parasite size} = 1000 \text{ x } 1.0\mu\text{m} = 1.0\text{mm}$$

Also, the slide is recommended to be examined where the RBCs are closest together – about 400 RBCs per field; and the estimation of the density made from the percentage of infected RBCs by counting 500 to 2000 RBCs. (CDC, 2018).

2.6.4 Recording Malaria Microscopy Results

WHO (WHO, 2016) gives the following as being the recommended means of recording microscopy diagnosis of malaria.

1. Positive or negative
2. Species type
3. Presence of gametocytes
4. Single or mixed infections
5. Parasite count per 500 WBCs and per 5000 RBCs
6. Parasite density per microliter, which is determined from true WBC count
7. An optional record for concordance or discordance with validation results

3 REVIEW OF OPTICS, 3D-PRINTING AND SMARTPHONES

3.1 Optics

3.1.1 Lens Parameters

There are two indicators that are said to be the basic indicators of the performance of a lens, and therefore determine their market value. They are focal length and numerical aperture:

3.1.1.1 Focal Length

It is the distance from the lens to the point where parallel rays of light passing through the lens are focused or converge on the principal focal point or the optical axis. When a lens is described as a 30mm lens, then it is indicating the focal length of that lens. Focal length is an important parameter as it determines the lens strength – the indication of how much the lens enlarges the image. Different focal lengths result in different levels of magnification as well as the viewing angle of the resultant image. (Radcliffe, 2017; Edmund Optics , 2018; Panasonic, NA).

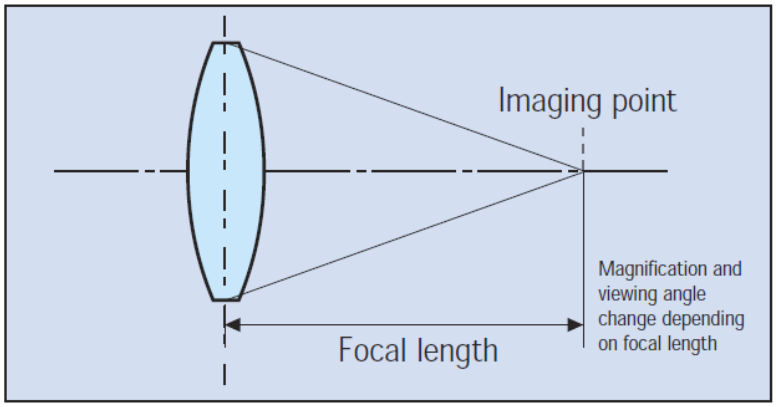

Figure 3: Illustration of focal point of a lens. (Panasonic, NA)

Magnification: This defines the amount of time the image enlarges in size relative to the object. Magnification aids the human eye to see particles of sizes less than 0.1; as it is said that the smallest object the unaided human eye could see is about 0.1 mm long at a 250 mm viewing distance (University of Utah , N.A) . Therefore, a simple magnifier of 10X should aid and observer to see a 0.01 mm object; and a compound microscope of 100X should also magnify a 0.001 mm object to 0.1 to enhance visibility by the unaided human eye – in the right lighting conditions. Consequently, in the right conditions, it is expected that one could see things like amoeba proteus (0.5 mm) and a human egg (0.13 mm) without having to rely on magnification.

3.1.1.2 Numerical Aperture

This indicates the maximum amount of light the lens can allow to penetrate; that is, it shows the overall brightness of the lens. The extent of brightness of any lens is said to be determined by both the focal length and lens diameter. In essence, given that two lenses have two different diameters but the same focal length, the lens with the bigger diameter would be the brighter.

Numerical aperture is also known as F-stop and written as f/n, where n represents the number or range of numbers indicated on the lens. Example is given as f/3.5 – 5.6 being the indication on most budget lenses. F-stop is mathematically analysed with the computation below as given by (Panasonic, NA):

$$F - Stop = \frac{focal\ length}{Lens\ diameter}$$

It is worth noting that the smaller the number the better the grade for transparency. In essence, the lower the number indicated, the higher the amount of light that could penetrate the lens – consequently the more blurred the background becomes. (Petrovski, 2015).

> *Resolution*: Numerical aperture is said to influence the resolving power of an object. And the total resolution of the entire microscope optics is also influenced by the aperture of the sub-stage condenser. To achieve a better resolution, the numerical aperture or F-stop for the totality of the system must be higher. Also, accurate alignment of the optical systems of the microscope is very crucial to achieving a maximum resolution.

3.1.2 Components of a Microscope

A microscope is said to be a compound microscope when it contains multiple lens elements. It works like a simple magnifier that makes use of the magnifying capacity of a single lens to magnify a small object to make its details relatively discernible by the human eye. In the case of a microscope, relay lens system is employed to serve the

purpose of a simple magnifier, with an improved magnifying capacity. That is, an objective and an eyepiece work in relation to each other to project an object to be visible by the eye, or even the camera of a smartphone as applicable in this project. There are two sources of magnification of a microscope that enhances the overall effect. They are:

- The objective or base magnification: This is located closest to the object and relays the real image of the object to the eyepiece. This is discussed further in next sub-heading
- The eyepiece*:* This can be found closest to the eye point or sensor. It projects and magnifies the real image as relayed by the base magnification and yields a virtual image of the object. These magnifications are typically at 10X, but could vary from 1X – 30X.

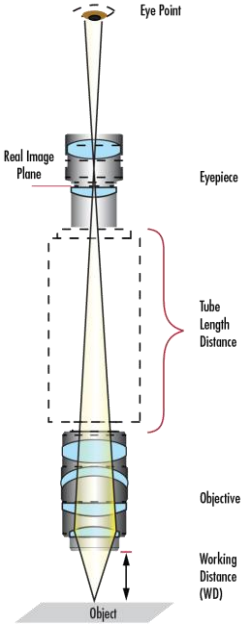

Figure 4: Illustrative outlook of optics within a microscope. (Edmund Optics , 2018)

Total magnification of the system therefore is given as:

$$\text{Magnification}_{\text{system}} = \text{Magnification}_{\text{objective}} \text{x Magnification}_{\text{eyepiece}}$$

(Edmund Optics , 2018)

3.1.3 Microscope Objectives

The objectives of microscopes are categorised into two main sections. They are said to be using either finite conjugate or infinity corrected optical designs:

3.1.3.1 Finite Conjugate Objectives

These are commonly used in traditional microscopes. They focus image to certain specific finite position, without requiring secondary lens. Such objectives are designed in a way that the focal length does not match the object distance. This allows to focus the image to a specified magnification.

Figure 5: Illustrative design of finite conjugate objective. (Edmund Optics , 2018)

3.1.3.2 Infinity corrected objectives

These objectives direct light into parallel rays, which can be focused at infinity. They are designed in such a way that the focal length matches the object distance. A tube lens is required to be put at a specific distance from the objective; to help to focus an image. This is illustrated below:

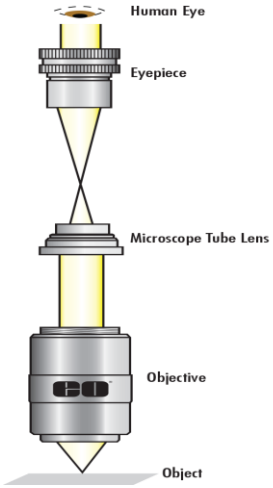

Figure 6: Illustrative design of infinity corrected objective. (Edmund Optics , 2018)

This type of objective has some important advantages over the finite conjugate objective in the sense that:

- It permits the introduction of optical components such as filters, polarizers as well as beam-splitters into the optical pathway. This provides the avenue for additional image analysis and extrapolation to be performed. For instance, adding a filter in the setup, between the objective and tube lens affords one the chance to view and manipulate certain wavelengths of light for the most desired outcome.
- Also, this type of objective provides the possibility to vary magnification accordingly. This is due to the associated ratio given below:

$$\text{Magnification}_{\text{objective}} = \frac{\text{Focal Length}_{\text{Tube lens}}}{\text{Focal Length}_{\text{Objective}}}$$

According to the above ratio, the focal length of the tube lens varies directly proportional to the magnification of the objective. (Edmund Optics , 2018). This provides room for increasing or decreasing the total magnification of a setup so as to provide desirable imaging.

