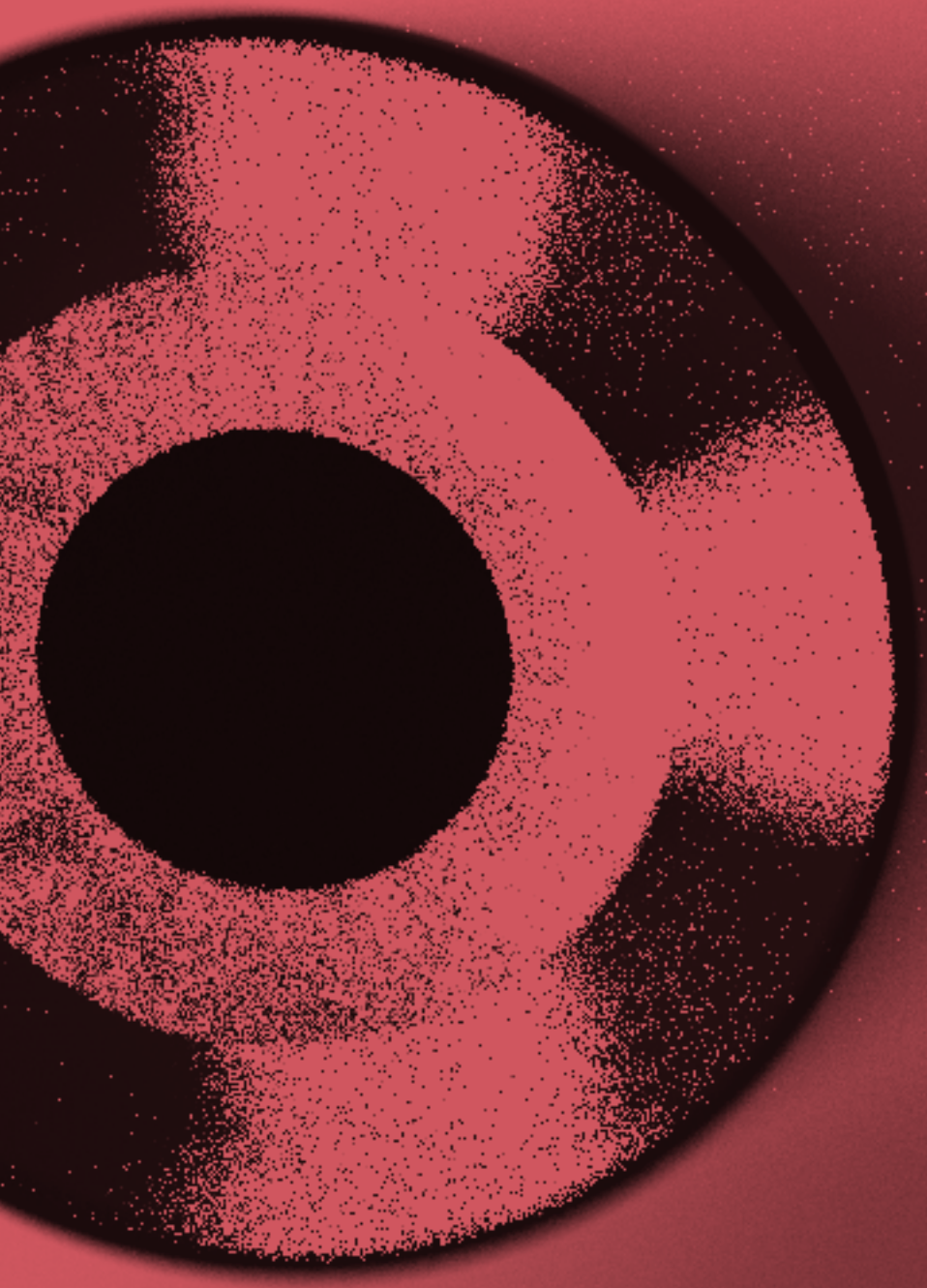
Low-cost endoscope design for AI-based cervical cancer detection

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MASTER GRADUATION THESIS

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0. Executive summary

0.1 Context

Cervical cancer remains a major global health crisis as annually over 350,000 women succumb to the disease with more than 90% of these deaths occurring in low and middle-income countries (LMICs). This thesis focuses particularly on Ethiopia where it is a leading cause of cancer mortality among women, along with breast cancer. In 2023 alone, Ethiopia recorded an estimated 8,168 new cases and 5,975 deaths.

One of the important methods in the prevention of cervical cancer is by having regular screenings, where pre-cancerous lesions can be detected. The primary obstacles to effective screening in LMICs like Ethiopia include severe shortage of specialised gynaecologists, an overburdened medical infrastructure and large geographical distances to healthcare centres, forcing many patients to travel an average of 239 km, with extremely long wait periods to reach tertiary care facilities. Existing low-cost visual inspection capabilities in regional health centres often suffer from inconsistency, highlighting the urgent need for a more reliable, decentralised and accessible diagnostic approach.



Figure 0.0: Original C-spec design with camera channel

0.2 Focus Of The Thesis

The focus of this project is to develop a low-cost, AI-assisted cervical endoscope system designed to revolutionise early detection of cervical cancer in Ethiopia's primary and secondary healthcare settings. The project integrates and builds upon the outcomes of related research projects to create a complete diagnostic system for screening. The solution described in the thesis integrates optical systems, robust hardware, and diagnostic artificial intelligence in a cost-effective manner to support enhanced regional screening and diagnosis of cervical cancer. The hardware components were built from readily available, off-the-shelf components to ensure easy availability and easy replacement in case of a defect. The system is designed to consistently capture high-quality images. These images are used to create a dataset that enables further AI-based learning, allowing non-specialist healthcare providers, such as general practitioners and nurses in secondary hospitals or clinics, to perform accurate diagnoses. This approach aims to significantly reduce unnecessary referrals and alleviate the immense pressure on tertiary hospitals.

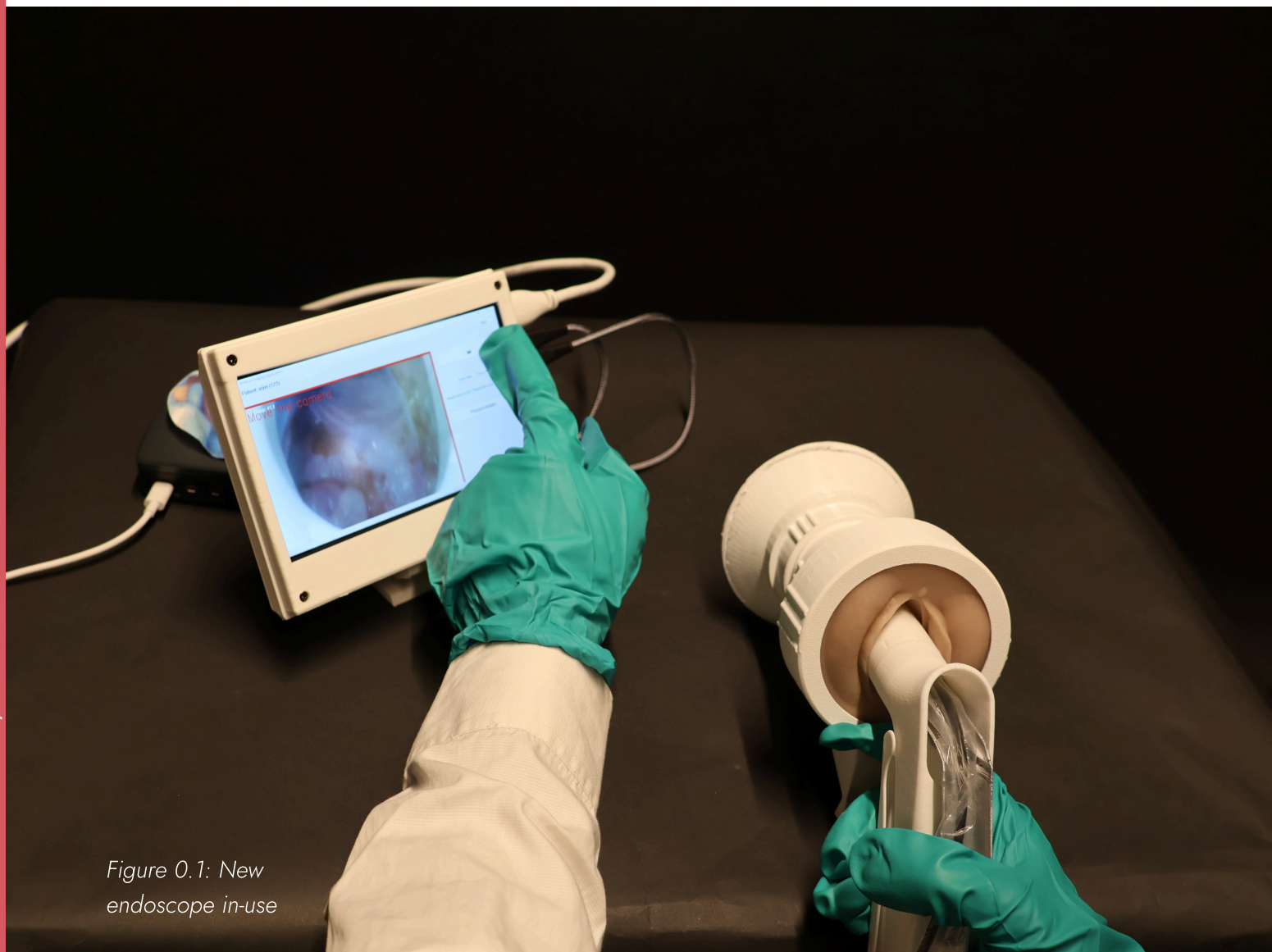


Figure 0.1: New endoscope in-use

0.3 Final Product

The final product is a compact, AI-assisted cervical imaging system designed for use in low-resource clinical settings. It combines:

- High-quality cervical imaging using a low-cost, off-the-shelf endoscope with cross-polarised lighting to reduce glare and improve visibility of the regions of interest.
- A stabilising camera guide that ensures repeatable positioning, protects against tissue contact, and leaves space for instrument access such as swabs or sprays.
- Real-time feedback that guides users (e.g., nurses) to adjust camera positions until optimal focus and sharpness are reached, even without specialist training.
- Offline-functioning with battery backup during power outages to allow for continued functionality
- AI-based classification of VIA/VILI images, enabling diagnosis of cervical cancer, while also allowing clinicians to review the images and identify patients who may need referral, improving early detection.
- Sterile-friendly design using easy to assemble/disassemble, cleanable components that can be disinfected or replaced easily without disrupting clinical workflows.
- Cost-effective, ensuring that the whole system costs less than 200 euros



Figure 0.2: Full screening kit

Chapter 1: Introduction

This chapter focuses on the pressure on low- and middle-income countries (LMICs) caused by cervical cancer. It provides an overview of the problem, background, major challenges, project objectives, and scope. The section emphasises the motivation for the research and the importance of reducing the burden on healthcare systems through AI-based interventions. It also introduces the context, motivation, and overarching goals of the research and product development. Additionally, related work and the methodology are discussed in this section.



1. Introduction

1.1 Motivation

Cervical cancer is one of the most preventable forms of cancer, yet it remains one of the leading causes of cancer-related deaths among women globally. Nearly all cervical cancers are caused by an infection with certain high-risk types of human papillomavirus (HPV)(NHS,2024). Highly effective prevention strategies, such as HPV vaccination and regular cervical screening followed by the treatment of pre-cancerous lesions, are well-established. However, the success of these interventions hinges on good implementation and widespread accessibility. While global initiatives are making progress in improving access to HPV vaccines, for this strategy to have the maximum impact, it needs to be accompanied by widespread screening and treatment services, particularly in the first few decades following vaccine rollout (CRUK, 2024).

Every year, more than 350,000 women die from cervical cancer, with over 90% of these deaths occurring in low and middle-income countries (LMICs) (International Agency for Research on Cancer, n.d.). Sub-Saharan Africa bears a disproportionately high burden, with 87% of deaths being from this region (Bray et al., 2018) (Figure 4). This disparity is due to systemic challenges in access and infrastructure.

Cervical cancer screening is critical to prevention as it enables the detection of high-grade cervical intraepithelial neoplasia (CIN2/3), the lesions most likely to progress to cancer (Sellors & Sankaranarayanan, 2003). However, conventional screening methods such as Pap smears or HPV testing (discussed in Section 2.2) often fail in resource-constrained settings due to a combination of individual and systemic barriers.

Studies have identified key individual or personal barriers, including limited awareness, cultural misconceptions, fear of cancer, and the belief that screening is unnecessary unless symptomatic (McFarland et al., 2016).

Systemic issues such as a shortage of specialists, inaccessible testing facilities, and the need for multiple follow-up visits make timely screening and treatment difficult for many women (Bruggen, 2024).

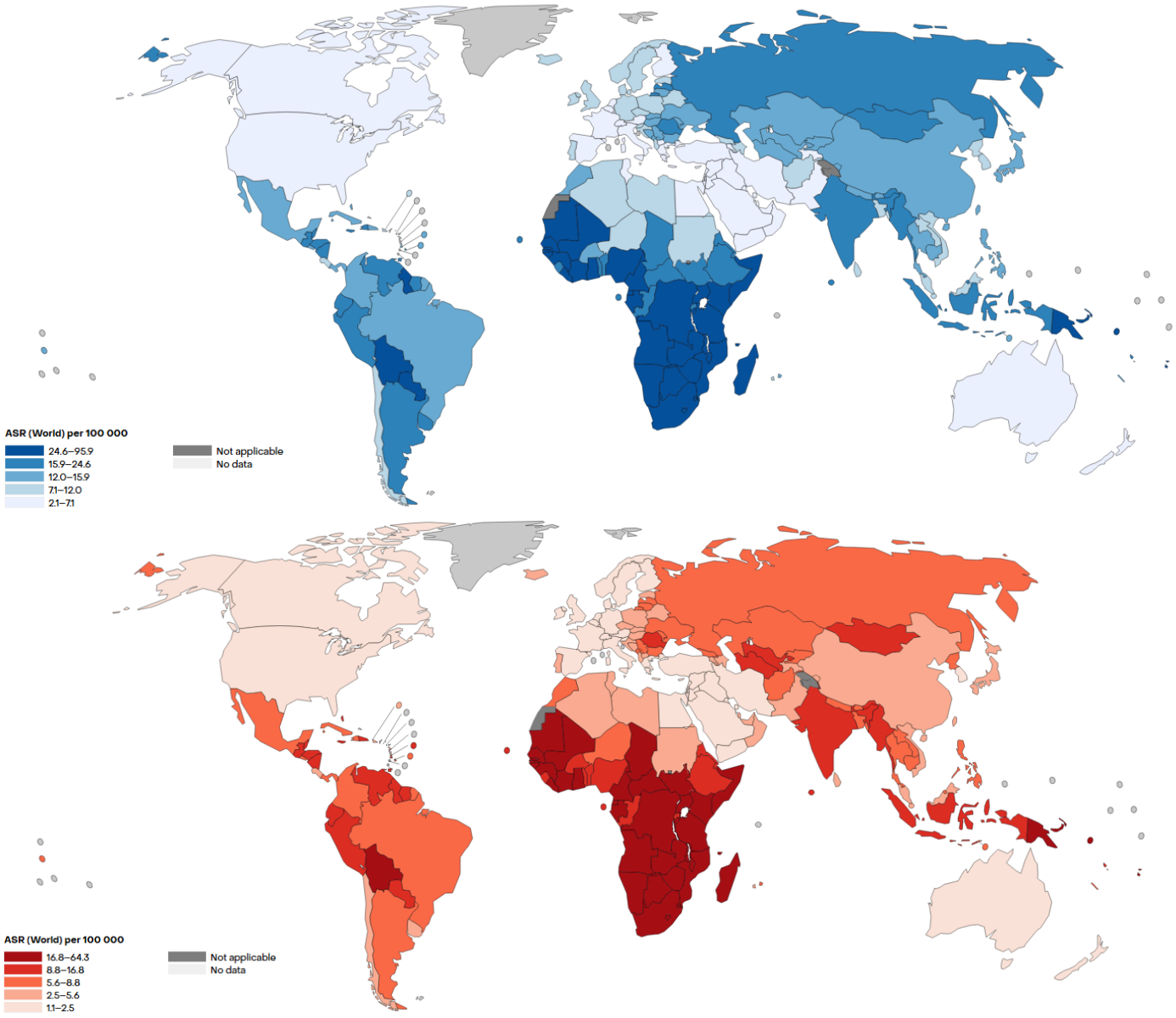


Figure 1.1: Age-standardised incidence (above) and mortality rates (below) of cervical cancer by country in 2022(International Agency for Research on Cancer [IARC], 2022)

1.2 The Ethiopian Context

Ethiopia represents a critical case in point. In 2023 alone, an estimated 8,168 new cases of cervical cancer were reported, with an incidence rate of 22.3 per 100,000 women and a mortality rate of 16.8 per 100,000 (CRUK, 2024). Projections from studies indicate that without scalable interventions, the disease will claim lives of 191,876 Ethiopian women between 2020 and 2070. The challenges Ethiopia faces are similar to those of broader LMIC contexts: high disease burden, low specialist availability and infrastructural limitations. Most women are screened by general practitioners or nurses rather than gynaecologists, and travelling to centralised hospitals for diagnosis and results poses significant logistical and financial burdens.

This thesis focuses on Ethiopia not only because of the country's urgent public health needs, but also due to ongoing PhD research in the field, existing partnerships with local stakeholders and health organisations that enable interactions with stakeholders for feedback. Furthermore, Ethiopia's healthcare system makes it a representative setting for testing scalable, low-cost cervical cancer screening innovations suitable for LMICs.

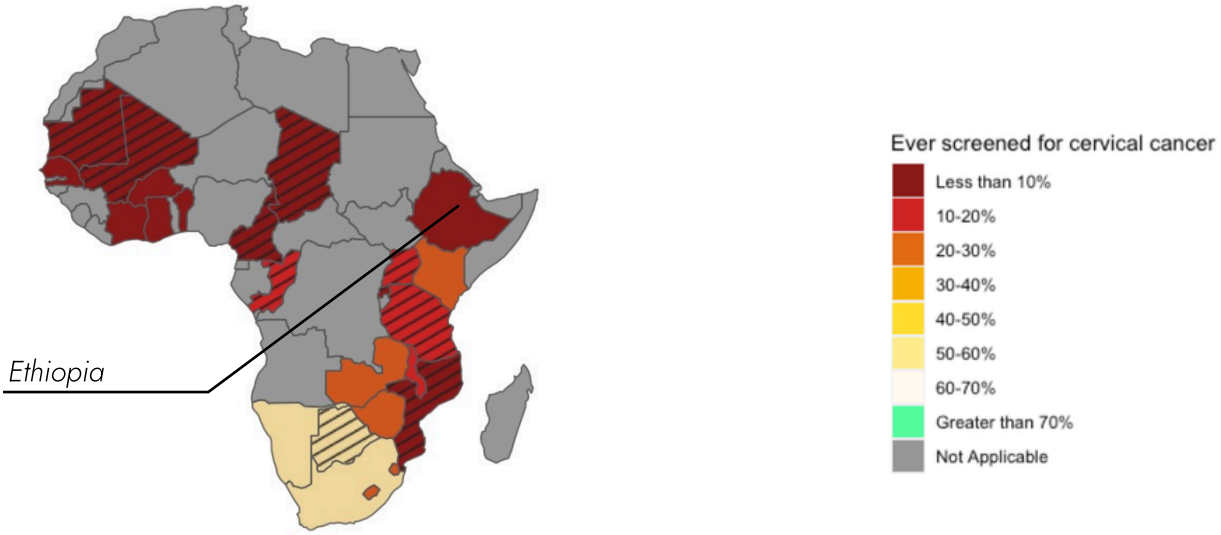


Figure 1.2: Map of the percentage of women aged 30–49 years reporting having been screened in their lifetime for cervical cancer in 2020.(Yang et al., 2023)

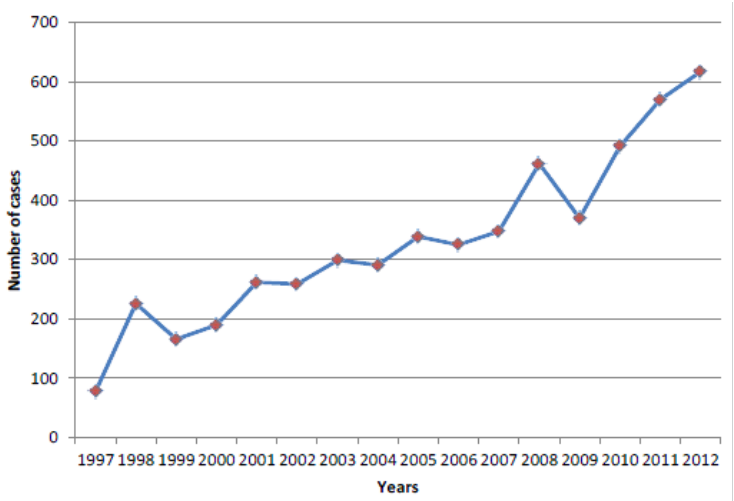


Figure 1.3: Trend of cervical cancer incidence in ethiopia

1.3 Project Goal And Research Question

The overarching goal of this project is to develop a low-cost cervical imaging device suitable for deployment in low and middle-income countries (LMICs). Building upon previous MSc research efforts (see Section 1.5), this work aims to integrate and refine existing components like an AI-assisted classification model and the C-Spec speculum to create a new and complete imaging system. The intended users are non-specialist healthcare providers in secondary care settings, where access to gynaecologists and advanced imaging equipment is often limited.

However, reaching this objective requires addressing a number of foundational questions. The key research question being:

Is it feasible to create a usable, robust and AI-supported cervical imaging device for LMIC screening contexts?

This can be further broken down into further sub-criteria:

Technical Feasibility:
How can image capture be optimised to ensure the best possible input for AI-based cervical lesion classification, keeping in mind the constraints of low-resource settings (e.g., power, connectivity, sterility and cost)?

Clinical Utility and Desirability:
What design and interaction features are essential to ensure that non-specialist healthcare providers can capture diagnostic-quality images reliably, consistently, conveniently and safely?

Deployment Viability:
How can the device integrate seamlessly into existing clinical practices in LMIC healthcare settings, especially where training and infrastructure are limited?

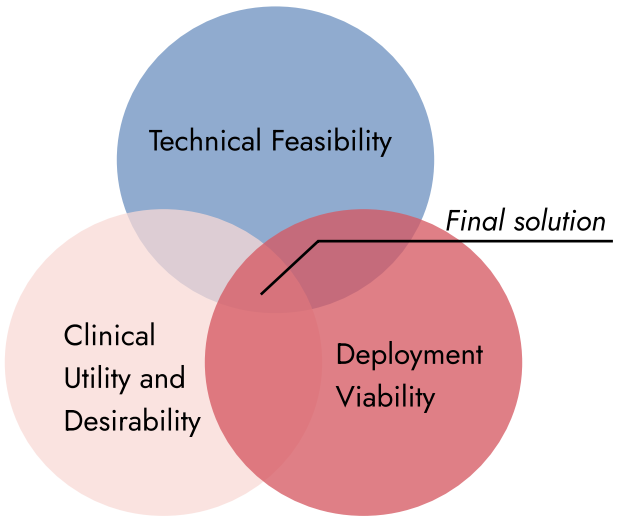


Figure 1.4: Desirability, feasibility viability Venn diagram

1.4 Scope

The project involved the building of the system, which utilises an off-the-shelf camera in scope:

Developed during the project

- Design of a guidance system for a camera to take repeatable images
- AI classification model fine-tuning for real-time cervical image analysis
- Hardware–software integration
- Camera modification for better image quality

Tested during the project

- Image quality improvements through lighting and positioning
- System usability validation with healthcare providers
- Clinical integration scenarios

Out of scope

- Redesign of the camera itself
- Major re-designs of the c-spec speculum
- Full clinical trials with real human subjects
- Sterility analysis
- Medical device risk assessment and analysis
- Training curriculum development



Figure 1.5: Interventions developed during the project surrounding the camera

1.5 Related Work

The project derives from and builds on top of two other projects conducted in the past. These were thesis projects undertaken at TU Delft in collaboration with GIC Space, a Cameroonian startup focused on improving access to cervical cancer screening. These thesis projects laid the foundation for both the hardware and AI components of a novel cervical imaging system aimed at use in low and middle-income countries (LMICs).

1.5.1 Redesigning the C-Spec

M.Hofstede's project is associated with the commonly used specula used in visual inspection-based screening. Recognizing that fear and discomfort are major barriers to women going for screenings, particularly in Cameroon, where only 6% of women aged 30–49 have ever been screened. This project focused on improving the C-Spec, a new type of speculum that opens only at the ends of the tubular structure (Figure 1.6) to allow cervix visualisation.

Her work introduced a redesigned mechanism with a speculum-style squeeze handle to intuitively control the flaps of the C-Spec, using a linear cam mechanism for ease of disassembly and sterilisation. This allowed healthcare providers to perform visual inspections more intuitively.

The interventions in this project are designed keeping this speculum design in mind, building to work with this particular instrument.

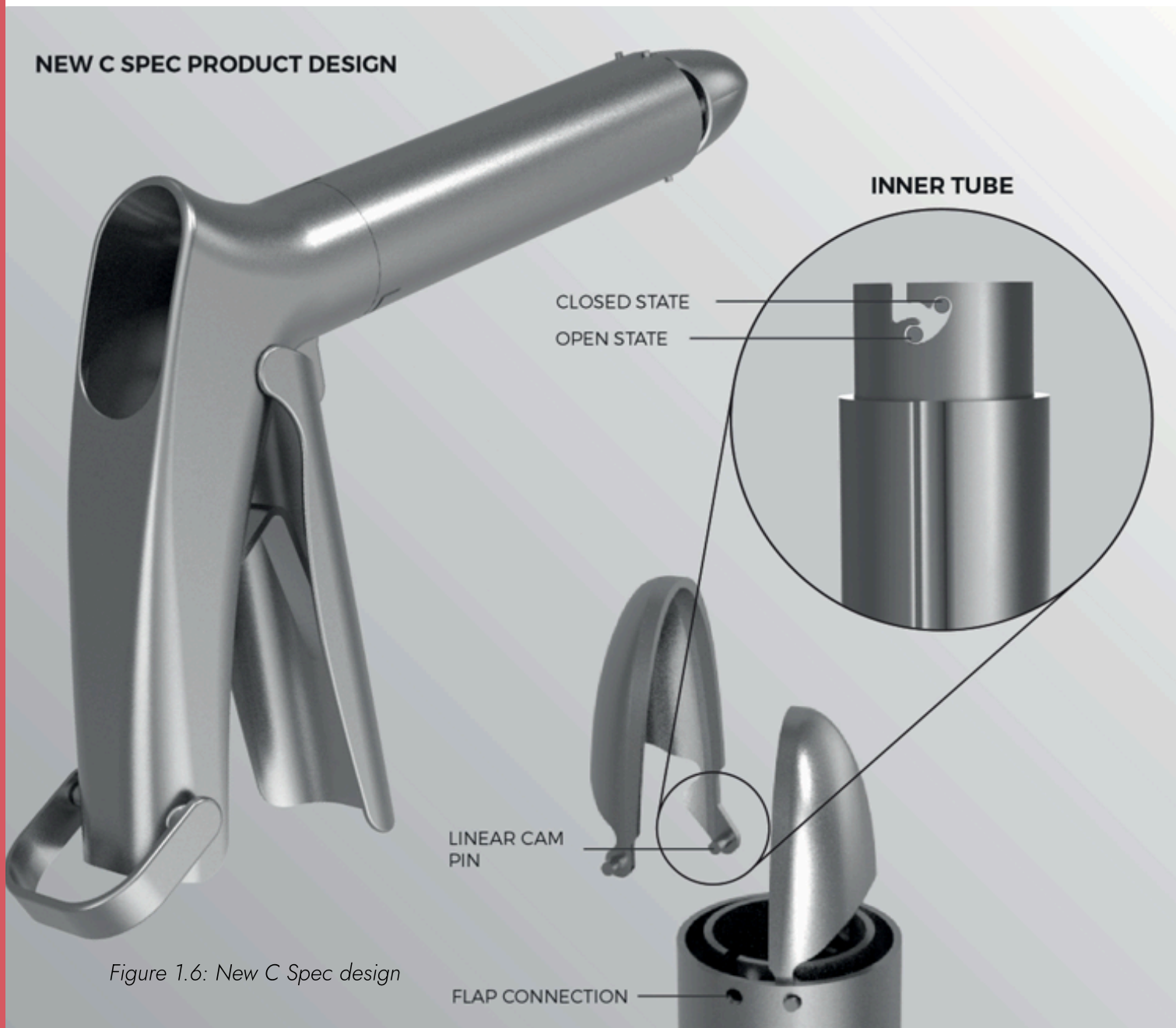


Figure 1.6: New C Spec design

1.5.2 AI-Assisted Screening: Enhancing Diagnostic Support

Marijke Spijk's thesis focused on the development of the AI model for diagnosis of cervical cancer. It tackled the variability and expertise-dependence of Visual Inspection with Acetic Acid (VIA), which is the most commonly used screening method in LMICs due to its low cost and simplicity (described in detail in section 2.2). Her work proposed an AI-driven screening pathway, evaluating three convolutional neural networks - EfficientNetB0, MobileNetV2, and YOLOv8n.

Among these, EfficientNetB0 emerged as the most promising, achieving a sensitivity of 0.71, specificity of 0.79, and AUC (Area under the curve) of 0.83, exceeding the WHO's benchmark of 60% accuracy(World Health Organization, 2021) for manual VIA sensitivity. The project concluded that AI integration could significantly improve diagnostic accuracy and consistency, potentially enabling a feasible "screen-and-treat" strategy, especially in contexts where follow-up visits are logistically challenging.

The AI model evaluated and developed during her project is the same one used in this project. The model she developed has been built upon and trained differently to achieve the intended goal of real-time usage by medical professionals and deployment in the field.

1.5.3 Building on efforts

While these projects made significant progress individually, they remained disjointed in application: one dealing with mechanical design and patient comfort, the other an AI model for diagnostic enhancement. This thesis seeks to integrate and add to both efforts by developing a complete cervical imaging device.

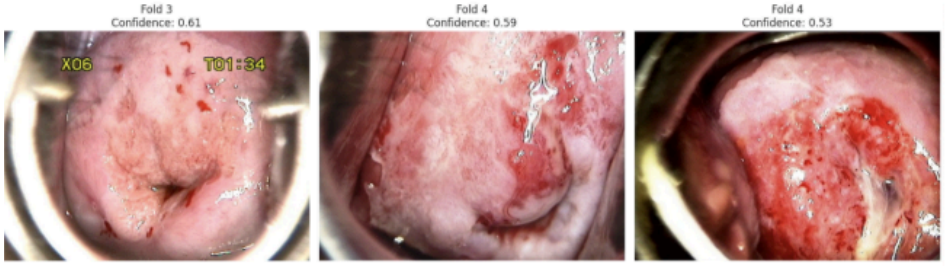


Figure 1.7: Suspicous for cancer classified images with confidence scores

	Accuracy Suspected Cancer	Accuracy VIA Positive	Accuracy VIA Negative	Sensitivity	Specificity	AUC
Overall	**0.59**	**0.59**	**0.79**	**0.71**	**0.79**	**0.83**

Figure 1.8: Overall Performance of EfficientNetB0.

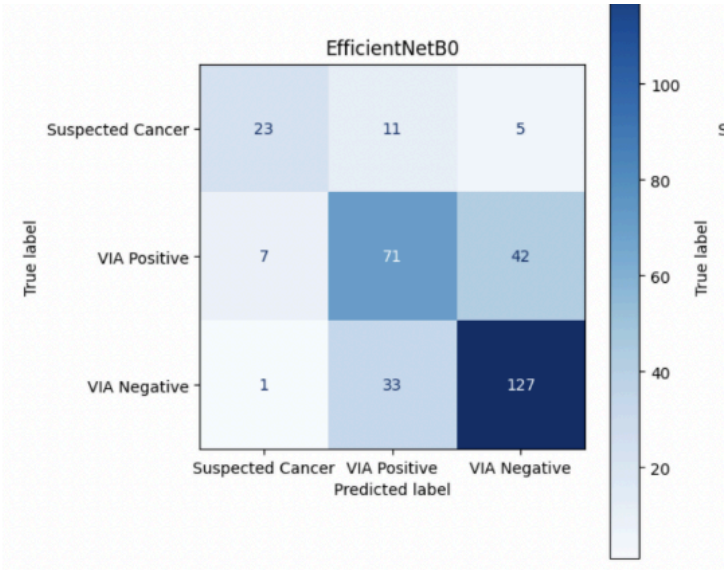


Figure 1.6: Overall Confusion Matrices

1.6 Design Methodology

This project followed a Double Diamond design approach, adapted for a technical medical device development based on previous research. The methodology consisted of two diamonds: the first focused on understanding and defining imaging requirements, while the second concentrated on developing and delivering an integrated solution.

1.6.1 First Diamond: Image Quality Optimization

Discover Phase

Building on extensive prior contextual research (Bruggen, 2024.), the project began with the exploration of cervical imaging challenges. This involved comprehensive experimentation in simulated environments with lighting and image analysis to understand the fundamental technical barriers to achieving a good image for AI training and diagnostic classification.

Define Phase

From the imaging experiments, specific technical requirements were defined. Key variables for optimal image quality were identified and this included lighting conditions, positioning requirements and other environmental constraints that would inform subsequent design decisions.

1.6.2 Second diamond: System integration and Validation

Develop Phase

With imaging parameters established, the project moved into parallel development streams:

· AI model development: Training and refinement of the AI for real-time usage based on previous studies using GradCAM mapping (detailed in section 8) and using the optimised imaging conditions identified in the first diamond.

· Hardware exploration: Investigating different camera guide mechanisms and integration with the C-spec.

· Stakeholder validation: Conducting targeted interviews with field-experienced practitioners to validate design assumptions and gather more requirements.

Deliver Phase

The final phase integrated all components into a working prototype. This involved porting the complete software solution onto a Raspberry Pi platform and integrating it with the mechanical guidance system to create a fully functional device ready for usability testing.

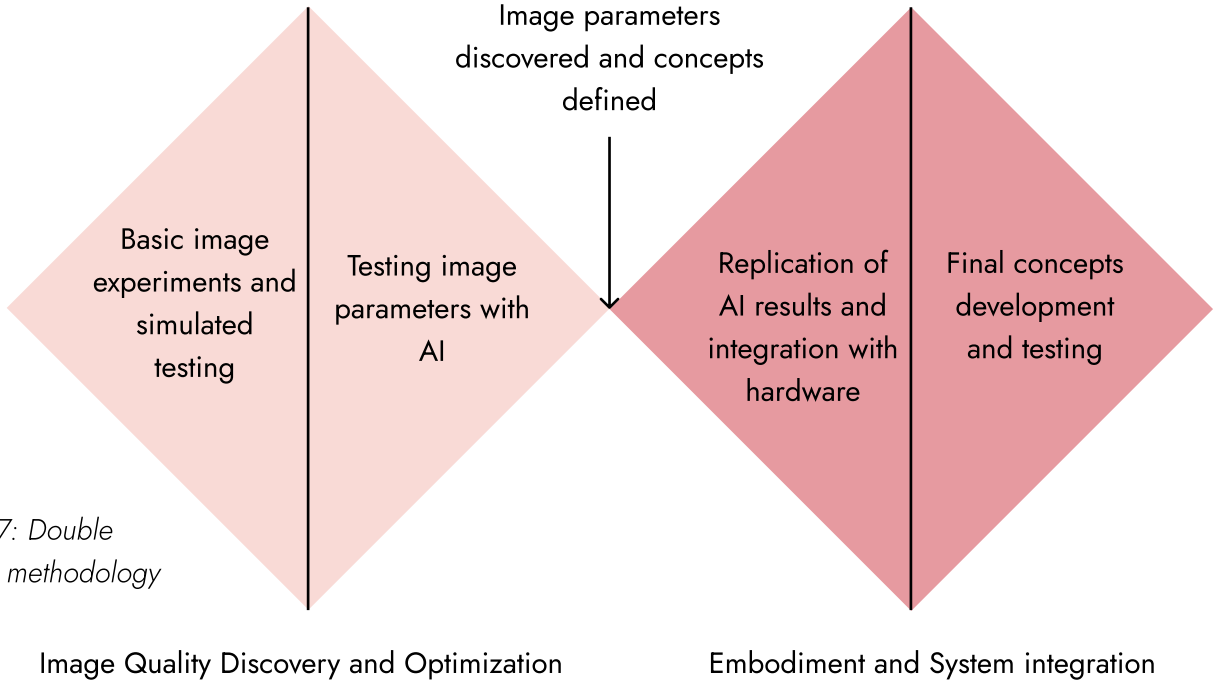


Figure 1.7: Double diamond methodology

1.7 Stakeholders

Various stakeholders were involved in the project in order to create and validate requirements and gain an understanding of the unfamiliar context. These stakeholders will be mentioned throughout the thesis.

Role	How Their Input Was Used	Stakeholders
Clinical Experts	Defined and tested usability, sterility, and orientation. Helped simulate the real usage scenario.	2 LUMC doctors with working experience in Ethiopia and other LMICs
Context Experts	Clarified the healthcare structure in Ethiopia and screening gaps between tiers.	Dr. Milkias – Junior doctor from Ethiopia who has completed his OBGYN rotation Netsanet, a PhD candidate from Ethiopia
AI Experts	Validated model architecture and supported design of the training process.	AI engineer from AIDx Medical
Medical Device Experts	Helped in understanding sterilisation requirements and requirements to create a robust device	A medical device designer from Layco

1.8 Reading Guide

There could be multiple approaches to read the thesis depending on what you as the reader would like to get out of it

Key:

🟢 Quick Overview: For readers who want a quick and high-level understanding of the project's problem, solution, and impact.

🔵 Technical Focus: For readers interested in the technical engineering, AI, and design methodologies.

🔴 Clinical Perspective: For readers focused on the medical context, patient journey, and usability within the healthcare context.

Chapter No.	Chapter Title	Recommended Reading Paths
0	Executive Summary	🟢
1	Introduction	🟢 🔴 🔵
2	Medical & System Context	🔴
3	System Design Objectives	🟢 🔴
4	Imaging experiments	🔵
5	Hardware Design Development	🔵
6	AI Model Design & Training	🔵
7	Integrated System	🟢 🔴
8	Evaluation	🔵
9	Reflection & Future Work	🔴
10	Conclusion	🟢
11	References	
	Appendices	

Chapter 2: Medical and System Context

Understanding this project requires an understanding of the clinical and systemic challenges it addresses. This chapter provides a detailed discussion of the disease, including its progression and the clinical significance of early detection. Following that an exploration of the various diagnostic tests used to detect cervical cancer screening, with particular emphasis on Visual Inspection with Acetic Acid and Lugol's Iodine (VIA/VILI) methods that are important for the project's AI development, is conducted.

The chapter also discusses the Ethiopian healthcare system, mapping its three-tier structure and examining the specific challenges that create barriers to effective cervical cancer screening. This helps identify the intervention points where technology can meaningfully address existing gaps.

To understand the basis of this work within the bigger picture of cervical cancer screening projects and past projects conducted, closely related projects and previous research efforts by students of the TU Delft Masters programme are discussed in more detail.

Finally, insights from key stakeholder interviews with clinicians, healthcare administrators, and technical experts provide crucial context about real-world implementation challenges and design requirements.