3.2 3D-Printing

3.2.1 Introduction

3D-printing, also referred to as additive manufacturing, is a process which involve the use of machines to print solid objects, in layers, from digital files like CAD data or scans - It consists of the guided addition of successive layers of the printing material to achieve a desired 3-dimensional object. The material serving at the "ink" used in this type of printing is usually plastic; in the form of a filament, powder, or liquid depending on the type of 3D printing technology; but other materials like epoxy resins, titanium, silver, wax and silver could be used. The type of material to be used for is dependent on the application of the output product. (World Bank Group, 2016, pp. 327-329).

3D printing technology first emerged onto the scenes in the 1980s and 1990s; during the mid-2000s, 3D desktop printers become available on the market; then industrial Additive Manufacturing systems soared to initial commercial maturity – promoting "the idea of 3D printed production parts". Currently, 3D printing has evolved into a powerful technological tool applicable in the value chain, either applied alone or to complement traditional manufacturing methods. (Marin, 2018).

Therefore, this technology is said to have a transformational potential for manufacturing. That is due to the fact that it enables its users to produce smaller batches of highly personalised products at reduced costs.

According to a research, as reported by World Bank Group, 3D-printing is one of the six digital technologies earmarked for substantial growth in these modern days of technology. This group of six digital technologies, in no particular order, are:

1. 3D printing
2. 5G mobile
3. Artificial Intelligence,
4. Robotics,
5. Autonomous vehicles and
6. Internet of things. (World Bank Group, 2016, pp. 327-329).

3.2.2 Complementary Processes Involved for 3D printing

In order for a successful 3D printing, certain actions are necessary complement. The steps below inform about such actions:

3.2.2.1 Model File

3D printing begins with soft copy file of the desired object. Two main means of attaining such file are designing from scratch or scanning existing object:

3.2.2.1.1 Model Design

3D printing starts with design. The part to be produced would have to be design with Computer-Aided Design software like Solidworks, for example. Therefore, computer skills would be required for a productive start of the process. It should be noted that 3D printing according to (Stratasys , 2019), unlike the conventional design and manufacturing which have reasonable constraints, allows freedom for design, so there is not much restrictions at to what one can design for printing - provided the size could be oriented to fit the printing platform.

A desirable design would then be exported in an STL format. This format is said to be the standard file extension for 3D design. STL represents Standard Tessellation Language or stereo lithography – implying that the files have been translated into triangulated surfaces and vertices. Consequently, the files are sliced up into several hundred or thousand 2D layers. The 3D printer is capable of reading those 2D layers as building blocks, laying one atop the other, to form a 3-dimensional object. The exported file would need to be put through some suitable settings to enhance the subsequent printing.

3.2.2.1.2 Scanning

Objects could be scanned with 3D scanner and processed for 3D printing. The 3D scanning is the process of analysing and capturing real or physical objects or environments to create a virtual 3-dimensional model with the collected data. (Wobith, 2019). The resulting file would then be saved and exported in and STL format.

3.2.2.2 Settings for Printing

The exported file is put through a 3D printing software like Makerbot, for example, to apply suitable settings. Some relevant areas of interest are:

- The thickness of the layers
- Density of the infill
- Structure of the infill.

- A raft – to provide a cohesive platform for the main object
- A support – to serve as "scaffolding for features that cannot be built in air" (Stratasys , 2019). Such features include overhangs, cavities and holes, as well as undercuts.

The selections made in the above areas go to affect the lead time or duration of printing objects. Also, they affect the mechanical and physical property in terms of required toughness, application effectiveness and durability of the object, albeit also dependent on the printing material.

The ready file could then be transported to the 3D printer through internet connection or external drive among others. Operational know-how of the machines would be required for a successful print

3.2.3 Types of 3D printing Technology

With the ever increasing inventions and development in 3D printing technology, (Marin, 2018) reports of four (4) primary types of 3D printing. They include:

3.2.3.1 Vat Polymerization

Vat polymerization also known as Stereolithography (SLA or SL) is one of the first additive manufacturing processes to be developed and commercialised in the mid-80s; and thus, considered the original 3D printing technology (Marin, 2018). It is a photo-curing process; that is, it involves a process whereby liquid photopolymers are cured by light activated polymerization. In other words, a precise UV laser is used to cure and solidify thin layers of photo-reactive resin layer by layer.

After every single layer is cured, the build platform retracts into the liquid material in a bathe for a recoating blade to evenly distribute the liquid plastic across each new layer. After the desired build is achieved, the object is drained of excess material and then placed in UV oven for thorough curing. (Stratasys , 2019). Objects produced from this could be used for applications like prototypes, casting patterns and concept models.

3.2.3.2 Filament Extrusion

Filament Extrusion type of 3D printing involves the dispensing of material through an extruder head or a heated nozzle. After the extrusion of each layer, the platform moves down, or the nozzle moves up, to make room for the subsequent layer.

With this type of printing, the thickness of the layers can be varied. Technologies that use this type of printing are Fused Deposition Modelling (FDM) as well as Fused Filament Fabrication. The first commercial system is said to have been developed in 1991. (Marin, 2018). Thermoplastics such as ABS, PLA and ASA are commonly used as material for this type of 3D printing.

3.2.3.3 Powder Bed Fusion

As the name implies, this type of 3D printing uses powdered material to form the product. It process relies on thermal energy to fuse cross-sectional regions of the powdered material. The heat or thermal energy melts the powdered energy, which then solidifies as it cools. During the process, a chamber of powder drops periodically while each layer is processed to form the desirable object as a "powdered cake" of unused material, from which the solidified part must be excavated. The powdered material could be plastic or metal. Example of this type of 3D printing is laser sintering, which was commercialised in 1992.

3.2.3.4 Material Jetting

This type uses multi-nozzle print heads, and therefore makes it one of the fastest additive manufacturing methods. The process deposits droplets layer by layer in building the object. Material jetting systems could be used to print multi-material as well as graded material parts – consequently, the possibility to produce a parts with variety of colours and range of materials. Examples of this technology are applied in Multi-jet Modelling and Polyjet to create anatomically realistic medical models, casting patterns and rapid prototypes among others. (Marin, 2018).

3.2.4 Contemplation for Choosing a Process

According to Marin in (Marin, 2018), the following points are some of the necessary contemplations for choosing a 3D process;

3.2.4.1 Application

Considering that 3D printed components can serve at any stage of a product's life cycle, it becomes paramount to consider whether a part is to serve as a prototype of final part for a production. This helps to choose the appropriate process for a sample.

3.2.4.2 Performance Needs

The performance needs influence the build style and material to be used. This helps to consider whether a part ought to cosmetically appear similar to the final product or hold it shape firmly during operation among others.

3.2.4.3 Environment

The environment consideration deals with considering the temperature and humidity conditions of the operational area of the part. This is crucial as photopolymers used to print a part to be used outdoor would rapidly be degraded by UV light – therefore, considering the environment of usage informs the need for us of UV-stable material instead in this example.

3.2.4.4 Endurance

Some parts would be used in several cycles during their operational life, and thus, considering the needed level of endurance helps in choosing the right process for printing. Stress and strain are common endurance issues that could be considered to ascertain appropriate thickness and density of a part.

3.2.4.5 Cost and Time Efficiency

Time and cost are critical considerations as some of the process options provide avenue for saving cost and reducing lead time, and still produce a relatively quality part. Therefore, one can avoid wastefulness and stride for efficiency by making the right call in choosing the appropriate 3D printing process.

3.2.5 Applications of 3D-Printing

There are numerous applications of 3D-printing, some of the applications including:

1. Prototyping: 3D-printing could serve as cost effective and easier means for modelling early product ideas or concept. This possibility allows for avenue for improvement considerations for concept designs until a desirable end is reached.
2. Health and Biological applications: 3D printing has biological applications in the sense that it could be used to produce bodily parts like titanium jaws, spines and exoskeleton as well as prosthetic limbs. Clinical laboratory supplies like finger splints, umbilical clamps, casts and microscope could be obtained with 3D-printing.
3. Transportation: Parts of automobile engines are made by 3D printing. Also parts of rockets could be produced with advanced 3d-printing.
4. Construction application: special 3D-printers are designed with the size and capability to 3D-print buildings. This provide cost efficient housing solutions.
5. Domestic applications: simple household usable like toothbrush, key holders, children toys, cups among others could be made from 3D-printing. Also, food could be made with certain designs with the aid of 3D-printing.
6. Unclassified applications: 3D-printing has several applications beyond the classified applications above. There are printers designed for highly personalised objects which are comparatively expensive and also require replicable results. Some rather potentially unfortunate use of 3D-printing includes the printing of guns and controlled drugs. (World Bank Group, 2016, p. 329).

3.2.6 Cost Savings

3D printing provides savings in manufacturing or production cost. This according to (Stratasys , 2019), is achieved through three advantages which connote to shorter lead time and consequently provides costs savings.

3.2.6.1 Zero Tooling

Tooling mainly involves the machining or fine-tuning of the sides of a design. A variety of manufacturing processes require tooling – like lost wax tooling for investment casting as well as steel tooling in injection molding.

There are a lot of design and manufacturing limitations inherent to tooling. Some examples include; tool designs need to take into consideration certain crucial features like release points, to help get the molded part out of the tool with ease; angles and holes can become difficult to execute because the tool cannot have floating interior features that are unattached to the tool and features should not inhibit the release of the molded part.

3D printing builds a part from bottom up, and therefore does not require any form of tooling – even in cases of executing more complicated designs. Thus, labour for building tools and its related costs are totally eliminated.

3.2.6.2 Zero-Cost Complexity

This implies the possibility to produce complex designs without extra cost in terms of tooling and other labour. 3D printing provides the avenue to build parts with interior floating part; eliminates the use of pins and manual extraction of pins which could be necessary in tooling and molding; also eliminates the reliance on multiple coding and reorientation of a part with regards to machining.

3.2.6.3 Relatively Reduced Labour

Compared to conventional processes, 3D printing has very limited amount of manual labour as the only tangible labour involved is the removal of the build supports or possible smoothening of surfaces, while on the other hand, conventional processes could involve many difficult labour like tooling, manual pin extraction among others. Also, 3D printing has the capacity to consolidate multiple parts into a single unit, whereas conventional processes could require assembly lines and labour with its related cost.

3.3 Smartphones Availability

From its entrance into the consumer market in the late 90s, to gaining mainstream popularity with the inception of Apple's iPhone in 2007 – with their touch screen interface and virtual keyboard, smartphone users are increasing across the world. For

the year 2018, statistics show the estimated users of smartphone at some 2.53 billion, being about a third of the world's population and the projected addition until 2020 is 1.71 billion users. (Statista, 2018).

In Africa specifically, the number of smartphone users as of the end of 2016 stood around 294 million, it is projected that the year-on-year growth rate stands around 53%. This projects to about 930 million users in the year 2021. (Matinde, 2016). If the same pattern should befall Ghana, being part of the African continent, a substantial increment would be seen from its current estimated 10 million smartphone users, which in itself is quite a significant number for a population of about 30 million – a third of the population (Citibusinessnews Ghana, 2018). This would increase the availability and capacity for the functioning of the theme project of the work – a 3D-printed microscope being operationalised with a smartphone.

Most of smartphones currently available are well-equipped with advanced camera features, with rear camera capacities in the range of 5 – 20 Mega Pixels; and other relevant technologies like advanced computing capabilities and connectivity. These developments have propelled smartphones to be an ideal platform for advanced imaging. They are very viable in sensing Mobile-Health (mHealth) applications that have resulted in a lot of portable field-ready point-of-care healthcare around the world. Consequently, providing opportunities for the delivery of an improved quality of healthcare throughout the world with low cost, portable and energy efficient alternative for imaging modalities. (Pirnstill & Coté, 2015).
Dominant smartphones in Ghana are relatively cheaper brands with appreciable product quality like Infinix, Huawei as well as Tecno (Matinde, 2016). Samsung and IPhones are also available, but in fewer quantities.

4 REVIEW OF 3D-PRINTED MICROSCOPY ADAPTERS FOR SMARTPHONE

There exist some systems of microscopy that fall under the theme of this project. Some of them are:

4.1 Clip-on

Researches have 3D-printed device that could be used with a smartphone to work as a microscope. This clip-on device with the smartphone could examine samples as tiny as 1/200th of a millimetre.

Figure 7: A 3D-printed clip-on attached to a smartphone. (England, 2018)

4.1.1 Advantages

- The clip-on is said to require no external light or power source – but has internal illumination tunnels which relies on the camera flash of the phone to sufficiently illuminate a sample, to produce clear images of microscopic organisms from blood, animals and plants.
- There is anticipation that this simple form of microscopy could be used to analyse water cleanliness, and also to analyse blood samples to detect parasites; as in the case of malaria. (England, 2018).

4.1.2 Limitation

The main limitation with this system is with the simplicity of the system – and per the efficiency output of the singular lens, the required lens would be of high power and thus:

- relatively unavailable

- relatively expensive.

4.2 3D-printed parts of full microscope

A 3D-printed part designed to serve as the foundation for building a workable microscope. The complementary accessories like lenses, mirrors and others are added to complete the system. (Kwalus, 2013).

Figure 8: A 3D-printed platform for phone attachment. (Kwalus, 2013).

Such similar versions of cheaper microscopy are provided in some parts of Kenya where the actual microscope is expensive to come by (Hoek, 2018, p. 132). This provision enhances the delivery of healthcare.

4.2.1 Advantage

The main advantage with this system is that design has made room for addition and removal of lens and thus varying magnification to desired levels

4.2.2 Limitations

- The system has many different parts and requires a relatively higher level of assembly of parts.
- Relatively cumbersome.

4.3 3D-printed Lenses (On-lens)

This system uses an on-lens device that relies on refractive element that is directly attached to the smartphone's camera at the focus, or a ball-lens that is mounted on the lens of camera. The type of 3D printing could be stereolithography.

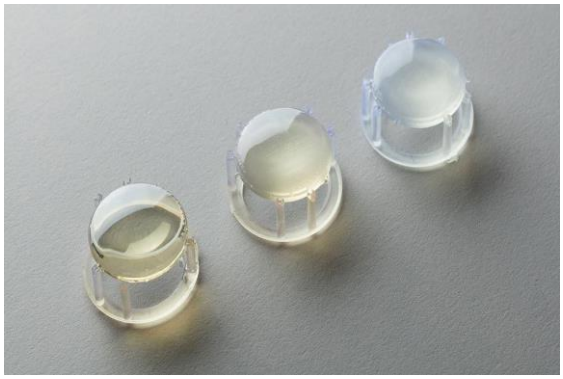

Figure 9: 3D-printed lenses (Formlabs 3D Printer, 2016)

4.3.1 Advantages

- This alternative is said to be simple and cheap.
- It produces resolutions that are comparable to other cell-phone based microscopy.

4.3.2 Limitation

- Limitation with this is that the ball lens creates a spherical focal plane, consequently allowing for only a small field-of-view (FOV) of the image

captured to be in focus – image processing correction techniques are then needed to adjust the out of focus areas in the FOV. (Pirnstill & Coté, 2015).