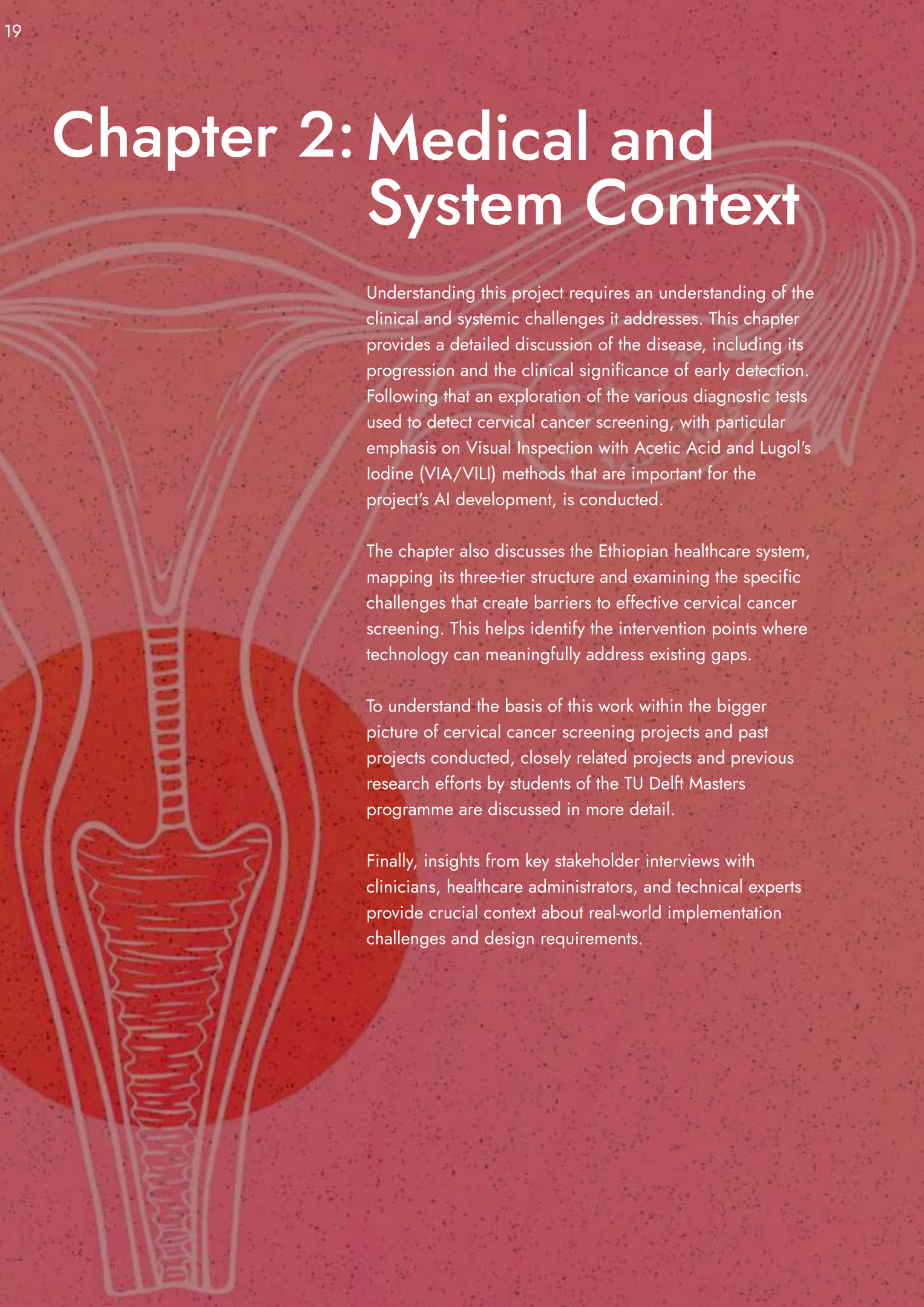


Image source:What Are the Signs of Cervical Cancer?(Kuschmider, 2023)

2. Medical and System Context

2.1 Cervical Cancer : The Disease

Cervical cancer originates in the cells of the cervix, the lower, narrow portion of the uterus that serves as the critical junction between the uterus and the vagina (Figure 2.1). This is a small but anatomically significant structure that performs essential functions like regulating fluid passage and serving as the birth canal opening during delivery.

The cervix comprises several distinct anatomical regions, each with a specific clinical significance:

- **Internal OS**: The opening that connects to the uterine cavity. (In the cervix, "os" refers to the opening or orifice; it is not an acronym)
- **Endocervical Canal**: The narrow tunnel extending from the internal OS toward the vagina
- **Ectocervix**: The visible portion that protrudes into the vaginal vault
- **External OS:** The opening leading to the vagina
- **The Transformation Zone (TZ)** represents the most clinically critical area where the endocervical canal meets the ectocervix. This junction is where the majority of cellular changes occur, making it the primary focus for screening procedures and the target region for both clinical examination and AI-based diagnostic systems developed in this project.

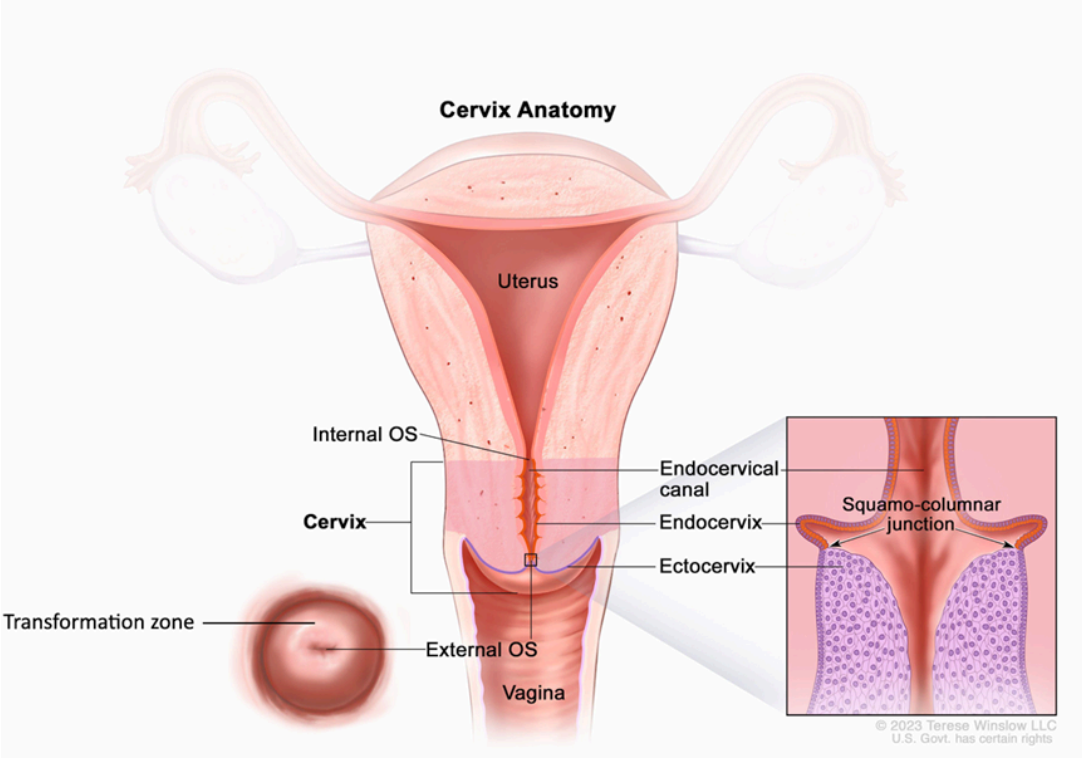


Figure 2.1: Cervix anatomy diagram

2.1.1 Progression of cervical cancer

Before invasive cancer develops, cervical cells undergo abnormal changes called dysplasia or Cervical Intraepithelial Neoplasia (CIN). These precancerous lesions are classified based on severity:

- CIN 1 (Low-grade Squamous Intraepithelial Lesion - LSIL): Mild dysplasia that often regresses spontaneously without treatment
- CIN 2-3 (High-grade Squamous Intraepithelial Lesion - HSIL): Moderate to severe dysplasia requiring close monitoring and repeated treatments, as these lesions have higher progression potential to become an invasive cancer

As noted by clinical experts: "Generally for CIN 1 it does regress on its own and for 2,3 we need to pay attention since it could become a cancer" (Interview with Dr. from LUMC, 2025).

2.1.2 Cancer Staging and Prognosis

Once invasive cancer develops, staging determines the extent of disease spread and directly correlates with survival outcomes. The table(Table 2.1) shows cervical cancer staging with the survival rate (Cervical Cancer Stages, 2025)

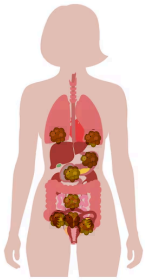
Stage	Description	5-Year Survival Rate	
Stage 1	Microscopic cancer confined to cervical tissues	80-99%	
Stage 2	Cancer spread beyond cervix, not reaching pelvic wall or lower vagina	60-90%	
Stage 3	Cancer involving pelvic wall, lower vagina, or causing kidney dysfunction	30-50%	
Stage 4	Cancer spread to bladder, rectum, or distant organs	~20%	

Table 2.1: Trend of cervical cancer incidence in ethiopia

2.1.3 The Critical Window for Intervention

The dramatic difference in survival rates between early and late-stage disease underscores the vital importance of early detection(Table 2.1) . Detection of Stage 0 (pre-cancer) and Stage 1 cancers offers:

- Excellent survival outcomes with 5-year survival rates approaching 100%
- Less invasive treatment options that can preserve fertility
- Reduced treatment costs and healthcare system burden
- Better quality of life during and after treatment
- Prevention of progression to life-threatening advanced disease

The device is specifically developed to target the detection of Stage 0 and Stage 1 disease, focusing on identifying precancerous lesions and early invasive cancers when intervention is most effective. The transformation zone's accessibility through visual inspection methods makes it an ideal target for image-based AI-assisted diagnostic systems designed to support healthcare providers in resource-limited settings.

2.2 Screening Methods

Screening is essential for early detection and prevention of cervical cancer. Various screening methods are available, each with distinct advantages and limitations. In this section some of the most common methods are discussed.(Figure 2.2 of the methods)

1. **Visual Inspection with Acetic Acid (VIA) and Visual Inspection with Lugol's Iodine (VILI):** VIA/VILI represents the most common screening approach in low-resource settings due to its simplicity and cost-effectiveness (Bruggen, 2024). This method requires minimal equipment and can be performed through visual inspection alone (Parashari et al., 2015), enabling decentralised testing in areas with limited healthcare equipment. The accessibility of VIA/VILI makes it particularly valuable for LMIC settings where more sophisticated diagnostic equipment may not be readily available.
2. **Colposcopy:** This is considered the gold standard for visual-based inspections (Nam & Korean Society of Obstetrics and Gynecology, 2018). The procedure involves the use of a special lighted microscope by the doctor to take a close look at the tissue lining the cervix. Tissue samples of any concerning areas are collected and tested in a lab. However, the high cost of colposcopic equipment (approximately €8,500) limits its availability in resource-constrained settings, making it only accessible in well-equipped medical facilities.
3. **Pap Smear:** The Pap smear involves the collection of cervical cells through gentle scraping, which are then sent to a laboratory for microscopic examination to detect precancerous and cancerous changes. While this method has been widely used in developed countries, the lack of facilities in low-resource settings prevents its widespread adoption.
4. **HPV DNA:** The HPV DNA screening method involves testing for the presence of human papillomavirus (HPV) using vaginal mucus samples. Since cervical cancer originates from a persistent HPV infection (WHO, 2022), the World Health Organisation (WHO) has recommended switching to this mode of testing over the long term due to its effectiveness in detecting and preventing cervical cancer, providing an objective diagnosis free from human error. However, the infrastructure is not yet in place to support this switch.
5. **Biopsy:** The doctor can remove cervical tissue and test it for signs of cancer. The tissue is obtained through the cutting of a piece of the cervix (Professional, 2025). While this procedure offers the highest reliability for cancer detection, they are also the most invasive and are typically reserved as the final diagnostic step when other screening methods indicate suspicious or positive cancer presence.



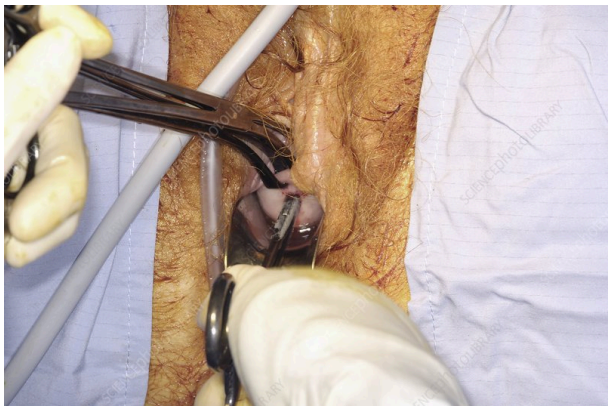
Spraying acetic acid for VIA procedure (Hofstede et al., 2024)



Colposcopy with simulated model(V' Mariee, 2017)



Pap smear showing vaginal mucus being smeared on a glass slide for analysis(Mph, 2022)



Uterus biopsy procedure to obtain a sample of uterine cells for analysis(Dr. P Marazzi, 2022)



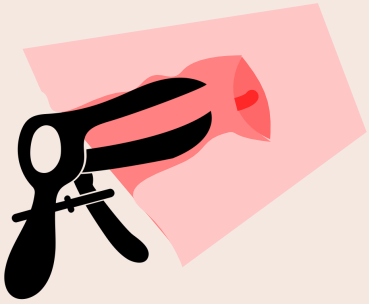
HPV dna test, cells infected with HPV (400× magnification)

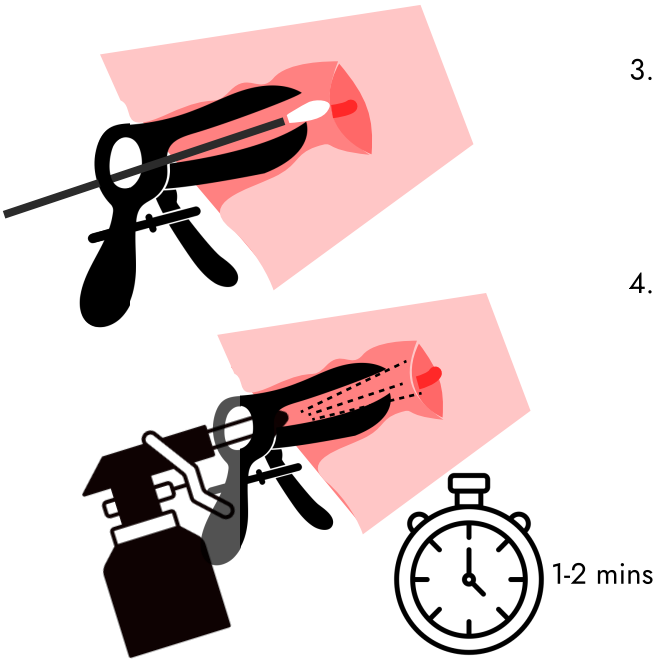
Figure 2.2: Images showing the various procedures for cervical cancer screening

2.2.1 VIA and VILI procedures

Both VIA and VILI are effective, low-cost screening methods that do not require laboratory facilities, making them particularly valuable for cervical cancer screening in resource-limited environments. This procedure is of particular interest to this project because it is visual in nature, presenting an intervention point where an AI camera system could be implemented to enhance diagnostic accuracy. Below, the procedure steps are examined as part of field studies conducted in past research efforts(Hofstede et al., 2024).

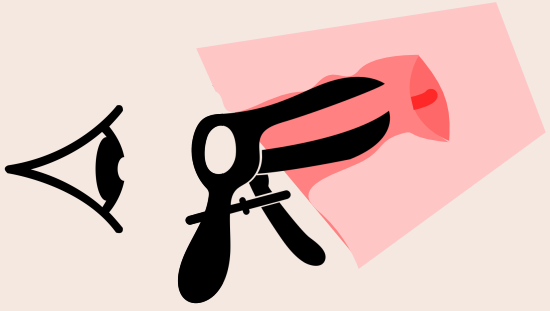
1. Patient Preparation: The patient is positioned appropriately, typically in a lying-down position, and a speculum is inserted to provide clear visualisation of the cervix.
2. Initial Examination: The clinician conducts a preliminary observation of the cervix under normal white light to identify any obvious abnormalities.





3. Application of Testing Solution:
   a. For VIA: A spray of 3-5% acetic acid (vinegar) is applied to the cervix
   b. For VILI: Lugol's iodine solution is applied to the cervix using a cotton swab or gauze
4. Waiting Period: A 1-2 minute waiting period allows the testing solution to interact with cervical tissue. During VIA, abnormal (precancerous or cancerous) cells turn white (acetowhite lesions), while normal tissue remains unchanged.

5. Visual Inspection: The clinician carefully inspects the cervix for acetowhite areas, particularly focusing on the transformation zone, as these areas indicate potential precancerous changes.
6. Result Interpretation: The presence of acetowhite lesions indicates a positive test result, suggesting the need for further investigation or immediate treatment such as colposcopy or cryotherapy.
7. Documentation and Follow-up: All findings are carefully recorded, and patients are informed of their results. When necessary, additional diagnostic tests or immediate treatment interventions are recommended.





2.3 Ethiopia's Healthcare System

Most of the VIA/VILI procedures are conducted at secondary care facilities; however, to better understand these terms and explore where these tests are performed within the context, it is useful to examine Ethiopia's existing healthcare structure.

Ethiopia's healthcare system operates on a three-tiered structure designed to provide specialised care while ensuring broad population coverage (Woldie et al., n.d.). Understanding this structure is important for identifying optimal deployment points for cervical cancer screening interventions and determining how AI-assisted diagnostic tools could be integrated across different care levels.



1. Primary Level:

· Health Posts (serving 3,000–5,000 people): Staffed by Health Extension Workers with basic training, they handle preventive and minimal curative care. "Health extension workers generally are only able to prescribe medication or refer you to another doctor. They can only handle very basic cases and don't need an advanced degree for the job." (Interview with Dr. Milkias,2025)

· Health Centres (15,000–25,000 people): Offer broader preventive, curative, and rehabilitative services and supervise local health posts.

· Primary Hospitals (60,000–100,000 people): Provide inpatient and emergency care and act as referral hubs for health centres.



2. Secondary Level

General Hospitals serve 1-1.5 million people and provide comprehensive medical, surgical and obstetric services. They are better equipped than primary health centres (PHCs), but they don't have specialised equipment like colposcopes and microscopes for biopsy. They act as referral points for primary hospitals and could be the highest level of care available regionally.



3. Tertiary Level

Specialised hospitals serve over 5 million people and handle complex cases in oncology, cardiology, and other disciplines. An example is Black Lion Hospital in Addis Ababa. Hospitals like these are highly capable, having up-to date equipment and serve as referral centers for the most challenging cases requiring highly specialized expertise and equipment.

2.3.1 Design Opportunity

Tertiary hospitals are overburdened, very few, and only available in major cities. Since health posts(primary care) lack the capacity for diagnostic procedures, the optimal intervention point emerges at the interface between secondary and tertiary hospitals. In regional or secondary care facilities, healthcare providers can perform basic diagnostic workflows, but they often lack the tools and training for consistent, accurate cervical cancer screening. A device that supports them in capturing and interpreting images locally could drastically reduce unnecessary referrals, such as biopsies or appointments, while also improving patient outcomes.

2.4 Patient Journey: Today And Envisioned Path

To understand the patient journey let us consider the story of a persona and following her story. While reading the story the figure shown (Figure 2.4) can be followed to understand the patient journey better alongside the narrative text



- Name: Amara Tadesse
- Age: 25
- Location: Oromia (Rural) , Ticho
- Children: 2
- Occupation: Farmer

Amara Tadesse, a 25-year-old mother of two from a rural village of Ticho in Ethiopia's Oromia region, had been experiencing unusual symptoms for months. Irregular bleeding and pelvic pain worried her, but the nearest general hospital(secondary hospital) offering cervical cancer screening was over 200 kilometres away (Hailu & Mariam, 2013) in the regional capital.

The journey would require her to arrange childcare, find transportation, and take time off from her small farming business, which would be unaffordable. When she finally made the difficult trip, spending her savings on bus fare and overnight accommodation, she waited hours at the overcrowded hospital

.

The manual screening procedure revealed concerning results. The healthcare worker, trying hard to see the cervical tissue under mobile phone lighting, marked her examination as "positive" but admitted uncertainty about the severity. "You need to see a specialist," they told her, handing her a referral slip for a tertiary hospital in Addis Ababa, another expensive journey, this time over 400 kilometres away.

Weeks passed before Amara could arrange the trip to the specialised hospital. The biopsy results were delayed, and the uncertainty gnawed at her. When she finally received confirmation of precancerous cells requiring a LEEP procedure, valuable time had been lost. The treatment was successful, but the delayed diagnosis meant more extensive intervention than would have been necessary with earlier detection.