- Some level of know-how is required to achieve a lens of desirable resolution quality – as polishing and washing of the printed lenses are required (Formlabs 3D Printer, 2016).

4.4 MOPID

Otherwise known as the mobile-optical-polarization imaging device, makes use of a smart phone's camera features to obtain high resolution images of objects that are about 10 times smaller than the human hair. 3D-printed fittings massively complement this system – as the holders of light source, diffuser, sample slide as well as the microscope attachment are all 3D printed parts.

Figure 10: The MOPID system - 3D-printed holders. (Garcia, 2015)

4.4.1 Advantages

- It has the potential to diagnose malaria rapidly, by providing microscopic resolution on a smartphone.
- The accuracy of this diagnosis is said to be on par with benchtop spectroscopy

4.4.2 Limitations

- Vital accessories like diffuser and polarizer are not common, and might prove bottlenecks to operationalizing this system
- Some level of optical know-how required to design and effectively produce the focus and zoom technique.

5 EXPERIMENTAL DESIGN, FABRICATION AND TESTING

5.1 Project Choice

By establishing the advantages of microscopy diagnosis over RDTs; and the prevalent inadequacy of standard microscopes due the cost of acquisition and operation in Ghana, this project seeks to use a 3D-printer to produce a mobile-optical polarisation imaging device otherwise known as MOPID.

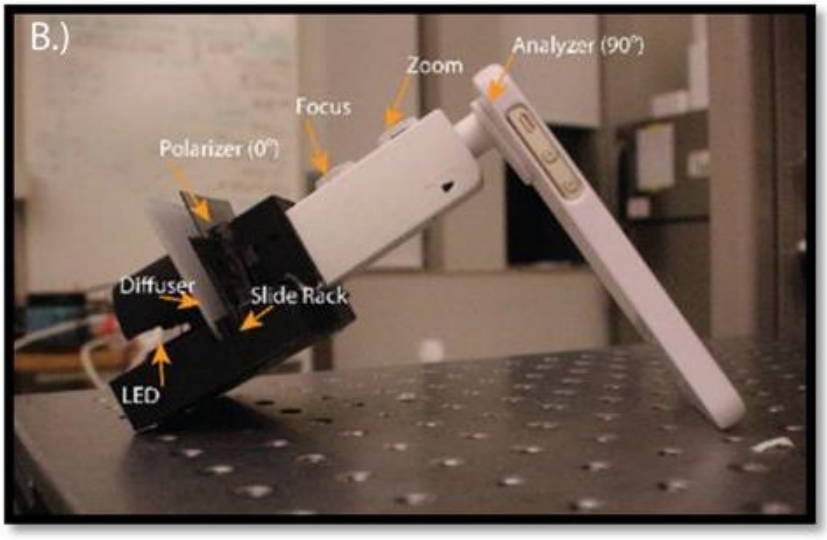

Figure 11: Parts of the MOPID system (Pirnstill & Coté, 2015)

5.1.1 Parts and Functions

LED: a low-power high efficiency white light emitting diodes to provide enhance visibility

Diffuser: this is a plate made of TiO_2, it is used to allow homogenous illumination across the sample.

Slide rack: this is the area that provides the space for the placement of the blood smeared slide.

Polarizer: this a sheet that seeks to generate linearly polarized light before its transmission through the sample. The polarizer enhances easy identification of a pigmented hemozoin.

Focus and zoom: these parts enable the adjustment of magnification and resolution of the image to achieve desired results.

Analyser: This is crossed at a 90 degrees to the polarizer, and both work in unison to provide a more distinct imaging.

5.1.2 Justification for Project Choice

Some few points to justify MOPID as the choice include:

1. This system is said to have a high diagnostic accuracy relatively close to that of:
    a. A standard benchtop microscope: as seen in figure below, an illustrated comparison of image from a standard microscope with a polarizer in the image plane (A), and an image from the MOPID via a smartphone, but without the polarizer (C) – both with same magnification of 40X from a Giemsa stained mouse blood.

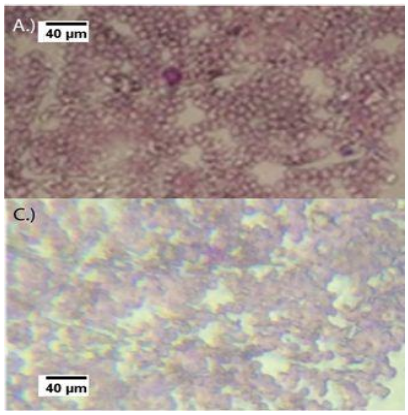

Figure 12: Polarizer-less imaging: Comparison of Standard microscope and MOPID. (Pirnstill & Coté, 2015)

b. The more complex polarized microscope: a comparison of standard microscope with a polarizer and an analyser crossed at 90 degrees in the image plane (B) to a fully assembled MOPID system, that is, including a polarizer and analyser (D) in the figure below. The closeness of the accuracy could be observed as birefringent hemozoin are distinguished and also correspond in both images.

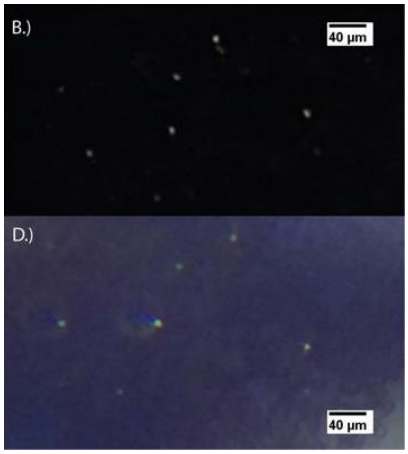

Figure 13: Polarized standard microscope imaging Vs MOPID imaging. (Pirnstill & Coté, 2015).

2. Reduced cost and complexity for conducting polarized microscopy for malaria diagnosis on a mobile platform
3. Low technical expertise required in its usage to diagnose malaria in the field

4. Tube lens could be varied to vary objective magnification according to the ratio:

$$Magnification_{objective} = \frac{Focal\ Length_{Tube\ lens}}{Focal\ Length_{Objective}}$$

5. Could serve as microscopy analyses for varied samples because of the possibility to vary the magnification and the object distance

5.2 Printing Material and 3D-Printing Type

During this project, the material used for the 3D printing was a biodegradable thermoplastic material derived from renewable resources like sugarcane or cone starch. It is called Polylactic Acid or PLA. Some of the important properties of this material that make it an effective choice for 3D printing according to Giang (Giang, 2019), are listed in the table below:

Table 3: Properties of PLA

Properties	PLA
Tensile strength	37 MPa
Elongation	6%
Flexural Modulus	4GPa
Melting Point	173 Degrees Celsius
Glass transition	60 Degrees Celsius
Density	1.3g/cm^3
Biodegradable	Yes, under the right conditions

The 3D-printing type or method used in this project was the filament extrusion. This type was used as it was prudent for the application of the part; it was also cost and time efficient for the production of the parts.