Figure 2.3: Map of Ethiopia to be traversed by Amara

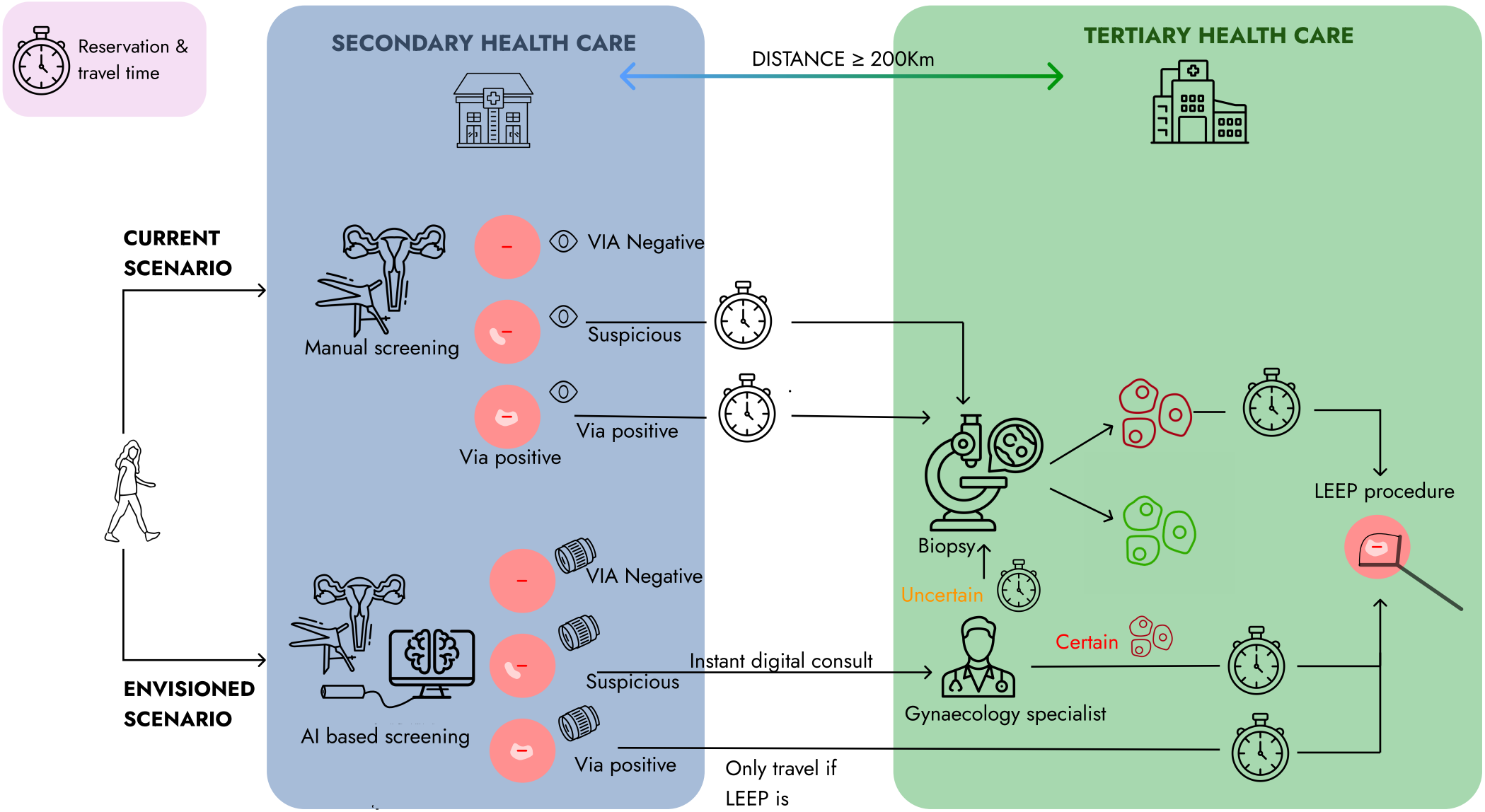


Figure 2.4: Current vs future pathway

2.4.2 Envisioned path

To understand the patient journey let us consider the story of a persona and following her story. While reading the story the figure shown (Figure 2.4) can be followed to understand the patient journey better alongside the narrative text

- Name: Hanan Tadesse
- Age: 25
- Location: Oromia (Rural) , Ticho
- Children: 2
- Occupation: Farmer



Two years later, Amara's younger sister Hanan, also 25, experienced similar symptoms. But by then, their local secondary health centre had been equipped with an AI-based screening system.

Hanan arrived at the regional health centre with no overnight stays, no lost income from days away from work. The AI-powered camera system captured high-resolution images of her cervix during the VIA procedure. Within minutes, the system provided a confident analysis: "Positive for precancerous lesions, high confidence level."

The local healthcare worker immediately initiated an instant digital consultation with a gynaecology specialist at Black Lion Hospital in Addis Ababa. Through the telemedicine link, the specialist reviewed the AI analysis and the captured images in real-time, confirming the diagnosis and providing immediate treatment recommendations.

"We can treat this today," the healthcare worker informed Hanan, showing her the clear diagnostic images on the screen. The early detection meant a simple outpatient procedure could address the issue completely. No referral journey, no delayed treatment, no progression to more serious stages.

Within hours of her initial screening, Hanan received definitive treatment at her local health centre. The AI system's accuracy eliminated the uncertainty that had plagued her sister's experience, while the instant specialist consultation ensured she received expert care without leaving her community.

n requires specific technical capabilities, which are discussed in the following section.

2.4.3 The Transformation

The contrast between the two experiences is meant to illustrate the potential of AI-assisted cervical cancer screening. Where Amara faced barriers of distance and waiting times, Hanan's care pathway was significantly shorter. Amara undertook a total journey of over **1000 kilometres: first, a 200 km trip to the regional secondary hospital, followed by multiple separate, 400 km trip to the tertiary hospital** in Addis Ababa. This multi-stage process, filled with cost and diagnostic uncertainty, delayed her treatment for several months.

In the transformed scenario, **Hanan only needed to travel the initial 200 kilometres to the same regional hospital.** There, the AI-assisted screening provided an immediate, accurate diagnosis. The need for the 400 km journey was could be completely eliminated(If LEEP is available at secondary health centre) , and her treatment could be scheduled within days, not months.

The local staff in regional hospitals in secondary care could now provide adequate and accurate screening with confidence, supported by AI analysis and real-timet expert consultation. The system reduced the burden on tertiary hospitals while ensuring that women in rural communities had access to the same quality of care as those in urban centres.

In order to create this type of transformation, technological innovation becomes necessary.

Chapter 3: System Design Objectives

To design the system, we first need to define the specific objectives we want the system to achieve. In this section, the discovery of the various design goals to be accomplished during the course of the thesis is discussed in more detail, including specific metrics on how they could be evaluated.



3. System Design Objectives

3.1 System Overview

The cervical screening system developed in this project integrates three core subsystems:

1. A hardware module consisting of a borescope camera, a mechanical guide, and its integration with a speculum.
2. A software interface which enables image capture, visual feedback, and device control.
3. An AI-based diagnostic model which analyses captured cervical images and provides classification feedback to the user.

These components are designed to operate cohesively, with each subsystem addressing a different aspect of the screening process: the hardware facilitates reliable image capture and fits into the routine workflow; the software offers an interface to capture and interact with the AI, and the AI enhances diagnostic capabilities.

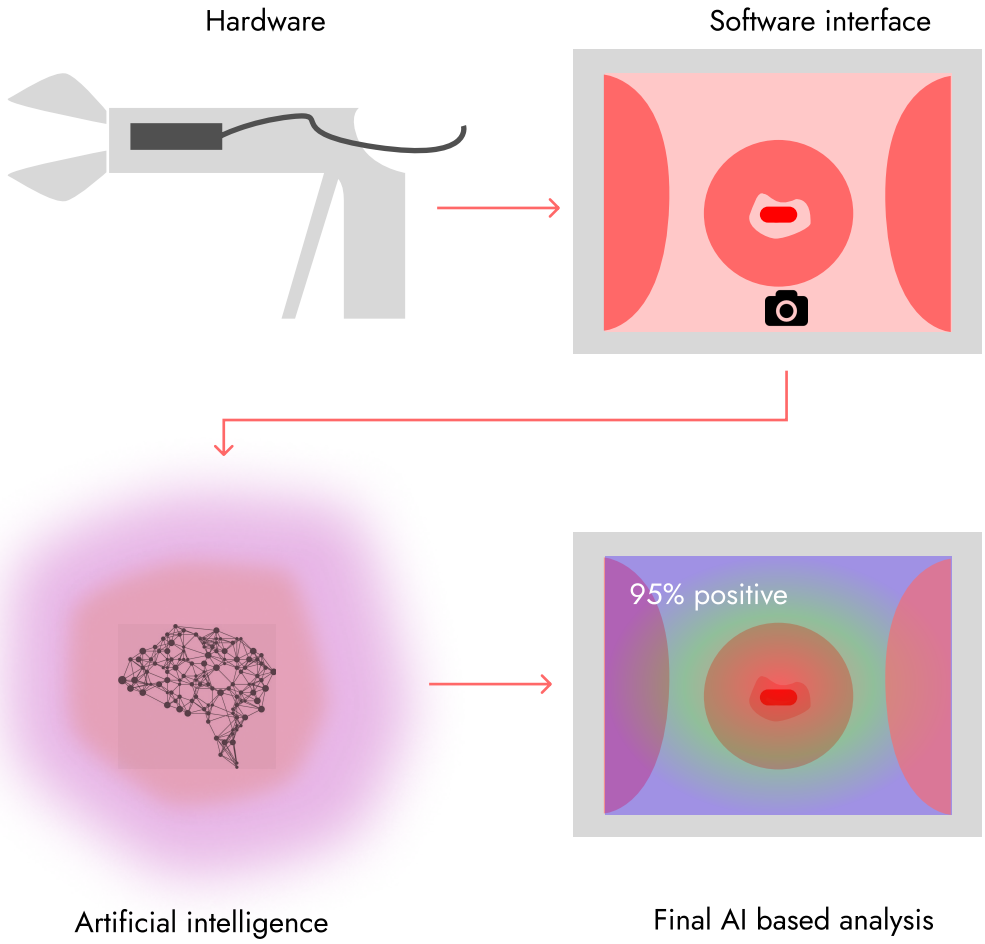


Figure 3.1: System overview

3.2 Design Goals

The design goals are categorised into two overarching themes: User Needs, based on the experience of healthcare workers using the device, and Clinical Needs, focusing on hygiene, diagnostic reliability, and patient safety.
It is that these design goals are from the perspective of a clinician taking images rather than what is the best image for an AI which is discussed more in detail in the following chapter (refer chapter 6).

3.2.1 User needs:

1. Intuitive and easy-to-use device

The device must be operable by non-specialist staff with limited training. Capturing and reviewing cervical images should be straightforward and guided.
"The nurses or staff largely have short-term training, and since the process is experience-dependent, it could be helpful to have guidance."
(Interview with Dr. Milkias, Ethiopia, 2025)

2. Minimal assembly or setup time

Attachments, adjustments, or calibration steps should be minimized to reduce errors and increase adoption.
"If there are too many additional steps or things to add to the device, they will try and skip it."
(Interview with LUMC doctor, 2025)

3. Ergonomic handling and form factor

The system should feel stable and manageable in one hand, particularly during vaginal procedures where access is limited.
"During procedures, you already have one hand occupied, to click a picture it is difficult if I don't have assistance and it is difficult to If the rest isn't quick and ergonomic, you lose the patient's comfort."
(Interview with Dr. Marlieke, 2025)

4. Low-cost and locally replaceable components

To support accessibility, the device should use affordable components that are easy to procure, making it easy to repair/replace.
"Imported medical devices are often broken and sit unused because you can't get spare parts or fix them locally."
(Interview with Dr. Milkias, Ethiopia, 2025)

5. Clear guidance and feedback for orientation

Since the cervix is a 3D structure and visualisation can vary from patient to patient, the system should aid clinicians with orientation cues. These may be mechanical (camera notches or rails) or visual (on-screen overlays).
"Sometimes you can't really tell if the cervix is being seen straight up, especially with a moving camera, some visual help would be useful."
(LUMC doctor interview, 2025)

6. Backup power source

The system must feature a filter to ensure power quality and include a backup power source to maintain operation during power fluctuations, which are frequent and unreliable.

"Power availability is intermittent and dirty a lot of the time. The system needs to have some type of filter and a backup if it's electronic"

(Interview with Layco designer, 2025)

3.2.1 Clinical needs

1. Sterilizable and compatible with existing clinical routine

Reusable components must survive standard LMIC sterilisation methods such as boiling, soaking in alcohol, or use of autoclaves.

"We don't have fancy sterilisation methods it's mostly hot ovens(autoclave) or chemical soak. In our hospital we boil speculums, so it's best if anything that goes inside the body can handle that."

(Interview with Dr. Milkias, Ethiopia, 2025)

2. Minimally intrusive for the patient

The device should not add to patient discomfort, particularly for women undergoing screening for the first time.

"The speculum exam is already stressful; the device's usage should not add to the feeling of discomfort in any way"

(LUMC doctor, 2025)

3. Capture high-quality, diagnosis-ready images

The device must consistently deliver images that are:

· Sharp and in focus
· Free of glare
· Well-illuminated
· Centred on the cervix

"If the image is blurry with a large white spot from the light (talking about image from endoscope), you can't say anything from it. Then it's better to just directly try to look with my eye, I may not necessarily save that type of image to make a diagnosis"

(Testing with Dr. Marlieke, 2025)

4. Stable AI compatibility

Captured images should be consistent in framing and quality, allowing the AI model to generalise from training data and operate without additional re-training.

"If the AI sees 10 different kinds of shaky pictures, it won't really know what to look for.
So it is better to either get a few stable images or several images and then try to do an average of the results"

(Interview with AI expert, 2025)

This implies the need for stable camera positioning, fixed lighting profiles, and minimal user-induced variability.

3.3 Design Constraints and Assumptions

Several constraints shaped the project scope and technical choices:

- The system is designed for offline use, assuming no continuous internet connection. Since, it is difficult to predict how the conditions could be region to region
- The C-Spec speculum previously developed and its dimensions are treated as a fixed physical constraint to which the propsed intervensions had to fit
- The system must function in low-power environments, using Raspberry Pi or mobile devices. Cannot assume the presence of a laptop or a computing device available, this also ensures that the system is more complete on its own
- Image capture and the AI processing, not real-time decision-making is prioritized to reduce processing burden.
- Only one operator (nurse or clinician) is expected to use the system at a time. This assumption came from images of the clinic which can be constrained and generally has only a single doctor in the room with the patient(Figure 3.2)



Figure 3.2 - Treatment oom at Sante Espoir Healthcare Practice in Yaounde, Cameroon

3.4 List Of Requirements

The integrated system is expected to:

- Guide users towards consistent, well-framed cervical images.
- Capture and store images reliably and quickly.
- Provide AI-based classification feedback for VIA/VILI assessment.
- Offer user feedback on image quality (e.g. blur, exposure).
- Operate with minimal supervision in low-resource clinical settings.

These functional objectives link the design goals with engineering requirements.

From these needs and discussions, a comprehensive list of requirements was created. While the reasoning behind some of these requirements is not yet clear, they will be explored and referenced in the following chapters as they are examined further and justification for each is provided. The requirements are divided into image requirements(Table 3.1 a) and hardware requirements(Table 3.1 b).

[HW1] (reference to hardware requirements will be made in this manner)

Code	Requirement Summary
HW1	No on lens condensation at 100% relative humidity
HW2	Tool-free attachment
HW3	Defined patient-contact constraint and camera range
HW4	Camera must not contact patient tissue
HW5	Construction must survive 1,000 use cycles
HW6	Smooth, cleanable surface geometry
HW7	Integrated access for swabs or acetic acid spray
HW8	Self-centering or alignment aid for image framing
HW9	Locking or friction-based positioning
HW10	Preferably monolithic or low part count

Code	Requirement Summary
IM1	Reduce specular glare to <10% of ROI using polarization or other methods
IM2	Maintain sharp focus from 30–80 mm distance
IM3	Minimize motion blur (max 2px shift at 720p over 1s)
IM4	Ensure ≥1500 lux illumination with ISO <800
IM5	Image resolution must be ≥1280×720 pixels
IM6	Maintain luminance uniformity within ±10% across ROI
IM7	Field of view should be ≥70° diagonal
IM8	Retain ≥90% of cervix in captured image frame
IM9	Provide real-time sharpness/blur feedback
IM10	Clinician view must show RGB; AI may use normalized inputs
IM11	Total capture + processing time < 5 seconds
IM12	Shutter latency must be <200 ms

Must have

Nice to have

Table 3.1:(Top to bottom) a- Hardware requirements, b - Imaging requirements

Chapter 4: Imaging Experiments

In this project, the AI model serves as one of the primary "users" of the captured images. Its ability to learn and make accurate predictions is entirely dependent on the quality of input data. Unlike human observers, who may use clinical experience to interpret suboptimal visuals with various artefacts (imperfections or distortions) (Dr. Milkias, 2025), AI systems rely exclusively on patterns learned from labelled training data. This makes it essential to capture images that are clear, well-lit, in focus, and free from artefacts such as glare, motion blur, or inconsistent illumination. Moreover, these images may also be used later by specialists for clinical review, especially in cases where the AI flags abnormalities. A poor-quality image can hinder not only algorithmic interpretation but also human diagnosis, potentially introducing delays or uncertainties in clinical decision-making. Ensuring high image quality, therefore, benefits both automated and human evaluators. It enhances the robustness and accuracy of AI classification, improves interpretability, and contributes to faster and more reliable diagnoses throughout the care pathway.

4. System Design Objectives

4.1 Image Quality Challenges

The accuracy of AI-driven image classification fundamentally depends on several critical factors. To understand this relationship better, it helps to conceptualise an image as a packet of information that we provide to the AI system. The clearer and more information-dense this packet is, the better the AI will perform at classification. This principle directly correlates to the quality of input images and the diversity of datasets used in the training of the cervical cancer screening application.

When the various parameters that contribute to creating high-quality medical images are systematically mapped, a complex interconnected network emerges (Figure 4.1). While this parameter web may appear overwhelming in its complexity, there is a fundamental core to achieving optimal image quality. Research focused on characterising 'information capacity' has revealed that the combination of sharpness, noise levels, and the effects of various imaging artefacts forms a fundamental figure of merit for overall image quality. These core parameters emerge from the parameter network as the primary factors to which almost every controllable variable ultimately connects.

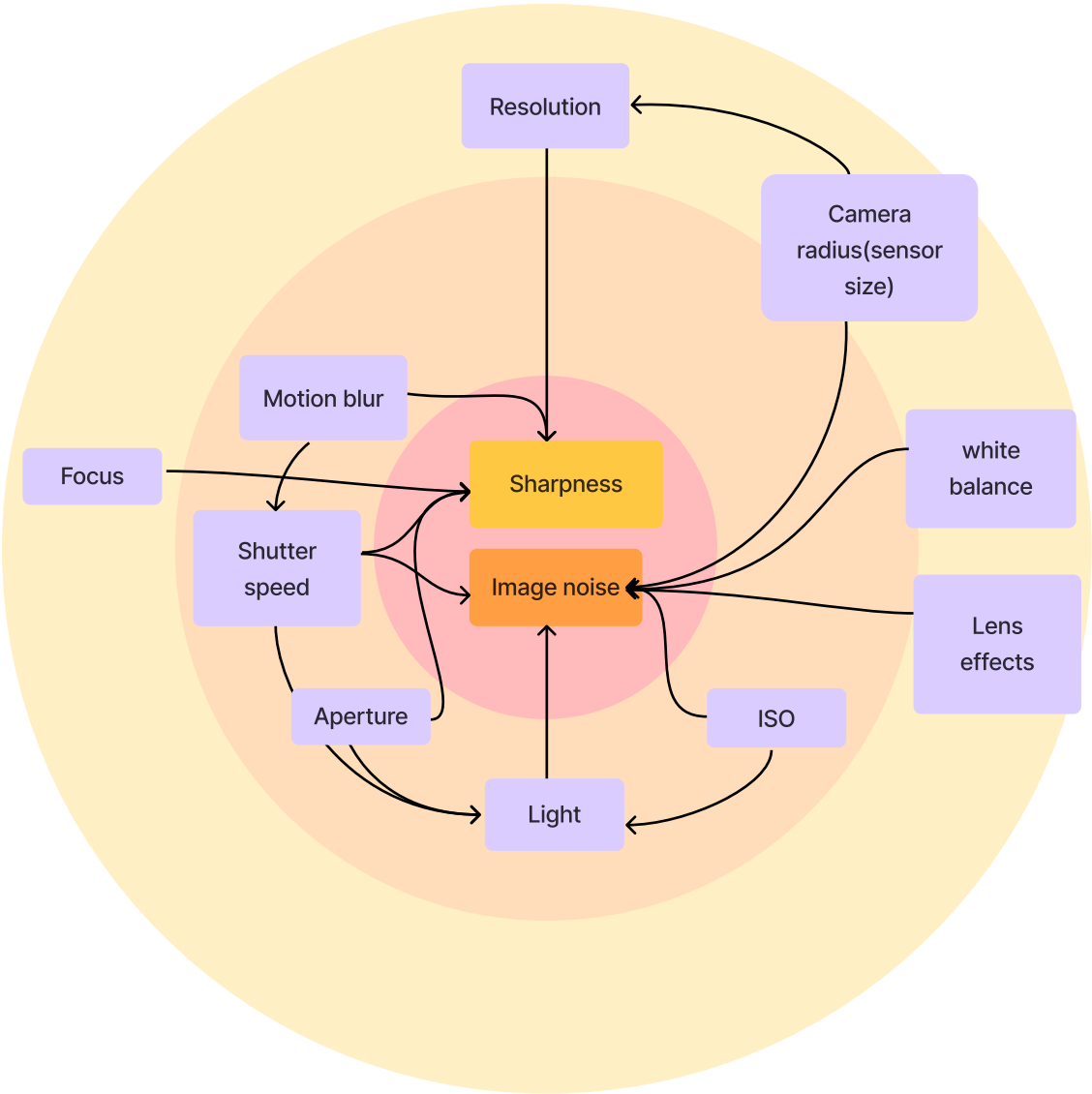


Figure 4.1: Factors affecting image quality

4.2 CLOE/Phantom Test Setup

The proposed experiment aimed to enable further iteration and gain a fundamental understanding of the conditions within the female gynaecological system. This would support continued refinement and testing of the imaging system. To achieve this, I explored various factors that could influence endoscopic imaging of the vagina.
Several gynaecological phantoms were available for reference, including models like the ZOE® Gynecologic Skills Trainer. However, this study took a different approach, not focusing on replicating the anatomical and tactile experience of performing the procedures but instead on accurately simulating optical conditions that affect the visualization of the cervix.