5.3 Project Cycle Chart

As the standard in any project, a chart was drawn to serve as a guide in regard of the steps necessary for a successful project outcome. Below is the chart for this project:

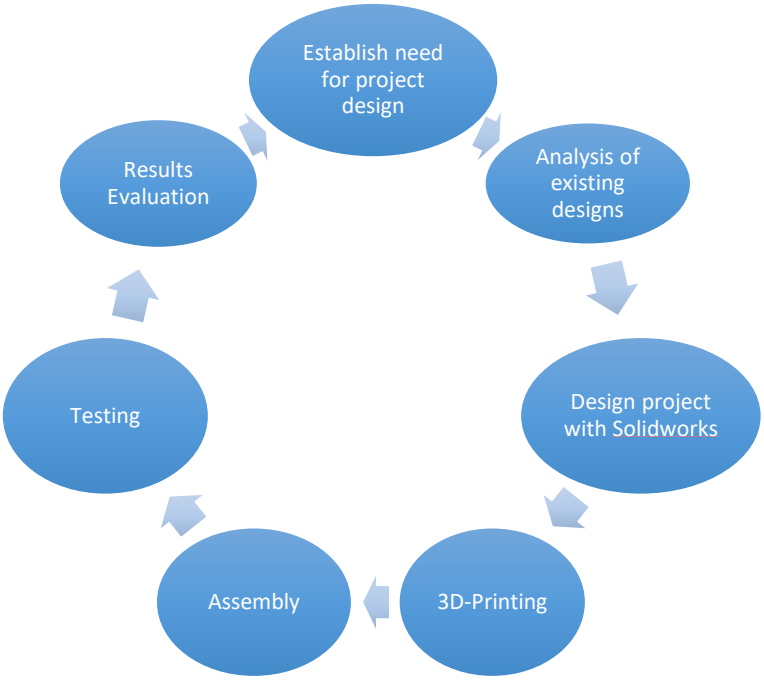

Chart 1: Project Cycle

5.4 Design and Production

An outlook of an example of a MOPID in operation could be seen in the Figure 14 below – a 3D-printed assembly with smartphone attached. Although it differs from the other MOPID system seen at Figure 11 in size and composition, but it is said to be relatively productive.

With regards to this project, the design of Figure 14 would be the design concept. Considering that an important accessory like the lenses used in this design concept below have different capacity to those to be used in this project, the dimension of the project design would vary to effectively accommodate the capacity of the available lens and a bid to achieving the highest possible magnification attainable with the available lenses.

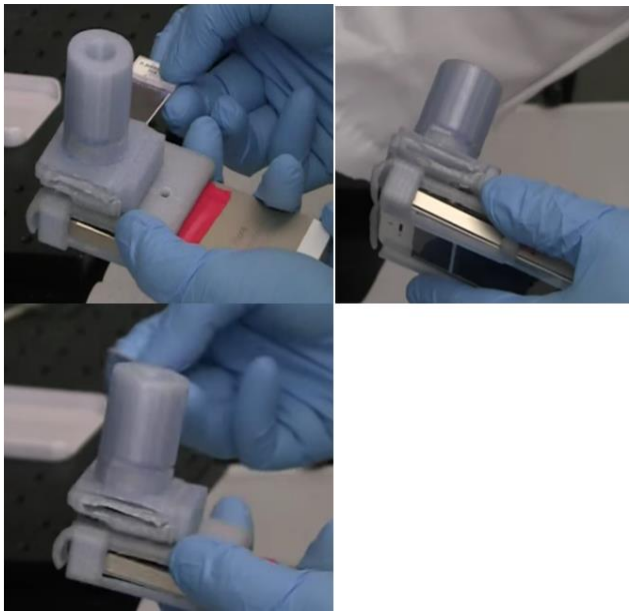

Figure 14: Outlook of the MOPID in use – obtained from Video (Garcia, 2015).

5.4.1 Project Design 1

Although the design concept as seen in the Figure 14 above is dimensioned to accommodate and iPhone 5, it is worth stating that the design freedom provided by 3D printing affords the chance to customise parts. It is with that capacity that the design of this project is dimensioned in relation to a private smartphone – Honor 7 lite. This is to provide an avenue for the possibility of Testing and evaluating the productivity of the design output, and thus, enable possible improvements.

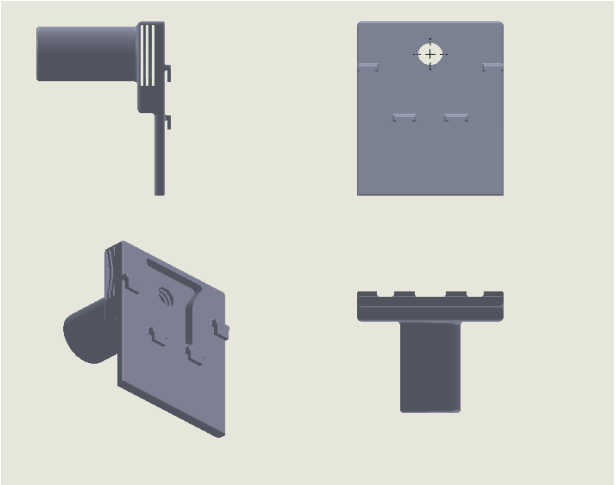

Figure 15: Project Design 1

5.4.1.1 Complementary Accessories

5.4.1.1.1 Phone Platform

This platform was designed to dimensionally accommodate a private smartphone – Honor 7 lite.

It has corresponding hooks to enable it get fitted onto the project design 1.

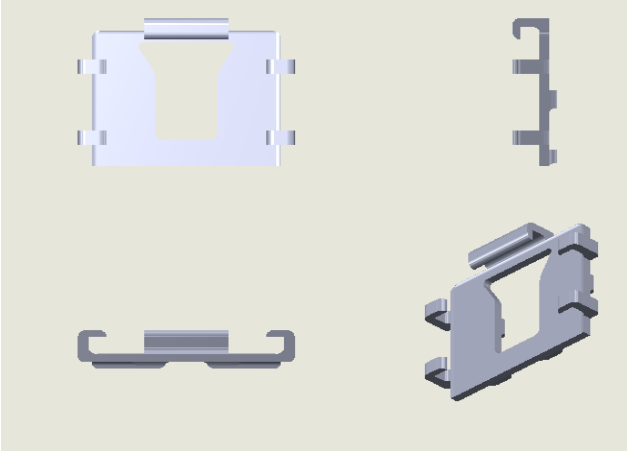

Figure 16: Phone platform

5.4.1.1.2 Lens 1

Lens 1 is plano-convex lens of 17X magnification. The diameter of the tube of project design was made to fit the Lens 1

Figure 17: Lens 1

5.4.1.2 Implementation

5.4.1.2.1 Assembly

- Part 1B is fitted with the lens by screwing the lens holder into the tube.

- Part 1A is then fitted into Part 1A to form 1AB.
- A smartphone is fitted into the phone holder of the project to complete the assembly.

5.4.1.2.2 Testing

- Lens capacity is tested by observing a sample which is inserted into the marked stage. The distance between this marked stage and the lens equates the focal length of the lens.
- The camera of the inserted phone is switched on to serve as the eyepiece.

5.4.1.2.3 Result and Analysis

- The camera captures the image of the sample under observation.
- The captured image was measured relative to the object so as to attain the magnification capacity of the setup.
- The resultant magnification was reasonably less than the desired level - therefore an improvement became necessary.

5.4.2 Improvements

Due to the inadequate magnification from Project Design 1 above, changes had to be made to the design, to accommodate more lenses. The stacking of the individual lenses needed further study to ascertain the appropriate spaces between them.

5.4.2.1 Items Needed

5.4.2.1.1 Lens Stacker

This design was designed to be fitted with lens holders and also accommodate a smartphone. The lens holders could be easily moved from one pot to another so as to vary the total magnification.

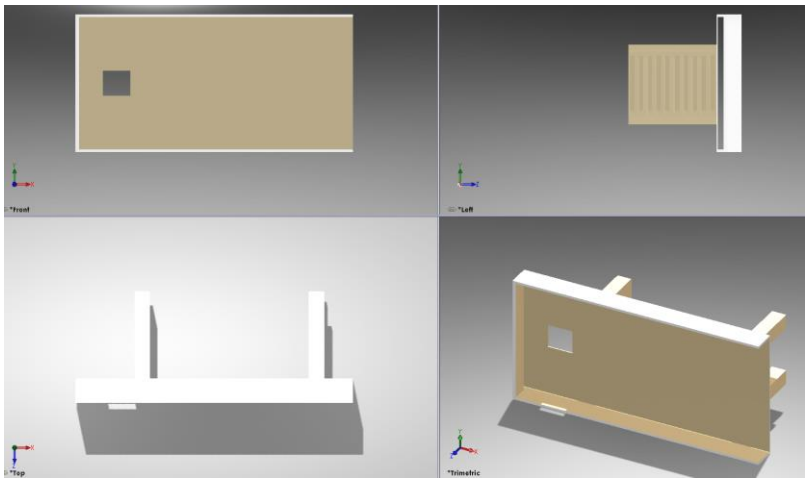

Figure 18:Lens Stacker

5.4.2.1.2 Lens Holders 1

These lens holders are designed to fit the available lenses. They are to hold the lenses in position to form linear correlation. There are three individual pieces to hold and align 2 lens of different dimensions;

1. Lens Holder 1: This lens is to be fitted with lens 1 above.

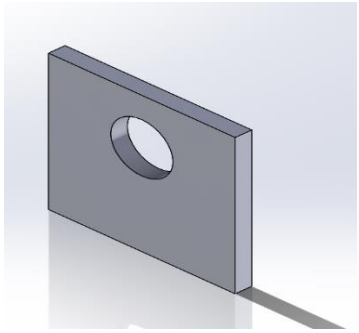

Figure 19: Lens holder 1

2. Lens Holder 1A and Lens Holder 1B: These lens holders are meant to work together to hold Lens 2 in Figure 22 to align with the other lenses.

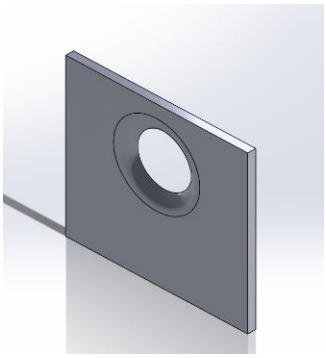

Figure 20: Lens holder 1A

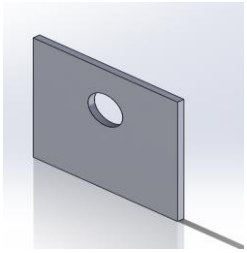

Figure 21: Lens holder 1B

5.4.2.1.3 Lenses

In addition to Lens 1 above, other cheap lenses were sourced for this project. They are:

Lens 2: A plano-convex lens harvested from an obsolete Linux camera.

Figure 22: Lens 2

Lens 3: This is a biconvex lens with a 12X magnification. Two of them were made available for the project.

Figure 23: Lens 3

5.4.2.2 Processes

5.4.2.2.1 Guidelines for Appropriate Stacking of Multiple Lenses

- The objective type employed in this analysis was the infinite corrected objective as discussed above. This was due to the need for utilization of other lenses that would serve as tube lenses, and more importantly, this project was designed based on available lenses; and the said lenses are effective when placed so that the focal length was equal to the object distance.
- It could be deduced from the discussions about the components of microscope and especially the Figure 4 above which gives detailed gives illustration about how the available lenses ought to be positioned within the objective, and thus given the two available plano-convex lenses for this project, the arrangement would be in such as a way as:
    - The flat surface of the smallest plano-convex lens faces the object
    - Followed by a wider plano-convex lens.

5.4.2.2.2 Stacking Analysis

1. Lens holders were fitted with their corresponding lenses.
2. The lens stacker was then stacked with these lens holders, guided by the guidelines as stated above.
3. An object of length 0.8 mm was observed under the setup

4. The intervals between the lenses were varied along the pots of the stacker until an apparent highest magnification was achieved.
5. The linear intervals of stacking combinations that provided the highest magnification was recorded as in **Error! Reference source not found.** below, to serve as dimensional guides for the design of the Project Design 2.

5.4.2.3 Results

The table below shows the outcome of the analysis from the stacking exercise:

Table 4: Results of lens stacking analysis

Lenses	**Distance from object /mm**
Lens 1	1.0
Lens 2	2.5
Lens 3a	57
Lens 3b	77

Consequently, the result for the magnification was calculated as follows:

Object height = 0.8 mm

Attained image height = 115.1 mm

$$Magnification = \frac{Image\ height}{Object\ height}$$

Therefore, $Magnification = \left(\frac{115.1\ mm}{0.8\ mm}\right) = 143.875$

That is, an approximately 144X magnification resulting as the outcome from the experiment.

5.4.3 Project Design 2

The stacking experiment provided basis for the dimensional designing of the Project Design 2. Differences between design concept of project design 2 and project design 1 are that:

1. There were changes in the size which were necessitated by the addition of tube lenses and objective lens
2. The phone platform was incorporated into a single design, as there would not be the need to screw a lens into the tube from above.

The resultant design is seen below:

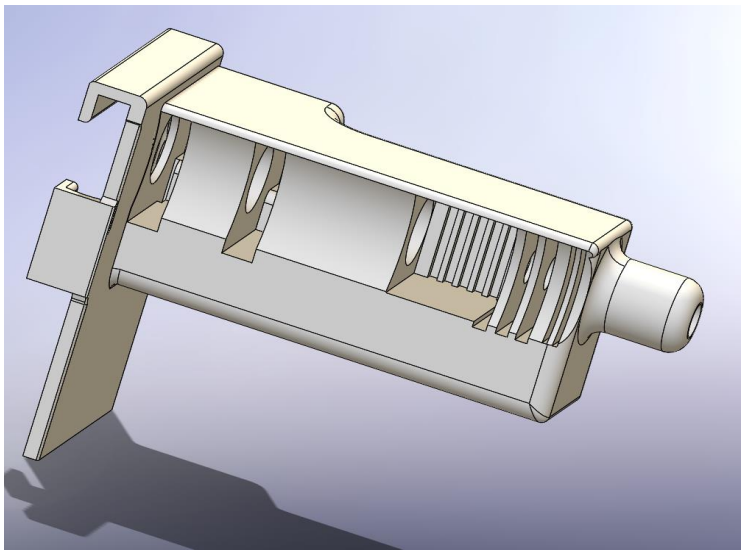

Figure 24: Project Design

Relative to the illustration of the composition of microscope as seen in Figure 4, below is the parts and composition of the design:

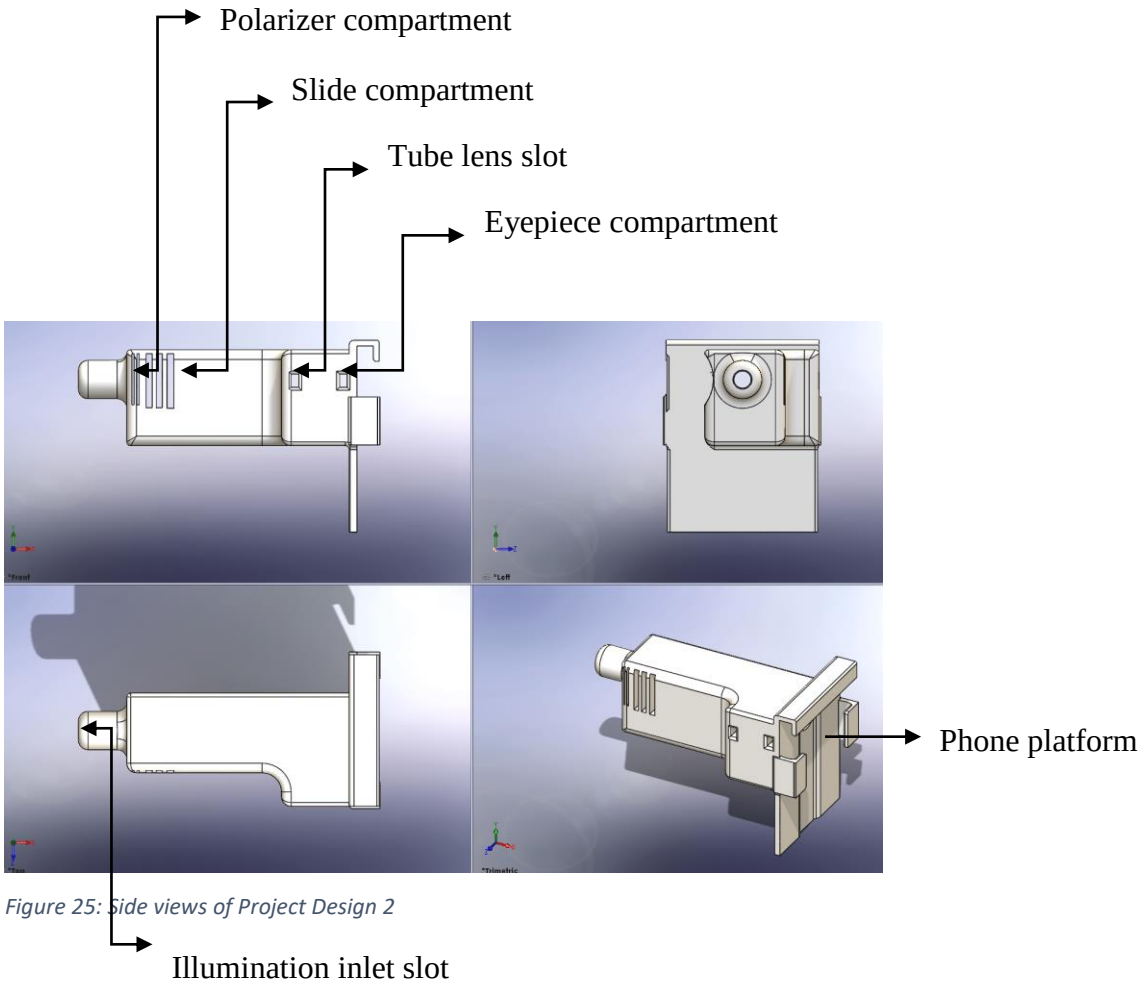

Figure 25: Side views of Project Design 2

5.4.3.1 Complementary Accessories

5.4.3.1.1 Lamp Holder

A lamp holder was design and produced; to serve as a platform to hold the illumination source – an LED torchlight. This part was designed to align with the illumination inlet of the main body.

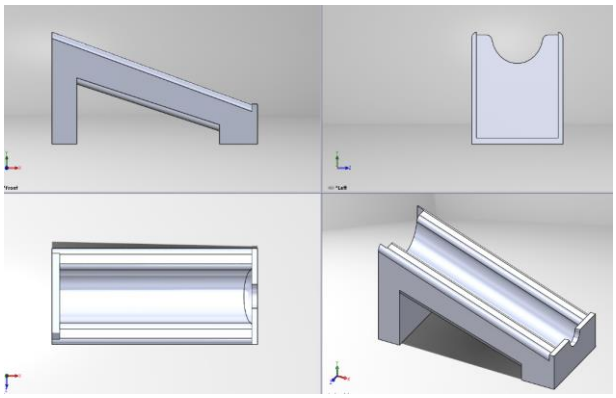

Figure 26: Lamp holder

5.4.3.1.2 Updated lens holders

The lens holders were adjusted to suit the new dimensions of the improved project design. Below is a compiled set of all three holders used in the final product output.

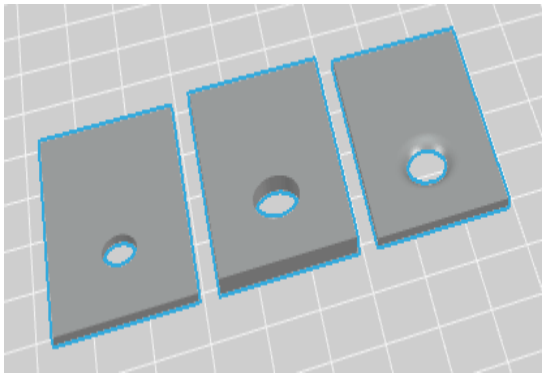

Figure 27: Lens holders

5.4.3.2 Implementation

5.4.3.2.1 Assembly

1. Lens holders are fitted with the corresponding lenses after thorough cleaning with lens wipers, and placed in their designated pots – according to the resultant dimensions as obtained in **Error! Reference source not found.** above.
2. The smartphone would then be fitted into its designated platform

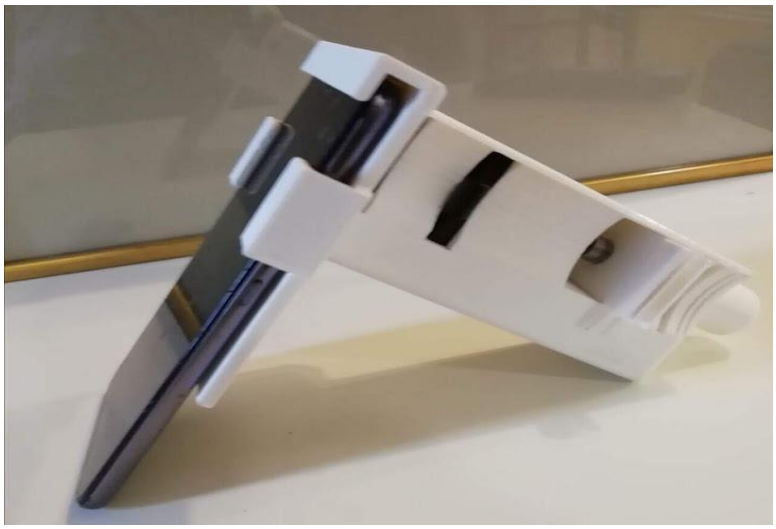

Figure 28: The assembled outlook of the project output

5.4.3.2.2 Testing

1. The sample used in this project for this testing was a strand of human hair of about 70 μm in diameter – placed onto a standard microscopic slide and held in place with a transparent adhesive tape.
2. The illumination source, a LED torchlight, would be fitted into the lamb holder; which would then be aligned with the illumination inlet.
3. Two polarizer sheets would have to be inserted at 90 degrees to each other to generate linearly polarized light
4. The camera of the smartphone was then turned; and zoomed to focus on the object, and subsequent image capturing.

5.4.3.2.3 Result and Analysis

The resultant image is shown below:

Figure 29: Image of a magnified 70 µm human hair

The follow could be deduced from the image above:

1. The resultant image measures about 9.7 mm on the screen of the smartphone, thus: $Magnification = \left(\frac{0.070\ mm}{9.7\ mm}\right) = 137X$

2. The absence of a diffuser affected the quality of the image; as the diffuser would have permitted homogenous illumination across the sample to reduce the blurredness.
3. Also, absence of zooming and focusing capabilities within the design implied the reliance on the smartphone for the quality of imaging. Consequently, the capacity of the smartphone camera – in terms of its megapixel limitations and focusing abilities influences the image quality.
4. Handling of the lenses created some scratches which affected the clarity of the image

6 CONCLUSION

The project was designed and implemented based on the available lenses, and thus the resultant magnification. The microscopy objectives concept which formed the basis for the design concept involved with Project Design 2 allows for addition of extra tube lenses to enhance magnification. Therefore, further improvements could be made in the future to achieve even higher magnification and resolution.

However, WHO recommends 1000X magnification for efficient malaria diagnosis. And the least size of malaria parasite is around 0.001 mm; but the unaided eye can see a 0.1 mm object. Therefore, achieving about 140X magnification; for a 0.14 instead of the recommended 1.0 mm is appreciable.

7 BIBLIOGRAPHY

Abreha et al, .., 2014. Malaria diagnostic capacity in health facilities in Ethiopia. *Malaria Journal,* July.

Attu, H. & Adjei, J. K., 2018. Local knowledge and practices towards malaria in an irrigated farming community in Ghana. *Malaria Journal,* 4 April.

Autodesk, 2018. *CAD SOFTWARE.* [Online]
Available at: https://www.autodesk.com/solutions/cad-software
[Accessed 14 May 2018].