This approach could be considered an optical simulation of the gynaecological organ
Key factors taken into consideration included:

· **Dark environment** – Since there is typically no natural light inside the vaginal canal, and there is often no surgical lighting (Interview with Dr. Milkias, 2025), the experiment needed to ensure a controlled lighting condition, where illumination could only enter through the vaginal opening. Similar lighting challenges were also reported in studies such as the Magni-Visualiser (Parashari et al., 2015).
· **Tubular structure** – The vaginal canal and uterus are anatomically tubular, with a widening near the cervix(Prendiville W, 2017), a characteristic shape that needed to be reflected in the simulation.
· **Moisture** – The human body maintains a temperature of 37°C, which can cause condensation on certain materials, particularly glass. Moisture and temperature fluctuations could impact visibility over time, especially during a procedure lasting approximately five minutes (LUMC doctor, 2025).
· **Vaginal fluid** – Fluid presence could obstruct the pathway and cause obscurement in the camera feed. The colour and consistency of the fluid could also affect image clarity. In discussions with doctors, it was noted that they typically swab excess fluid before beginning the procedure. However, this study considered the potential impact of fluid presence on endoscopic imaging.
· **Path to the cervix** – Finding the cervix can be challenging at times (LUMC doctor, 2025). However, for this study, it was not regarded as a major issue, as trained practitioners and nurses are expected to be familiar with visualization techniques. Additionally, it was ensured that there was some variability in the positioning of the image within the cervix by using a smaller image within the cone (image).
· **Reflections and Surface Smoothness-** The experiment also considered reflections caused by cervical surface texture and fluid presence, especially relevant when simulating VIA procedures where acetic acid sprayed alters surface reflectivity.

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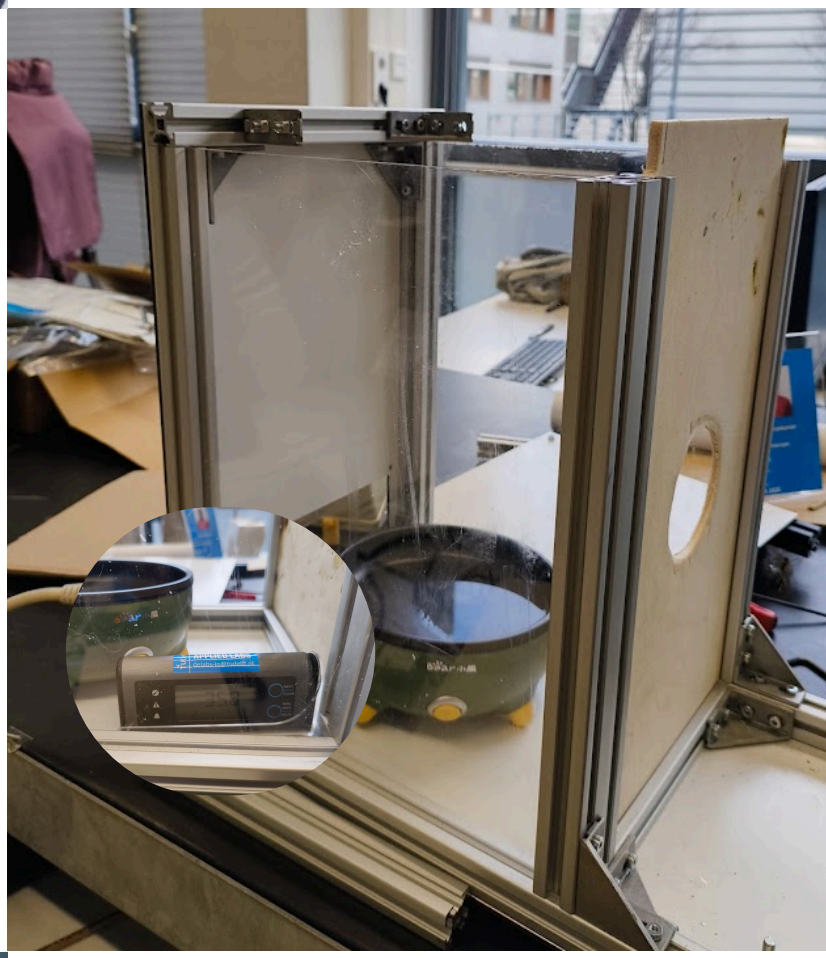
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*Figure 4.2: Creating a **dark environment** using a blanket along with a box-like structure, ensuring the only light sources are the intended ones for the experiment*

*Figure 4.3: **Moisture and temperature** was maintained by using a hot plate and steaming the area, this was also recorded with a temperature and humidity logger and was ensured that it maintained the temperature at close to 37 with a highly humid atmosphere*



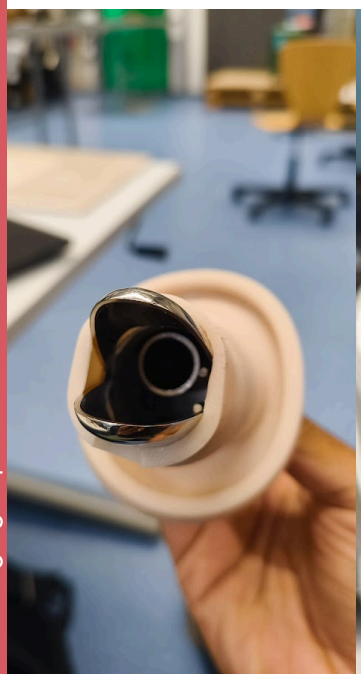




*Figure 4.4: **Vaginal fluid** was simulated with vaginal lubricant which is intended to mimic the consistency of vaginal fluid or discharge and mixed with colouring agents like other creams*

*Figure 4.5: **Path to cervix** was simulated with a silicone part which was part of the Chloe GTM. This was still a straight but elastic part, and could replicate any pushback or other obstructions caused by elastic vaginal walls*

4.2.1 Experimental Setup Components:

- Phantom Models: CLOE™ cervical simulator and VIOMERSE realistic GYN model
- Camera: USB endoscope with integrated LED lighting, 70° FOV
- Mounting: Custom 3D-printed guide within speculum
- Lighting Measurement: Lux sensor placed at 2 cm from the imaging target
- Environmental Logging: HOBO™ temp/humidity logger
- Computer Interface: Real-time video capture and image logging software (custom script)

4.2.2 Experimental Procedure

1. Record Environmental Constants

- Measure base and post-steam humidity
- Set and verify target temperature (~37°C)
- Record ambient light levels (lux)
- Determine focal range of camera

2. Lighting and Brightness Calibration

- Position endoscope 2 cm from the cervical phantom
- Record brightness levels at various depths

3. Moisture Simulation

- Boil water and allow steam to saturate the environment
- Monitor until high humidity is achieved (above 90%)

4. Phantom Preparation

- Insert cervical phantom into test rig
- Open speculum using mechanical hooks

5. Camera Insertion and Capture

- Insert camera into the speculum following distance markers
- Stop at predefined depths to capture images
- Record image characteristics at each interval

6. Image Analysis and AI Testing

- Process captured images using a similarity comparison algorithm
- Log brightness vs. similarity score
- Run classification tests with AI model
- Compare against reference images
- The procedure was repeated using the VIOMERSE GYN model to benchmark the custom setup against a high-fidelity procedural simulator.

4.2.1 Results and implications

- **Brightness and Classification Quality :** Image similarity to the reference increased with brightness and plateaued after a certain level (Figure 4.7). This suggests that slight sacrifices in brightness - such as from using a polarizer - do not significantly impact classification performance, offering flexibility in design choices.

- **Camera Depth and Field of View:** Classification accuracy peaked before the camera exited the speculum(Figure 4.8), indicating that optimal imaging can be achieved without protrusion, reducing the risk of patient contact and enabling a more compact design.

- **Simulation Model Validity:** The custom test rig provided comparable results to the VIOMERSE model(Figure 4.6), supporting its continued use for optical testing. Depth of field exceeded the depth of the transformation zone, allowing minor 3D surface irregularities to be neglected in optical evaluation.

- **Camera lens choice:** As long as the camera lens is not made of some type of glass and is instead made from a type of plastic like PMMA, the glass does not fog up even for over 3-5 minutes in a high humidity environment.**[HW1]**



Figure 4.6: Realistic Viomerse GYN model testing with 3D cervix

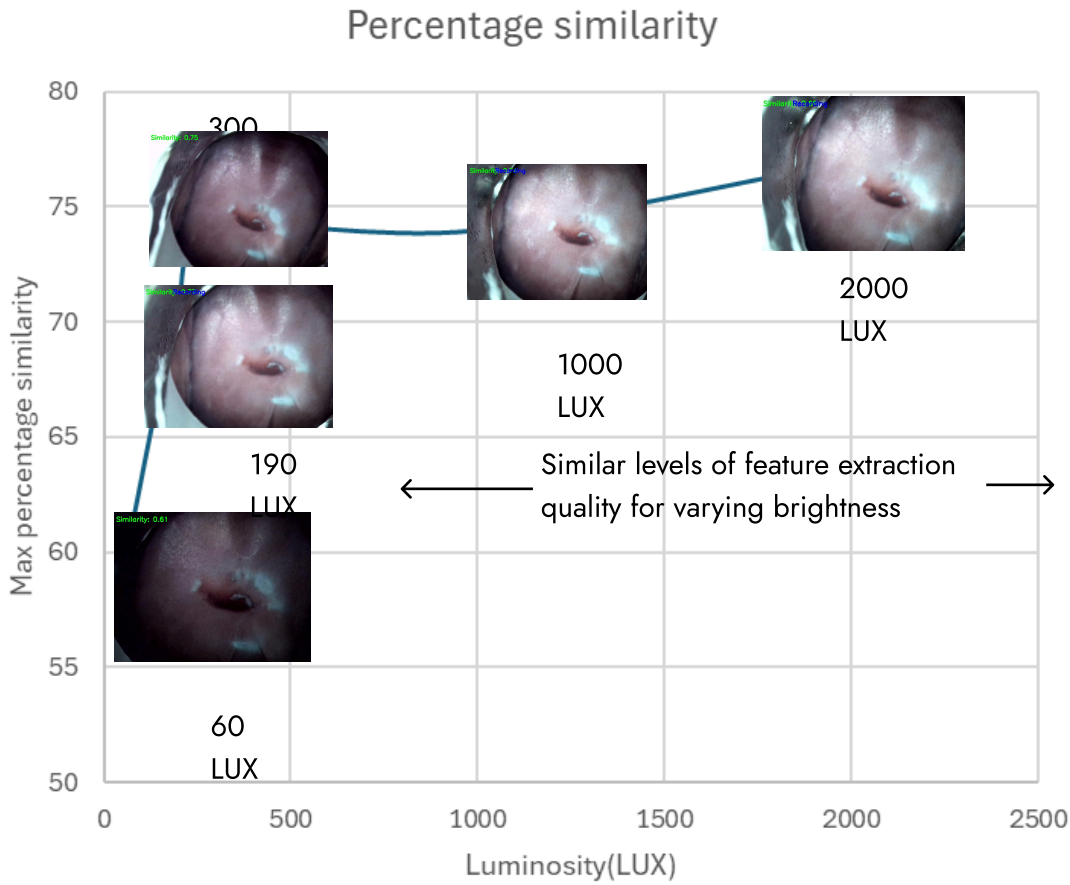


Figure 4.7: Max Percentage similarity vs Luminosity

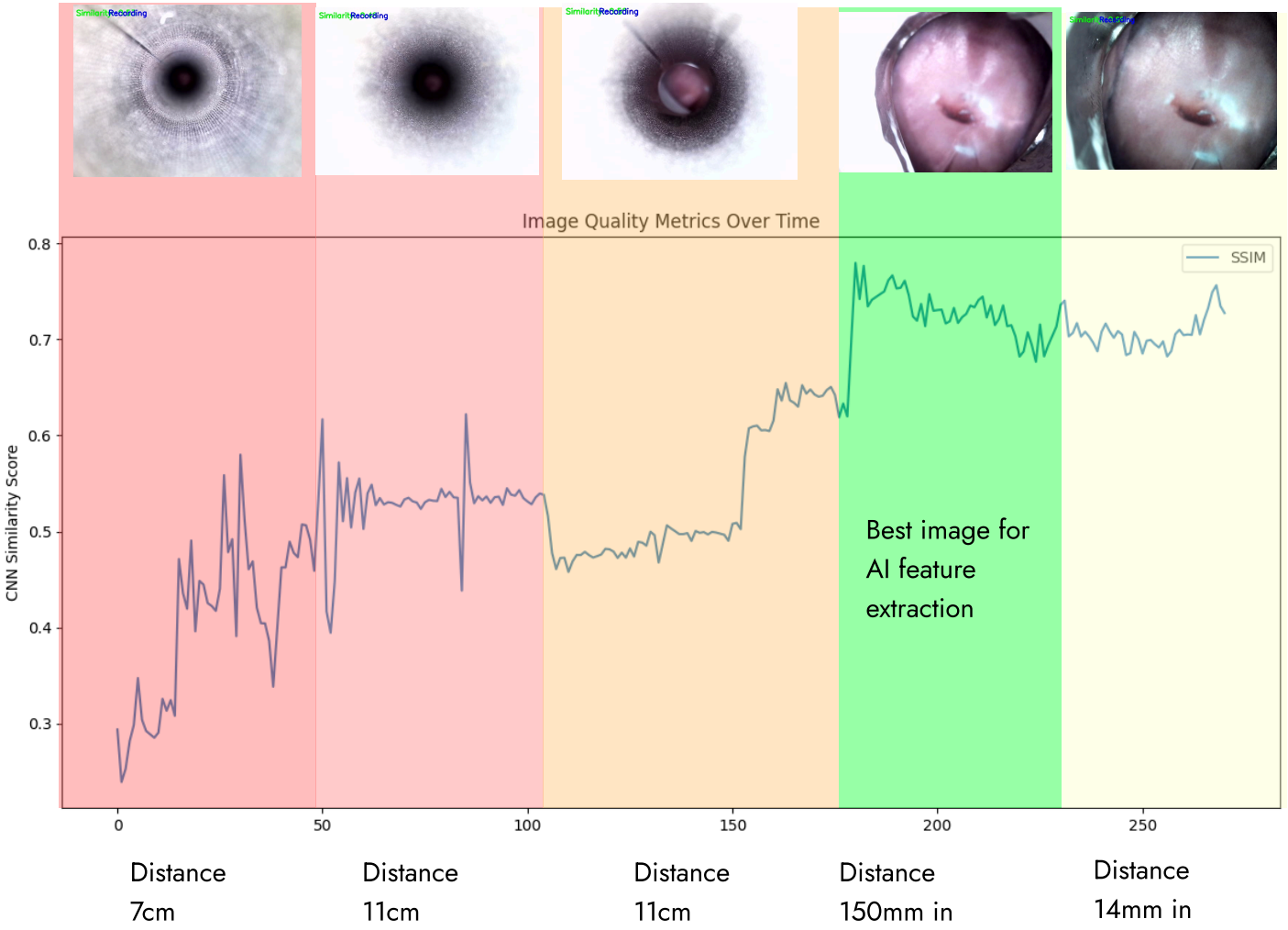


Figure 4.8: 2000 LUX constant luminosity - Similarity score vs distance

4.3 Polarisation And Lighting

One of the main criteria to avoid image noise, as shown in the diagram, is optimal lighting; in fact, having good lighting ensures a lower ISO and thus less noise.

4.3.1 Colour Considerations in Rural Settings

In many rural healthcare facilities, yellow lighting is commonly used due to its availability and cost-effectiveness. However, yellow light poses limitations for cervical cancer screening applications. With a colour temperature of 4000–4500K,(Parashari et al., 2015) yellow light lacks the full visible spectrum, which can obscure acetowhite areas, which are key indicators of precancerous and early cancerous lesions. This spectral limitation creates particular challenges for both human observers and AI-based diagnostic systems**[IM4]**.

In contrast, white light encompasses the entire visible spectrum, providing a more neutral and balanced illumination that optimises both AI-based analysis and human interpretation. While green light filtering has been explored in some cervical screening applications and is a common tool for healthcare professionals to observe vascularity, it is not considered in this study as it does not provide significant advantages for AI-based image classification. However, since images are digitally captured, they can be post-processed to simulate green-filtered images if necessary for specific diagnostic requirements.

4.3.2 Integrated vs. External Lighting

Relying on external light sources presents significant operational challenges in clinical settings. The operator's handling of the device may inadvertently block the light source, casting shadows(Figure 4.10) on the cervix and compromising image quality. This issue is particularly problematic during the precise positioning required for optimal cervical visualisation.

To address this challenge, integrating a built-in light source within the device ensures consistent and optimal illumination throughout the examination procedure. The current device incorporates a ring light configuration that provides uniform illumination from multiple directions, minimising shadow formation on the subject being examined by the camera **[IM4]**.

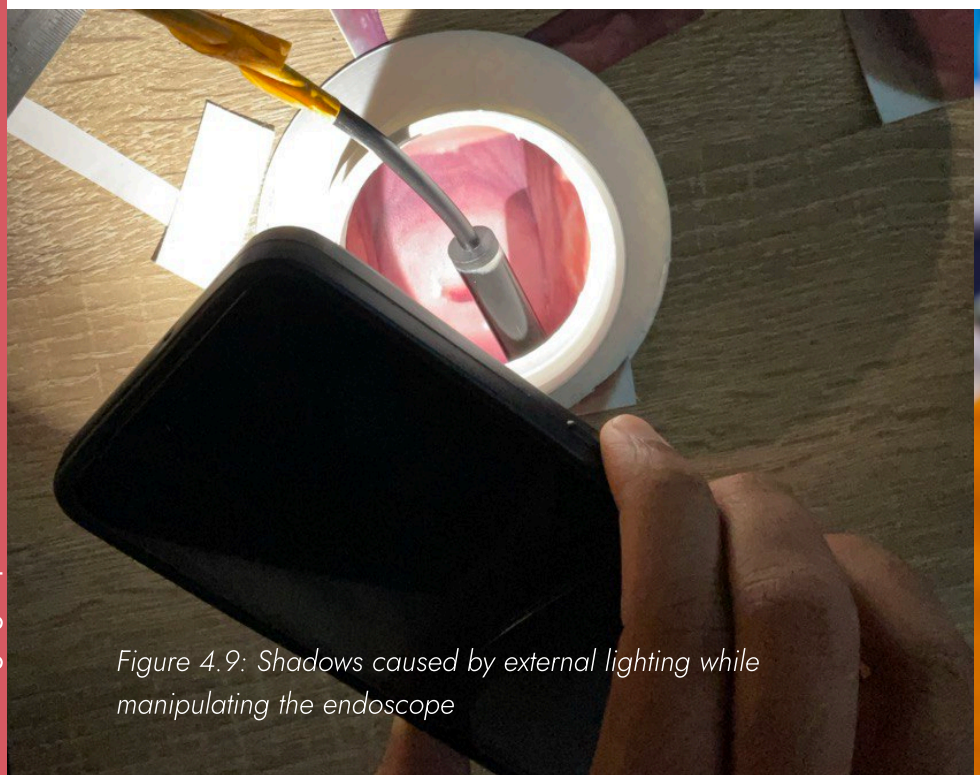


Figure 4.9: Shadows caused by external lighting while manipulating the endoscope



Figure 4.10: Lights of the borescope inside speculum

4.3.3 The Challenge of Bright Reflections

Having uniform, white, bright light helps significantly in lowering image noise and is a step toward getting a diagnosis-worthy picture. However, the wet cervical surface, particularly after application of acetic acid or Lugol's iodine, creates significant specular reflections when illuminated with light at close range. These bright reflections pose several problems:

- **Information loss:** Bright specular reflections contain minimal diagnostic information and can bias AI training data. For a machine learning model, this bright spot is a void of information.
- **Diagnostic masking:** Critical acetowhite lesions may be obscured by reflective areas

The impact of specular reflections on AI performance is clear when analysing gradient maps that show what the AI considers important. In images with bright reflections, the AI system tends to focus on areas away from the specular highlights, possibly overlooking key diagnostic features (Figure 4.11 vs Figure 4.13).