Boadu, N. Y., Amuasi, J. H., Ansong, D. & Yanow, S. K., 2016. Challenges with implementing malaria rapid diagnostic tests at primary care facilities in a Ghanaian district: A qualitative study. *Malaria Journal ,* February .

CDC, 2018. *Treatment of Malaria: Guidelines For Clinicians (United States).* [Online]
Available at: https://www.cdc.gov/malaria/diagnosis_treatment/clinicians1.html
[Accessed 30 May 2018].

Citibusinessnews Ghana, 2018. *Ghanaians among top smartphone users in Africa.* [Online]
Available at: http://citifmonline.com/2018/03/17/ghanaians-among-top-smartphone-users-in-africa/
[Accessed 15 May 2018].

Dagadu, S., 2017. *Improving access to healthcare in Ghana's remotest locations* [Interview] 2017.

Digital School, 2015. *A Quick Guide to Designing CAD Files for 3D Printing.* [Online]
Available at: https://www.digitalschool.ca/a-quick-guide-to-designing-cad-files-for-3d-printing/
[Accessed 14 May 2018].

Dr Rao, T. V., 2012. *Malaria.* [Online]
Available at: https://www.slideshare.net/doctorrao/malaria-13558965
[Accessed 30 May 2018].

Edmund Optics , 2018. *Understanding Microscopes and Objectives.* [Online]
Available at: https://www.edmundoptics.eu/resources/application-notes/microscopy/understanding-microscopes-and-objectives/
[Accessed 6 June 2018].

England, R., 2018. *3D-printed smartphone microscope is good enough for scientists.* [Online]
Available at: https://www.engadget.com/2018/02/20/3d-printed-smartphone-microscope-is-good-enough-for-scientists/
[Accessed 1 April 2018].

Formlabs 3D Printer, 2016. *Creating Camera Lenses with Stereolithography.* [Online]
Available at: https://formlabs.com/blog/creating-camera-lenses-with-stereolithography/
[Accessed 14 May 2019].

Garcia, R., 2015. *Texas A&M technology transforms cell phone into high-powered microscope.* [Online]
Available at: https://engineering.tamu.edu/news/2015/08/25/cell-phone-microscope.html
[Accessed 6 June 2017].

Ghana Health Service, 2017. *National Malaria Control Programme.* [Online]
Available at: http://www.ghanahealthservice.org/downloads/2017-1st_Quarter_Bulletin.pdf
[Accessed 14 April 2018].

Giang, K., 2019. *PLA vs. ABS: What's the difference?.* [Online]
Available at: https://www.3dhubs.com/knowledge-base/pla-vs-abs-whats-difference
[Accessed 24 April 2019].

Hoek, M., 2018. *The Trillion Dollar Shift.* New York: Routledge.

Karlen, W., 2014. *Mobile Point-of-Care Monitors and Diagnostic Device Design.* Vancouver: s.n.

Keck, L., 2016. *What is the relation between magnification and focal length?.* [Online]
Available at: https://www.quora.com/What-is-the-relation-between-magnification-and-focal-length
[Accessed 30 May 2018].

Kwalus, 2013. *A Fully Printable Microscope.* [Online]
Available at: https://www.thingiverse.com/thing:77450
[Accessed 1 April 2018].

Malaria Site, 2015. *Microscopic Tests.* [Online]
Available at: https://www.malariasite.com/microscopic-tests/
[Accessed 28 April 2018].

Marin, J., 2018. *How to Choose the Right 3D Printing Process and Materials for Your Application.* [Online]
Available at: https://www.appliancedesign.com/articles/96040-how-to-choose-the-right-3d-printing-process-and-materials-for-your-application?v=preview&fbclid=IwAR2_rp3pmkBffhwo1VhKHiUr8nYZQyOTbH4j58o36ps5BDisyk7DU6MbGFw
[Accessed 18 April 2019].

Matinde, V., 2016. *Africa 2017: Smartphone penetration, Open Data and less online freedom.* [Online]
Available at: http://www.idgconnect.com/blog-abstract/23175/africa-2017-smartphone-penetration-open-data-online-freedom
[Accessed 15 May 2018].

Panasonic, NA. *Lens Focal Length and F-stop.* [Online]
Available at: https://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow11.html
[Accessed 26 April 2019].

Petrovski, D., 2015. *This is How Lens Parameters Affect Your Photographs.* [Online]
Available at: https://www.lightstalking.com/lens-parameters/
[Accessed 24 May 2018].

Pirnstill, C. W. & Coté, L. G., 2015. Malaria Diagnosis Using a Mobile Phone Polarized Microscope. *Scientific Report.*

Radcliffe, S., 2017. *The Focal Length of Microscope Objectives.* [Online]
Available at: https://sciencing.com/focal-length-microscope-objectives-8596901.html
[Accessed 6 June 2018].

Senoo, C., 2017. *214 million cases of malaria recorded globally - Report.* [Online]
Available at: https://www.ghanaweb.com/GhanaHomePage/health/214-million-cases-of-malaria-recorded-globally-Report-531143
[Accessed 14 April 2018].

Statista, 2018. *Smartphones - Statistics & Facts.* [Online]
Available at: https://www.statista.com/topics/840/smartphones/
[Accessed 15 May 2018].

Stratasys , 2019. *WHAT IS 3D PRINTING?.* [Online]
Available at: https://www.stratasysdirect.com/resources/tutorials/what-is-3d-printing
[Accessed 18 April 2019].

The Guardian Labs, 2017. *Childhood mortality: six killer diseases and how to stop them.* [Online]
Available at: https://www.theguardian.com/breakthrough-science/ng-interactive/2017/jun/27/childhood-mortality-six-killer-diseases-and-how-to-stop-them
[Accessed 15 February 2018].

UNICEF , 2016. *Health.* [Online]
Available at: https://www.unicef.org/health/index_malaria.html
[Accessed 15 Febraury 2018].

UNICEF, 2016. *Supplies and Logistics.* [Online]
Available at: https://www.unicef.org/supply/index_40962.html
[Accessed 7 April 2018].

UNICEF, 2018. *Child Survival: Under Five Mortality.* [Online]
Available at: https://data.unicef.org/topic/child-survival/under-five-mortality/
[Accessed 26 February 2018].

University of Utah , N.A. *Cell Size and Scale.* [Online]
Available at: https://learn.genetics.utah.edu/content/cells/scale/
[Accessed 19 April 2019].

WHO, 2015. *How malaria RDTs work.* [Online]
Available at: https://www.who.int/malaria/areas/diagnosis/rapid-diagnostic-tests/about-rdt/en/
[Accessed 15 May 2019].

WHO, 2016. *Malaria Microscopy: Quality Assurance Manual ,* s.l.: WHO.

Wobith, M., 2019. *3D Printer Scanner – What Is It Exactly?.* [Online]
Available at: https://all3dp.com/2/3d-printer-scanner-what-is-it-exactly/
[Accessed 19 April 2019].

World Bank Group, 2016. *World Development Report 2016: Digital Dividends.* Washington DC: s.n.

World Health Organization, 2017. *Malaria.* [Online]
Available at: http://www.who.int/malaria/media/world-malaria-report-2017/en/
[Accessed 15 February 2018].

World Health Organization, 2018. *Malaria: Microscopy.* [Online]
Available at: http://www.who.int/malaria/areas/diagnosis/microscopy/en/
[Accessed 24 April 2018].

8 APPENDICES

Affordable	Bearing a cost that is not too high
Accessory	An object that adds to the effectiveness of something else
Diagnosis	The art of identifying a disease from its signs and symptoms
Efficient	Productive of desire results
Stacking	An orderly pile or arrangement
FDM	Fused Deposition Modelling
MOPID	Mobile-Optical-Polarization Imaging Device
PLA	Polylactic Acid
RDT	Rapid Diagnostics Test