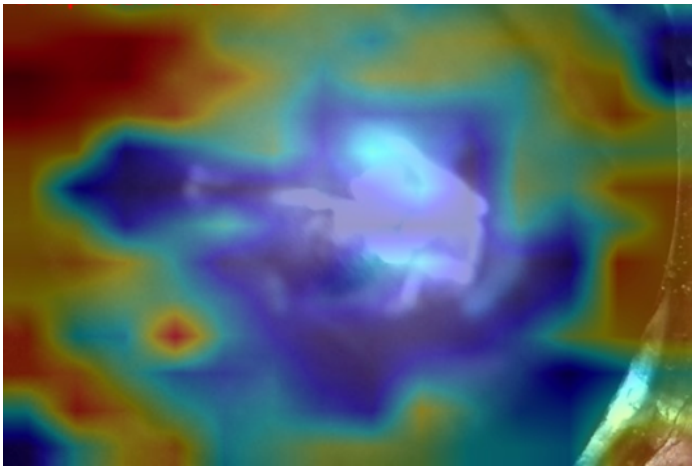


Figure 4.11: Gradient map of the priority features through the CNN network

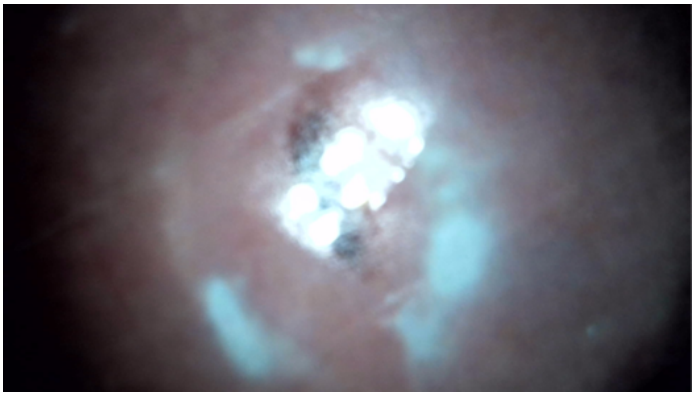


Figure 4.12: Original image captured by the endoscope

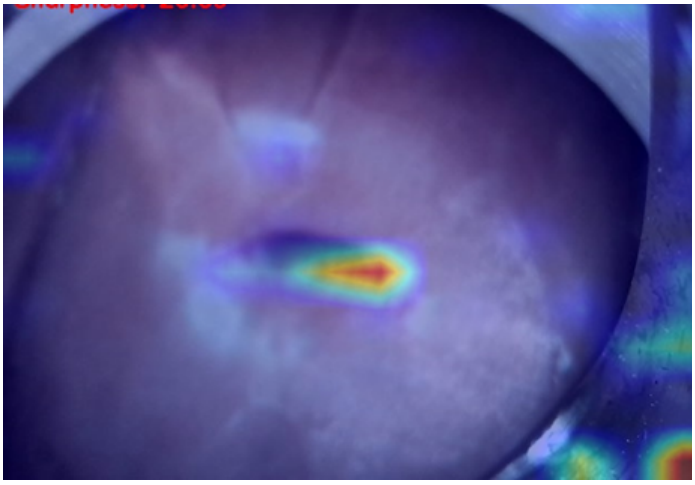


Figure 4.13: Image without bright specular reflections

4.3.4 Low-Cost Diffuser Development

To address lighting harshness while maintaining cost-effectiveness, several diffusion approaches were systematically tested:

Translucent Diffusers: Transparent acrylic pieces were cut and sanded to create diffusers with varying levels of opacity(Figure 4.14):

· Fully transparent
· Single-side translucent
· Fully translucent with different roughness levels

Testing Results

While sanding created different levels of light diffusion, this approach presented a critical limitation—the diffuser interfered with the camera's field of view, creating a visible ring pattern that would require software cropping and still failed to eliminate specular reflections(Figure 4.15).

Distance-Dependent Diffusion: Professional photography techniques, such as using light boxes and umbrella lighting setups, can achieve effective diffusion because there is a distance between the light source and the diffusion medium. However, implementing this approach in a compact endoscope would require sacrificing considerable visible area, making it impractical for cervical screening applications.

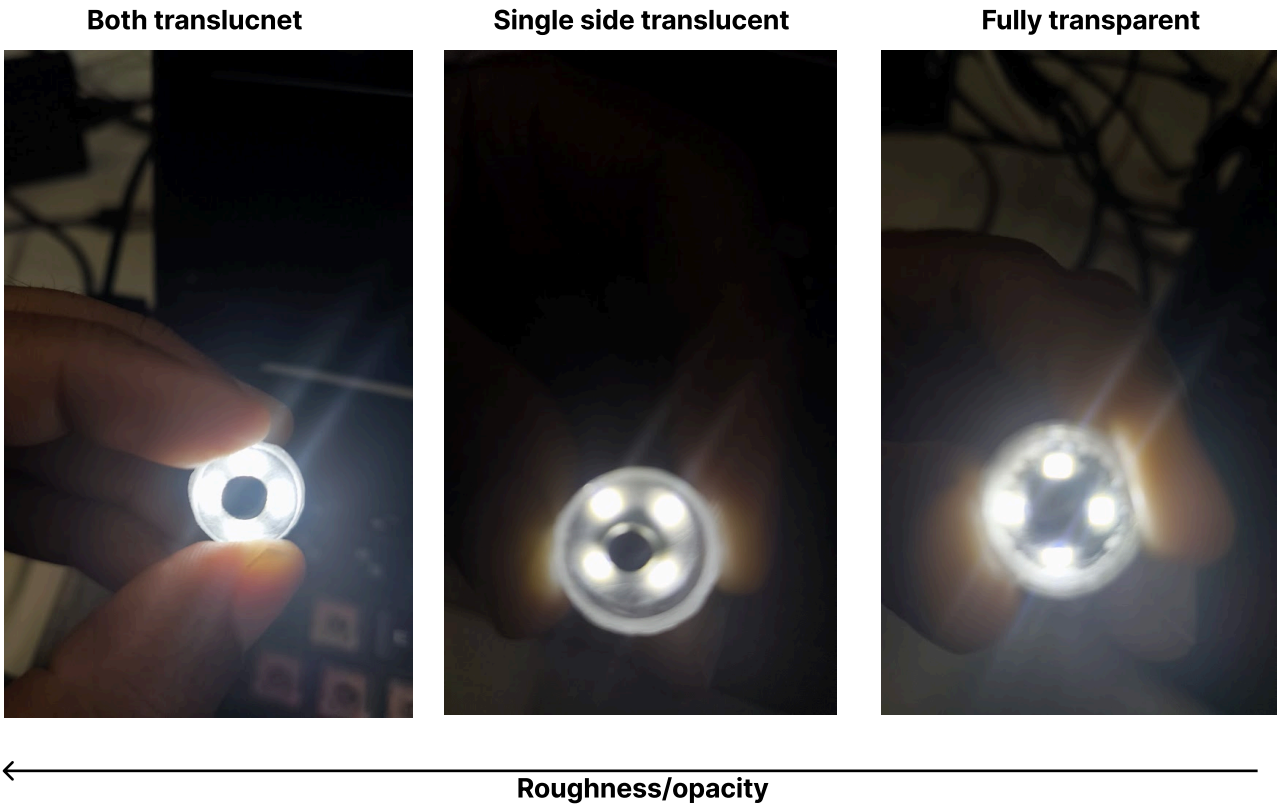


Figure 4.14:Different roughness diffusers

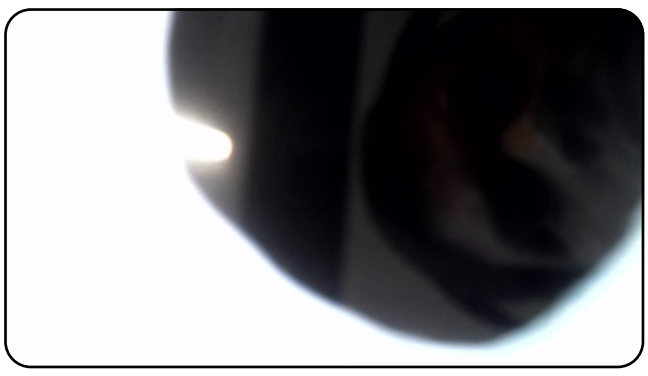


Figure 4.15:Ring of light due to diffuser

4.3.5 Polariser based filtering

The solution to achieving bright illumination without harsh reflections came from understanding light polarisation principles, the same phenomenon that makes polarised sunglasses effective against glare. This principle is successfully applied in macrophotography, where polarised light sources are paired with complementary polarised camera filters to eliminate unwanted reflections (Figure 4.17). Since the specular and highly reflective light waves are perpendicular to the surface of the incident rays from the source, these rays can be filtered, resulting in an image without specular reflection.

Experiments were conducted using polarising sheets applied to both the light source and camera lens in a cross-polarised configuration. The results demonstrated near-complete elimination of specular reflections (Figure 4.18) .
The polarisation approach delivered measurable improvements in image quality metrics:

- **Region-of-interest clarity:** Diagnostic areas previously obscured by reflections became clearly visible
- **Consistent illumination:** Uniform lighting across the entire cervical surface without hot spots

This approach directly addresses imaging requirements IM1 (glare reduction) and IM2 (consistent illumination quality):
[IM1]: Cross-polarisation effectively eliminates specular reflections that would otherwise compromise diagnostic accuracy.
[IM6]: Uniform polarised illumination ensures consistent image quality across different examination conditions

The final lighting solution combines white light illumination with cross-polarisation filtering to achieve optimal imaging conditions. This integrated approach:

- Eliminates specular reflections through polarisation
- Maintains compact device form factor
- Ensures consistent performance across varying clinical conditions

The polarisation implementation will be detailed further in subsequent sections, including specific technical specifications and medical-professional validation results.



Figure 4.16: (What Are Polarized Sunglasses?, 2021)

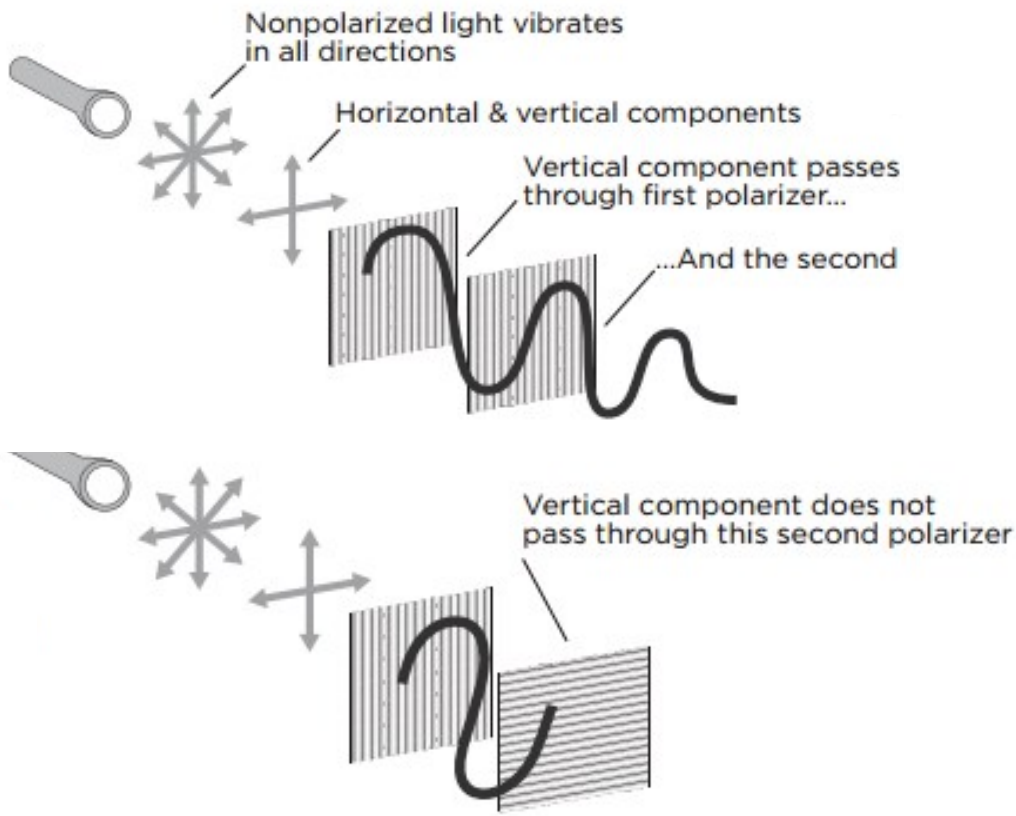


Figure 4.17 : Phenomenon of polarisation



Figure 4.18 Experiment with polarisation sheets

4.4 Focus & Exposure Testing

Sharpness represents one of the two core parameters that emerge from the complex web of imaging factors affecting AI performance. As established in information capacity theory, sharpness combines with noise reduction to form the fundamental figure of merit for image quality. For cervical cancer screening, where diagnostic decisions depend on detecting subtle tissue changes and acetowhite lesions, maintaining optimal sharpness across the entire region of interest is critical.

Quantitative Sharpness Metrics

The primary metric for measuring image sharpness is the Laplacian, which measures the spread of edge intensities(how defined or fuzzy the edges are) to indicate overall image sharpness. While alternative methods exist (Brenner Gradient, Sobel + Variance), the Laplacian method was selected based on superior performance and implementation simplicity (Moukthika, 2025).

Two primary factors significantly impact sharpness in cervical imaging applications:

1. Aperture limitations – Aperture refers to the size of the lens and, in a cylindrical geometry, is constrained by the diameter of the device.
2. Motion blur - from patient or operator movement

4.4.1 Aperture limitations

The three-dimensional nature of cervical anatomy presents a potential challenge for achieving adequate depth of field. The cervix, on average, has a diameter of 3cm (Prendiville & Sankaranarayanan, 2017), with the transformation zone - the area of highest diagnostic importance - lying on a single focal plane of most borescopes.

If the other factors are the same: aperture, focal length, camera-subject distance, a larger sensor will have a shallower depth of field (Mah & Alambra, 2024).

In general, cameras with smaller sensors have larger depths of field, which is demonstrated with the two different borescope cameras(Figure 4.19, 4.20). The smaller camera has both a larger depth of field and a smaller sensor, as demonstrated experimentally and by the clarity of the image produced for the exact same shot.

Device-Specific Constraints

· Borescope Form Factor Impact: The cylindrical design of borescope devices creates unique optical constraints that differ significantly from traditional camera systems:

· Sensor size correlation: Unlike DSLR cameras with larger lenses relative to sensor size, borescope cameras have a direct correlation between body diameter and Effective aperture

· Fixed aperture limitation: Web-camera style sensors generally lack adjustable apertures, restricting depth of field control options.

The various sizes of cameras can be compared (Table 4.1).



Figure 4.19: Image taken with 8mm borescope



Figure 4.20: Image taken with 12mm borescope

Table 4.1: Comparison between 8 and 12mm borescope



Parameter	8mm Borescope	12mm Borescope	Clinical Impact in Cervical Screening
Probe Diameter & Space	Slender (7mm)	Bulky (12mm)	This is the most critical factor. The 7mm's slim profile allows it to fit easily alongside other instruments (e.g., biopsy forceps, cytobrush), enabling a "see-and-treat" workflow. The 12mm would likely be too large, causing instrument clashing and obstructing the view of the cervix.
Manoeuvrability	High	Low	The 7mm can be easily angled and moved to inspect the entire cervical surface and vaginal walls without repositioning the speculum. The 12mm's size would severely restrict movement, making a complete examination difficult or impossible.
Depth of Field (DoF)	Deeper / Greater	Shallower	A deeper DoF is a major clinical advantage. It keeps more of the cervix in focus at once, reducing the need for constant focus adjustments while the clinician is concentrating on identifying lesions or guiding another instrument. This makes the procedure faster and more efficient.
Image Quality	Clinically Sufficient	High Definition	While the 12mm offers superior resolution, this is irrelevant if the device is too cumbersome to use. The 7mm provides image quality that is adequate for identifying key diagnostic indicators like acetowhite regions, mosaicism, or abnormal vascular patterns.

4.4.2 Camera size choice conclusion

For the specific context of cervical cancer screening within a speculum, the 8mm borescope is the far more practical and effective option.

Its main advantages are not just technical but procedural. The slender design is crucial for working in a crowded and confined environment, and its greater depth of field simplifies the examination process. The theoretical superiority of the 12mm's image quality is overshadowed by its large size, which makes it unsuitable for this application. The key factor is procedural viability, and the 8mm borescope allows for a smooth and complete clinical workflow where the 12mm would not.

4.4.2 Motion blur

Since the AI takes individual frames and processes, the image must remain stable when the pictures are taken. AI models work better with high-resolution input; blurriness reduces diagnostic accuracy (Figure 4.22).

Motion can be caused in two ways: movement of the patient or/and movement of the endoscope by the medical professional (Figure 4.21).

Patient-Induced Motion:

- Sway/Yaw movements: Lateral displacement due to patient discomfort or involuntary responses.
- Axial movement: Forward/backward motion during speculum positioning.
- Reflex responses: Sudden movements due to examination sensitivity.

Operator-Induced Motion:

- Endoscope handling: Direct movement of the imaging device.
- Rolling motion: Rotation around the device axis due to cable management.
- Speculum manipulation: External movement affecting patient positioning.

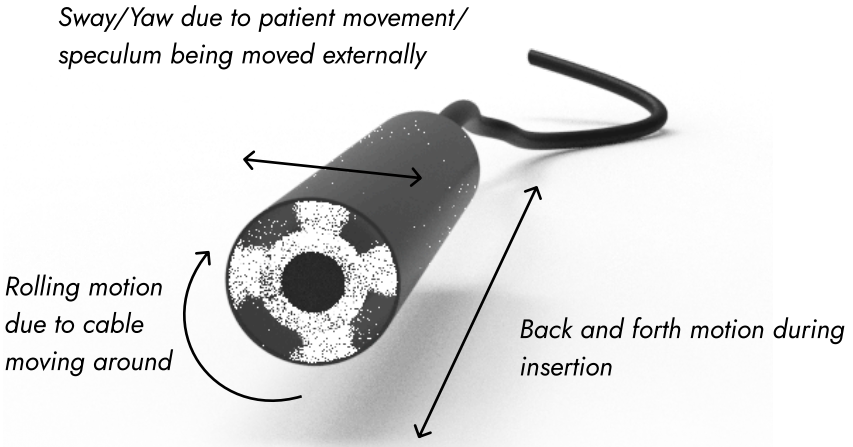


Figure 4.21: Motion of the endoscope



Figure 4.22: Motion blur due to movement of the speculum

4.5 Final Imaging Requirements

Out of the 12 imaging requirements, nine are defined here, and the remaining ones are related to software and AI and will be mentioned in chapter 6. With imaging requirements established, the next challenge is designing hardware that can meet these optical requirements while adhering to clinical constraints.

Table 4.2: Imaging requirements based on experiments

Code	Challenge	Final Requirement	Rationale / Design Implication
IM1	Specular glare (bright spots)	Reflection area < 10% of ROI; cross-polarized lighting with 90° offset	Glare obscures cervical texture and aceto-white changes (Section 4.33)
IM2	Depth of field, focus range	Sharp focus from 30–80 mm	Accommodates anatomical variation in cervix depth (Section 4.4.1)
IM3	Motion blur	Image shift < 2 px at 1280×720 over 1s	Stabilizes handheld jitter; ensures clear frame-by-frame analysis (Section 4.4.2)
IM4	Low-light image noise	Illumination ≥ 1500 lux; ISO kept < 800	Lower noise supports texture visibility for AI and clinicians (Section 4.2, from experimentation)
IM5	Resolution and detail detection	≥ 1280×720 px (HD)	Required for visualising and detecting smaller lesions, especially when scaled down (Sato et al., 2018)
IM6	Luminance uniformity	±10% illumination variance across cervix	Prevents hotspots and shadows which bias AI texture detection (Section 4.3.2)
IM7	Camera field of view	≥ 70° diagonal FOV	Needed to capture full transformation zone and cervix (LUMC doctor interview, 2025)
IM8	Image cropping and capturing regions of interest	Interventions introduced must preserve over 90% of the captured image	Interventions introduced need to ensure that most of the image is preserved and not cropped out to accommodate the intervention (Section 4.3.4)
IM9	Quality feedback loop	Real-time interventions for blur and sharpness correction	Increases user confidence during data capture, reduces poor data collection (4.4.2)

Must have Nice to have

Chapter 5: Hardware Design

The effectiveness of AI-assisted cervical imaging relies not only on the software components but also on the quality and usability of the hardware system that captures the images. In resource-limited environments, the hardware must be durable, easy to operate, and hygienic, while still enabling high-quality, diagnostic-grade image capture.

In this section, we discuss some of the hardware surrounding the borescope, assisting the clinician in working with the software to capture images. Other critical criteria for ensuring safety through maintaining a sterile system are also discussed. Key aspects include mechanical guides for camera positioning, integration with the speculum, considerations for cleanability and reusability, as well as physical ergonomics that facilitate the system's operation. Each design decision is guided by the specific challenges and constraints of low-resource clinical environments.

5. Hardware Design

From the clinical context and stakeholder interviews, the following hardware objectives were established:

- **Usability**: Assembly and disassembly must be intuitive, especially for nurses or midwives with limited technical training. This also includes feedback from doctors indicating that "if there are too many additional steps or things to add to the device, they will try and skip it" (LUMC Doctor, 2025).
- **Imaging Quality:** The device must support glare-free, sharp imaging of the cervix, under stable lighting conditions. This required careful co-design of optical components, lighting, and mechanical alignment.
- **Sterilizability:** All parts in contact with patients should either be autoclavable or easily wipeable with alcohol.
- **Affordability:** Total bill of materials should be kept below €200 to ensure deployment feasibility in LMIC clinics.

These goals arose from the design requirements gathered through expert interviews, literature review, experimental imaging needs (see Chapter 3, 4), and direct usability testing with clinicians.

5.1 Hardware Architecture

While several aspects of the design are iterative, others need to be fixed and become constraints based on system requirements and the project's scope, around which design iterations were made(Figure 5.1).

Fixed/Frozen components:

1. **Borescope camera:** The camera forms the core of the device, and the choice of camera was based on its features; it was fixed and did not change.
2. **Polariser:** The decision to incorporate polarisation early (discussed in section 4.3.5) meant that all subsequent housing and lens designs had to accommodate this addition to the camera without interfering with the field of view or increasing the device's tip diameter beyond what the C-Spec speculum could tolerate

Designable components:

The need for these components was established based on early design explorations (Appendix A2), which were based on experimental results (section 4.2).

These components were developed and refined over the course of the project through prototyping, feedback and usability testing.

1. **Camera housing:** The camera casing serves both as a protective shell and as an interface with the rest of the system. This was designed and optimised for protection and functionality.
2. **Camera guide:** This component was developed to help users maintain orientation and assist with holding the camera in a fixed position during image capture.

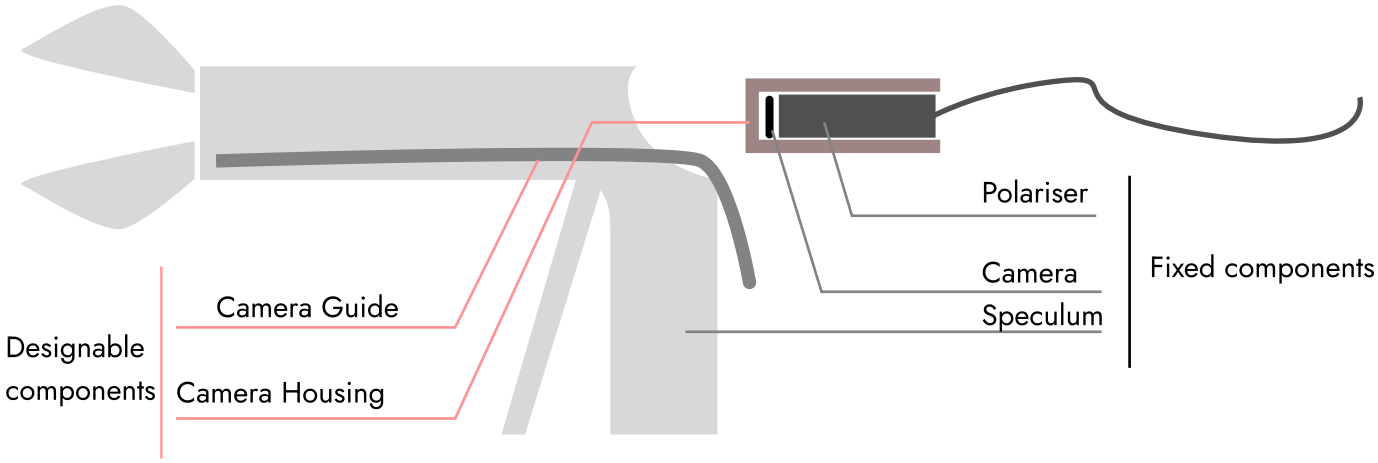


Figure 5.1: Hardware overview

5.2 Hardware List Of Requirements

Considering the fixed constraints, the hardware system was developed to meet the requirements outlined in Section 3.2, and Table 5.1 provides some rationale behind these derived requirements. Through this section, the hardware requirement codes will be referenced and how they drive the design and are met will be discussed

Code	Requirement Summary	Rationale / Design Implication
HW1	No on lens condensation at 100% relative humidity	No distortion to the image(Derived from experiments)
HW2	Tool-free attachment	Enables quick sterilization (e.g., with alcohol) and enables patient comfort supports field usability
HW3	Defined patient-contact constraint and camera range	Provides stability while allowing precise repositioning during imaging
HW4	Camera must not contact patient tissue	Ensures safety and hygienic barrier between electronics and patient. Ensuring that it is not an applied part(ISO 8600-1, 2015)
HW5	Construction must survive 1,000 use cycles	Supports long-term use in low-resource environments; avoids frequent replacement.(Interview Dr. Milkias, 2025)
HW6	Smooth, cleanable surface geometry	Prevents accumulation of biological debris and supports easy cleaning(Tandy et al., 2022)
HW7	Integrated access for swabs or acetic acid spray	Allows cleaning, swabbing, or spraying during VIA/VILI proceedures
HW8	Self-centering or alignment aid for image framing	Simplifies targeting and improves consistency of captured images
HW9	Locking or friction-based positioning	Prevents slippage and helps with easy clicking of pictures by the clinician
HW10	Preferably monolithic or low part count	Reduces assembly time, improves sterilizability, and limits loss of parts

Must have Nice to have

5.3 Camera Selection

At the centre of the system is a USB endoscope (borescope) that acts as the system's eyes. This camera's form factor was chosen because these modules are generally cost-effective, offer decent image quality, are compact, and have robustness (ingress protection)[HW5]. These features make them suitable for use in low-resource settings. They can also be sourced from various manufacturers, as many have similar features at comparable prices.

The specific module chosen for this project features:

- An 8 mm outer diameter, compatible with most vaginal specula, including the C-Spec.This choice balanced hardware compatibility in terms of size and image performance.
- The humid environment necessitates a borescope lens was also considered, with experiments indicating that an appropriate camera was chosen based on all these factors[HW1].
- A native resolution of 1280×960 pixels, sufficient for detecting lesions [IM5].
- 6 to 8 integrated white LEDs positioned around the lens, providing uniform illumination of the cervix during examination.[IM6]
- A 70° diagonal field of view, offering a balanced compromise between anatomical coverage and minimal distortion[IM7].
- USB 2.0 connectivity, ensuring compatibility with several systems

The camera is marked with an metallic line to signify which way is upwards to assist during setup.
Although a higher-resolution 5MP version was also evaluated and produced sharper images, its larger housing conflicted with the limited diameter of the instrument channel. Larger cameras would reduce space for essential tools like swabs or applicators and could affect patient comfort. Therefore, the 8mm module strikes an effective balance between hardware performance and clinical usability.

While the camera's integrated LED ring is crucial for capturing good images, specular reflections, as discussed in Section 4.3.5, are caused. This necessitates a polariser setup.

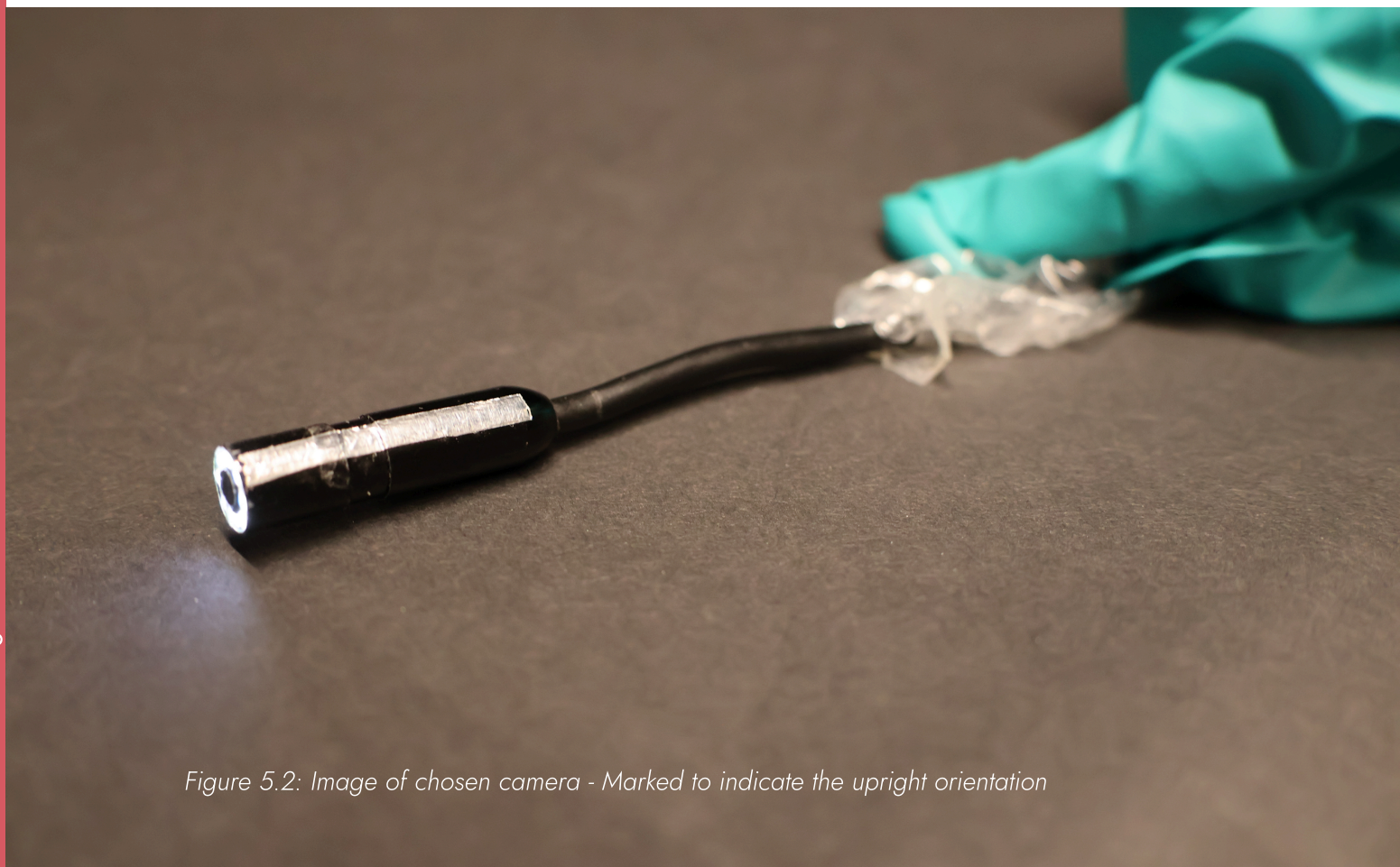


Figure 5.2: Image of chosen camera - Marked to indicate the upright orientation

5.3 Polariser Setup

The setup employs cross-polarisation using a polarising film over the lens and a film aligned in a complementary manner over the light source. This improves contrast and surface visibility, aiding both human observers and AI classifiers. The polarisers used in the imaging system must be precisely cut and aligned to ensure effective cross-polarisation (Figure 5.2).

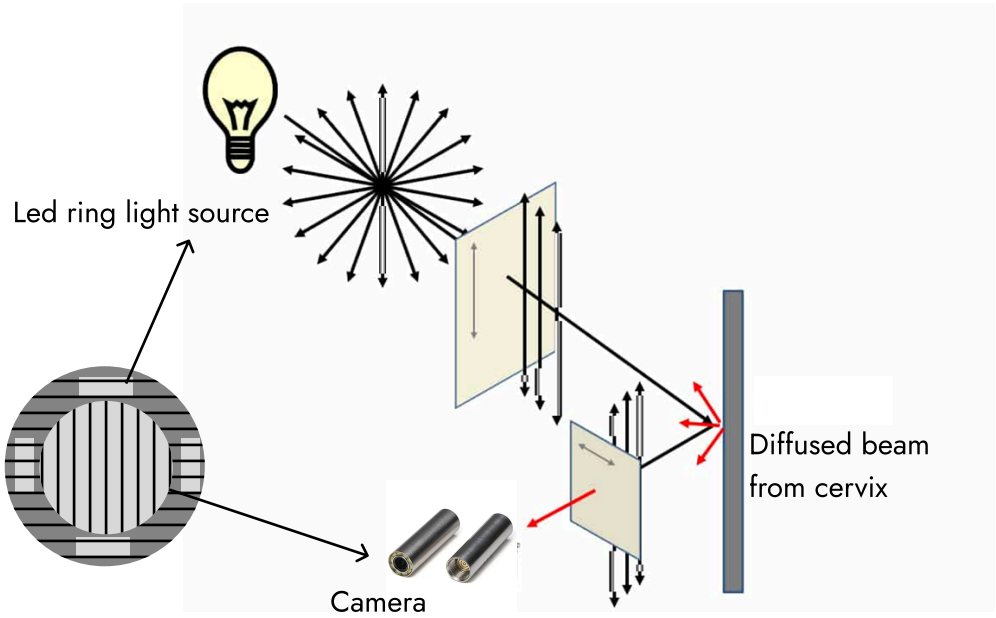


Figure 5.2: Polarization principle with the endoscope

5.3.1 Manufacturing and Assembly Process

To achieve this particular polariser size, a leather perforation tool was used to create accurately sized circular disks. This tool allows for precise cutting, particularly useful for producing uniform openings for the camera lens and light ring.



Figure 5.3:Cutting out polarisers using a leather hole puncher



Figure 5.4:Camera with polarised disks

The assembly process involves two steps:

1. A central hole is punched in the polarising film, and the resulting disk is adhered directly to the camera lens.
2. Second, a separate polariser is prepared for the LED light source. To achieve optimal cross-polarisation, the light ring polariser is manually rotated while observing the live image feed. The correct alignment is identified visually when specular reflections are minimised and overall image contrast is maximised. Once this optimal position is reached, the polariser is fixed in place (see Figure 5.4).

5.4.2 Evaluation of the polariser setup

To evaluate the polarisation effect, the system was tested on the inner surface of the mouth, a mucosal cavity with similar reflective properties to the cervix. This was confirmed by medical professionals(Interview with LUMC doctor, 2025), who suggested that the oral cavity may serve as an acceptable analogue for qualitative reflection assessments during initial prototyping.

The validation process relied on visual assessment of image quality improvement, with successful polarization characterized by noticeably reduced specular highlights(Figure 5.5) and improved tissue contrast as can be observed in the image that allows for better visualization of surface details and colour variations.



Figure 5.5:Cross-polarised light source and image inside mouth with minimised reflections (below) unpolarised light source and image inside mouth with specular reflections

5.4.3 Implementation Challenges in Compact Systems

The close proximity of the light source to the camera lens in this compact design presents a unique challenge. When the LED ring and camera are positioned extremely close (less that a millimetre of each other), diffused light can leak around the polarisation filters, particularly at the filter edges or through minor imperfections in the polarising film's positioning or cutting. This proximity constraint, while necessary for the compact form factor, can result in polarisation artefacts such as residual glare or light halos that would be less problematic in larger camera systems with more distance between the light source and the camera lens.

It was also observed that on occasion an unclean lens or scratched with particles could cause very heightened artefacts as well which cannot be corrected by simple image manipulation and the lens may need to be cleaned to continue to get good quality images.

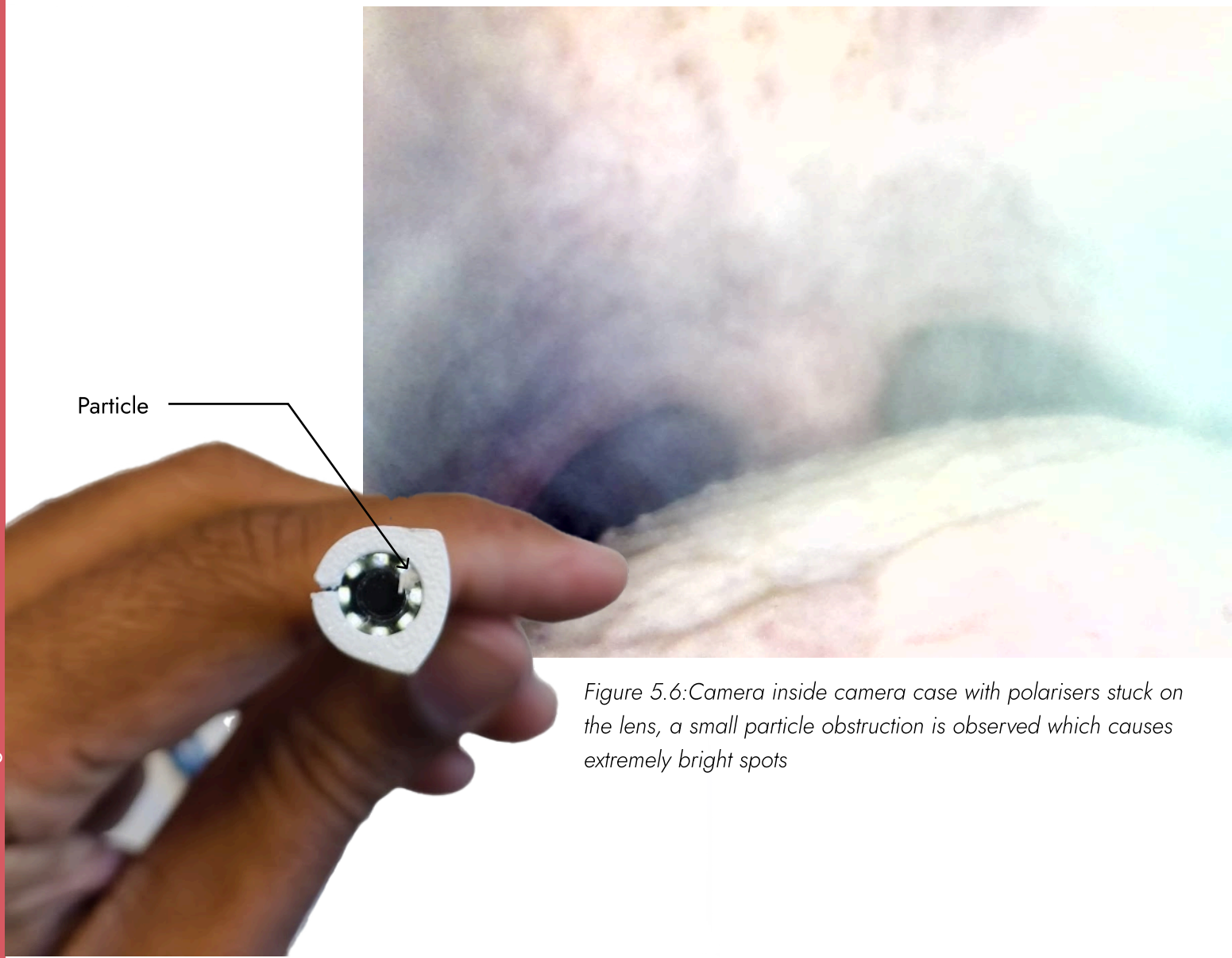


Figure 5.6:Camera inside camera case with polarisers stuck on the lens, a small particle obstruction is observed which causes extremely bright spots

5.5 Camera Housing And Guide

A critical challenge in the hardware development process was to securely stabilize the camera within the C-Spec speculum while ensuring that the camera's field of view remained unobstructed and that no part of the housing made contact with patient tissue. The camera housing serves as the mechanical interface between the optical system and the clinical examination tool.

The camera housing is meant to be the interface between the camera and the rest of the system(guide/speculum). For this critical piece of design, several iterations were made to get to the optimal solution.

1. **Ease of Cleaning and Sterilizability:** The housing had to be either alcohol-wipeable or autoclavable, depending on material of the part(Interview with LUMC doctor,2025). Smooth surface finishes and minimal seams and crevices were prioritized to reduce the risk of biofilm formation or contamination(Tandy et al., 2022).
2. **Ease of Manufacture:** To be suitable for scaling and potential local production, the housing had to be manufacturable using readily available methods. Initial versions were 3D-printed in PLA for quick testing, while final concepts were adapted for sheet metal fabrication. These processes are manufacturable and repairable in Ethiopia(Met FAB Manufacturing PLC, n.d.) and require minimal tooling investment.
3. **Mechanical Robustness:** The camera needed to remain securely fixed during insertion, examination, and removal, without shifting position. Mechanical interfaces had to tolerate repeated assembly and disassembly. The design also needed to prevent accidental detachment during use.

Concept 1:Magnetic Strip Concept

Overview:

The Magnetic Strip concept utilizes embedded magnets to guide and secure the camera within the speculum. As part of this concept, multiple cases were considered

Case	Guide strip
Magnetic	Magnetic
Metal	Magnetic
Magnetic	Metal

This design aims to offer discreet snapping movements and maintain smooth internal geometries, facilitating easy cleaning and providing ample space for the instrument channel.

Strengths

- **Ease of Cleaning:** The smooth geometry without complex crevices makes it ideal for cleaning.
- **Instrument Channel Accommodation**: The design allows for a spacious instrument channel, essential for swabbing and spraying instruments.
- **User Experience and stability:** Discreet snapping movements can improve the tactile feedback during camera positioning and allow the camera to stay where it was left by the user

Limitations

- **Sterilization Compatibility:** Requires specific types of magnets that can withstand autoclaving or cleaning with concentrated alcohol, potentially increasing material costs and complexity(Eec, n.d.). In order to have good resistance this increases the cost considerably.
- Sterilisation procedures could also accelerate galvanic corrosion - expending on the environment and other factors, the 304(magnetic) might corrode slightly to protect the 316(speculum material), which has better corrosion resistance. (Galvanic Corrosion - Komaspec, n.d.)
- **Manufacturing Complexity:** Integrating magnets into the design may complicate the manufacturing process.
- **Costly:** Small magnets which are autoclavable can cost as high as 30 euros(E-magnets, 2025).



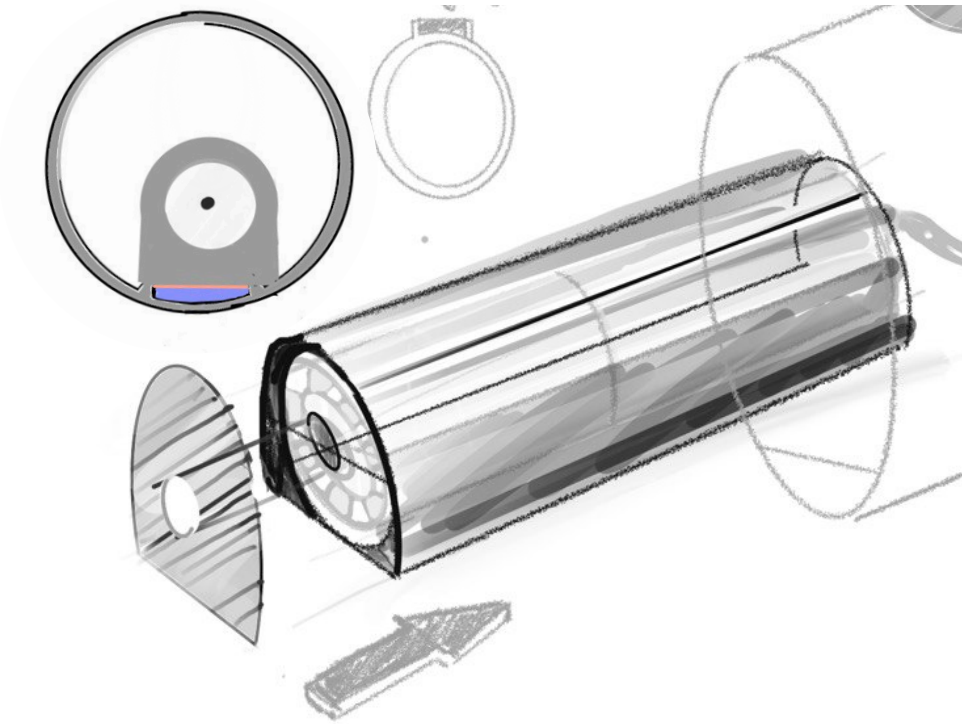


Figure 5.7: (left basic-prototype of magnetic strip, (right) Sketch vision for the prototype

Concept 2: Removable Guide Rail Concept

Overview:

The Removable Guide Rail concept introduces a detachable component that guides the camera. This design focuses on ease of cleaning and simplicity, aiming to prevent direct contact with patient tissues while being made from readily available materials.

Strengths

- **Ease of Cleaning**: The removable nature allows for thorough cleaning, reducing the risk of contamination.
- **Simplicity**: Straightforward design facilitates manufacturing and assembly.
- **Safety**: Physical separation between the camera and patient tissues enhances safety.

Limitations

- **Additional Component:** Introducing a separate part may complicate the assembly process and increase the risk of misplacement.
- **Instrument Channel Space:** The added component could reduce the available space for instruments, potentially impacting functionality.



Figure 5.8: Flat view of the prototype

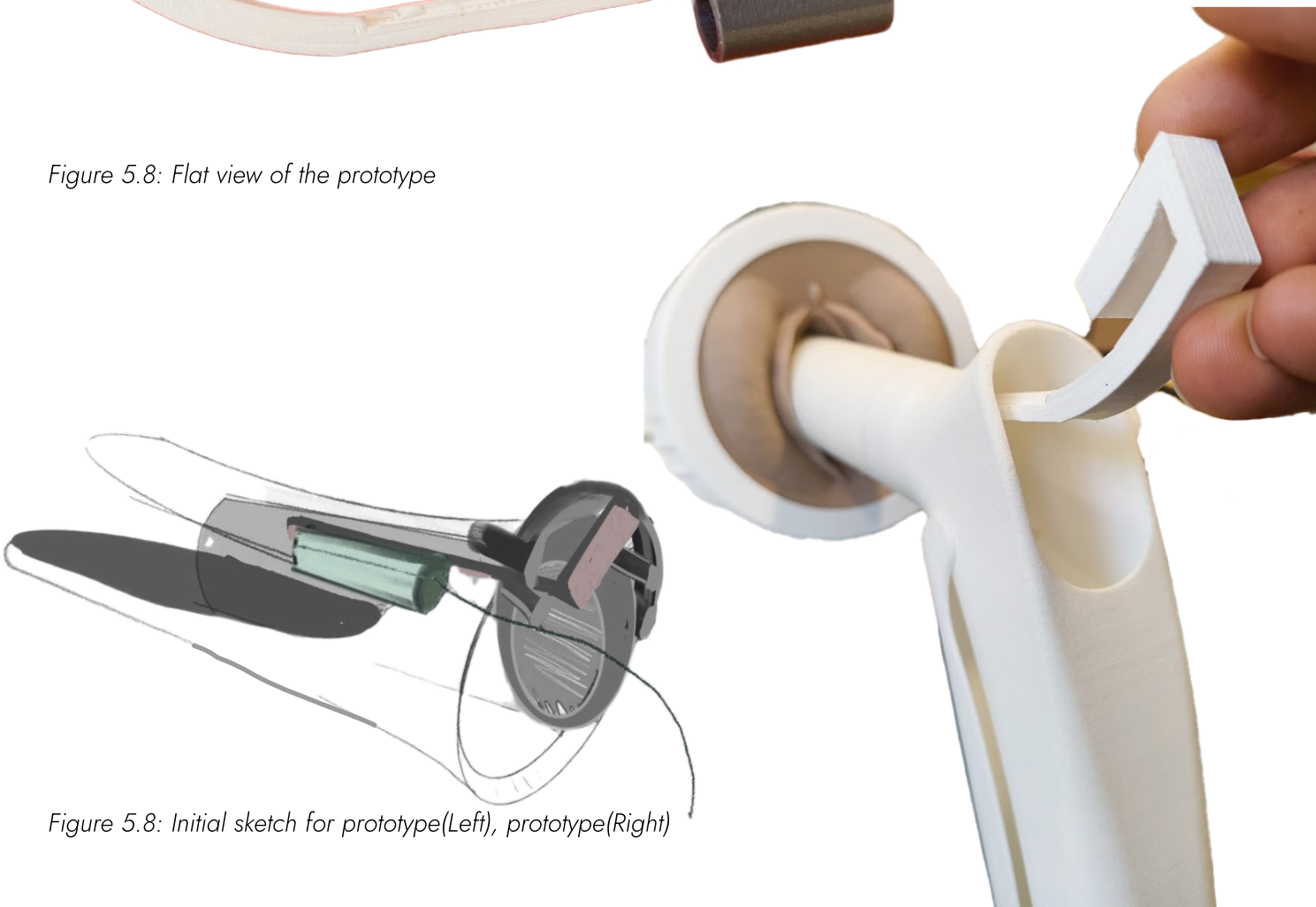


Figure 5.8: Initial sketch for prototype(Left), prototype(Right)

Concept 3: Integrated Guide Rails Concept

Overview

The Integrated Guide Rails concept features built-in channels within the speculum to guide the camera. This design emphasizes robustness and simplicity, aiming to prevent direct contact with patient tissues and accommodate various instruments.

Strengths

- **Robustness**: The integrated nature of the guide rails enhances structural integrity.
- **Safety**: Fixed pathways help prevent unintended contact with patient tissues.
- **Instrument Channel Space:** The design allows for sufficient space to accommodate necessary instruments.

Limitations

- **Manufacturing Challenges:** Creating precise internal geometries may be complex and costly.
- **Cleanability**: Internal grooves and channels could harbor contaminants, making thorough cleaning more difficult.
- **Insertion Difficulty**: Navigating the probe through fixed channels may be challenging, potentially affecting usability.



Figure 5.7: (Left) sketch showing groove and insertion of polariser, (Right) Different variations of the groove

5.5.1 Conclusion

To evaluate the design concepts, a Harris Profile was used with the primary design requirements serving as weighted criteria. This method was chosen because it offers a clear visual comparison of each concept's strengths and weaknesses, making it easier to identify the most viable option.

- Magnetic Strip concept, while offering good position-holding capabilities and an easy-to-clean geometry, was limited by the sterilization compatibility of the magnets and the high cost of the magnets themselves.
- Integrated Guide Rails concept provided a robust and safe design. However, it faced potential manufacturing challenges and compromised cleanability, as the internal channels would be difficult to access and sterilize thoroughly.
- The Removable Guide Rail concept excelled in simplicity and cleanability. While it introduces an additional physical component to the system, the Harris Profile analysis confirmed that its high performance in critical areas ease of cleaning, low cost, ease of manufacture, and robustness outweighed this single drawback. It also adds an extra physical component to the system, which is not ideal; however, the advantages of such a concept outweigh the disadvantages.

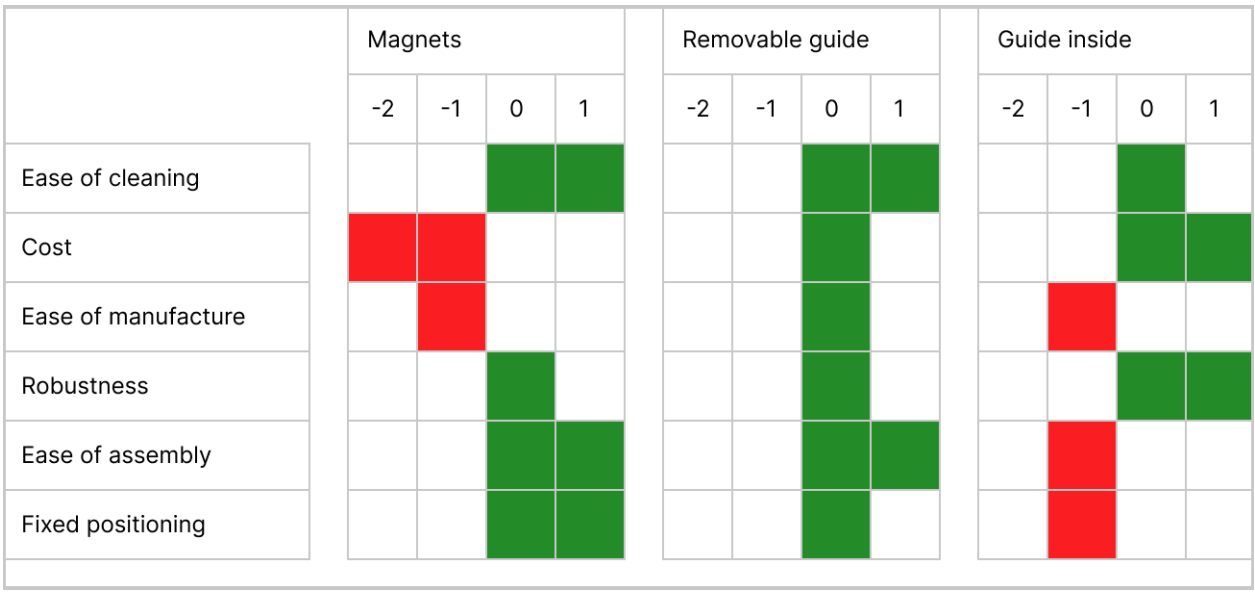


Figure 5.8: Harris profile comparison of prototypes

5.6 Final Design

The selected concept combines the stability of a fixed guide rail with the flexibility of a removable system, creating a removable guide rail that can be positioned inside the speculum. This hybrid approach addresses multiple clinical requirements simultaneously.

5.6.1 Core Functionality

The guide rail provides a stable sliding track along the length of the speculum for the camera housing [IM3], while maximising the available instrument channel space [GH6]. The rails that hold the camera case down mechanically are at a slight 10-degree angle (Figure 5.9), eliminating the need for additional fastening mechanisms.

The design fits into the clinical workflow by enabling rapid and intuitive attachment and detachment (see chapter 7) of both the guide rail and camera housing [HW2], facilitating quick setup and efficient cleaning protocols between patient examinations. A small extrusion at the distal end of the guide serves as a mechanical stop, preventing the camera case from advancing beyond the speculum and making unintended contact with patient's tissue [HW4].

Multiple cross-sectional profiles were evaluated during prototyping, with the final geometry optimised for two critical factors : ease of sterilisation [HW6] and maximisation of instrument channel space. The simple, robust design avoids narrow features or stress concentrators that could lead to mechanical failure during repeated use [HW5].

5.6.2 Design Trade-offs

While a centred camera position would provide optimal cervical visualization, the off-centre rail placement was necessary to preserve instrument access during procedures. This compromise ensures that clinical tools can be inserted with ease while maintaining acceptable imaging angles.

Multiple design iterations refined the rail dimensions and camera housing interface, with each iteration tested for fit precision and clinical usability. The final design represents an optimal balance between mechanical stability, cleaning efficiency and practical clinical implementation.

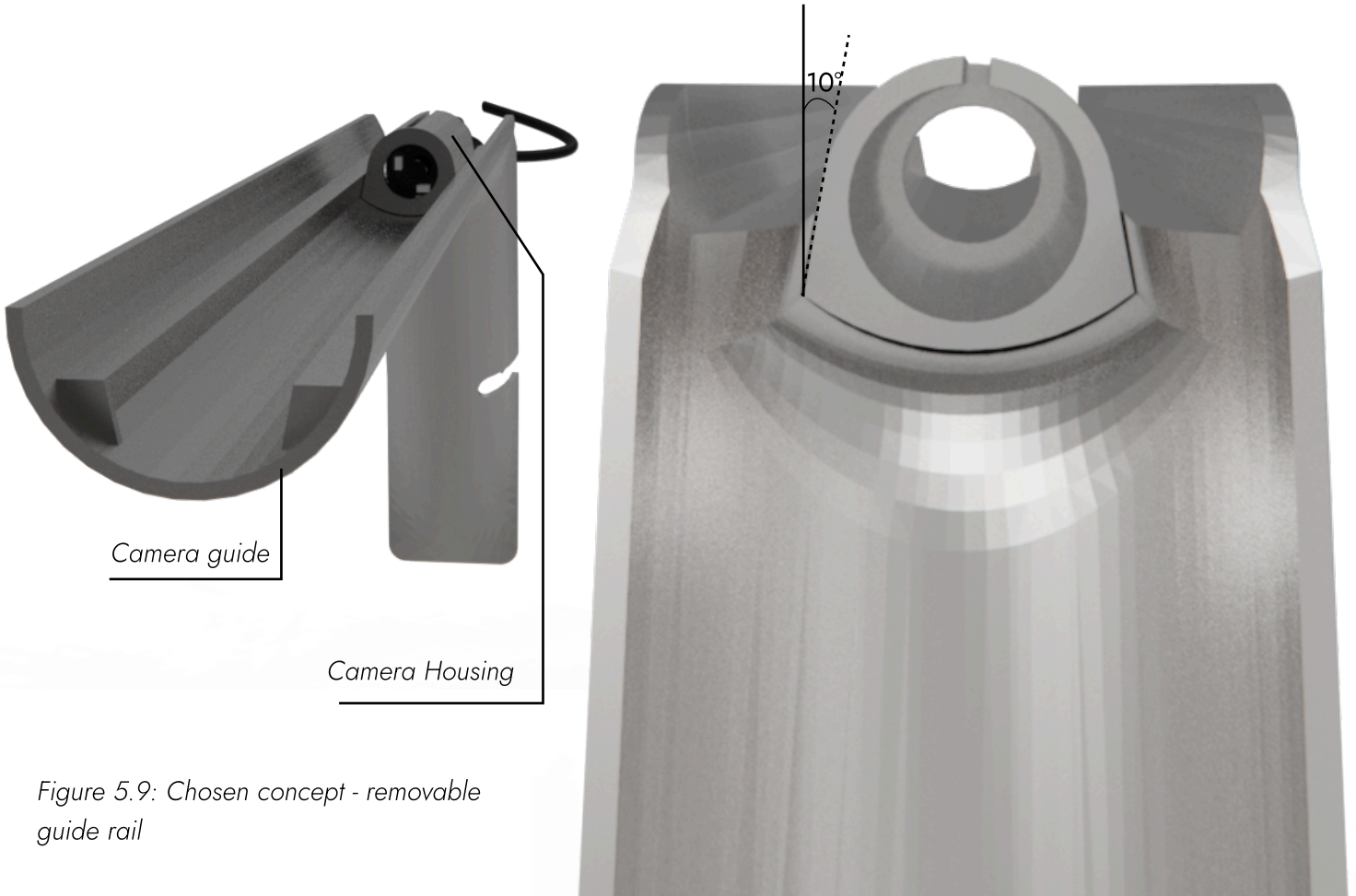


Figure 5.9: Chosen concept - removable guide rail

5.6.3 Manufacturing considerations

The hardware system was designed not only for performance and usability, but also for feasibility in low-volume, distributed manufacturing settings, such as local workshops or regional fabrication hubs in LMICs.

The guide rail and handle assembly are designed for metal fabrication using flat stock or extrusions. Two main manufacturing approaches are considered:

- **Extrusion and Welding:** The guide rail can be manufactured as a straight metal extrusion, with the handle as a separate element. The handle is then welded or brazed onto the rail, aligned using jigs for consistent positioning. This method is cost-effective at small scale and allows for simple local production. For low-volume prototyping however, the sheet metal was just hammered into shape with a core for support
- **Forged Flat Handle:** To reduce machining, the handle's profile can be achieved by mechanically flattening the extruded tube with a hammering process or hydraulic press. This creates a grip-friendly surface without additional joining processes. This could be cheaper than creating custom tooling

Figure 5.10: Low volume manufacturing steps



1. *Hammering the parts into shape using a solid core.*





2. *Guide and camera cover formed from 1.5mm sheet metal*



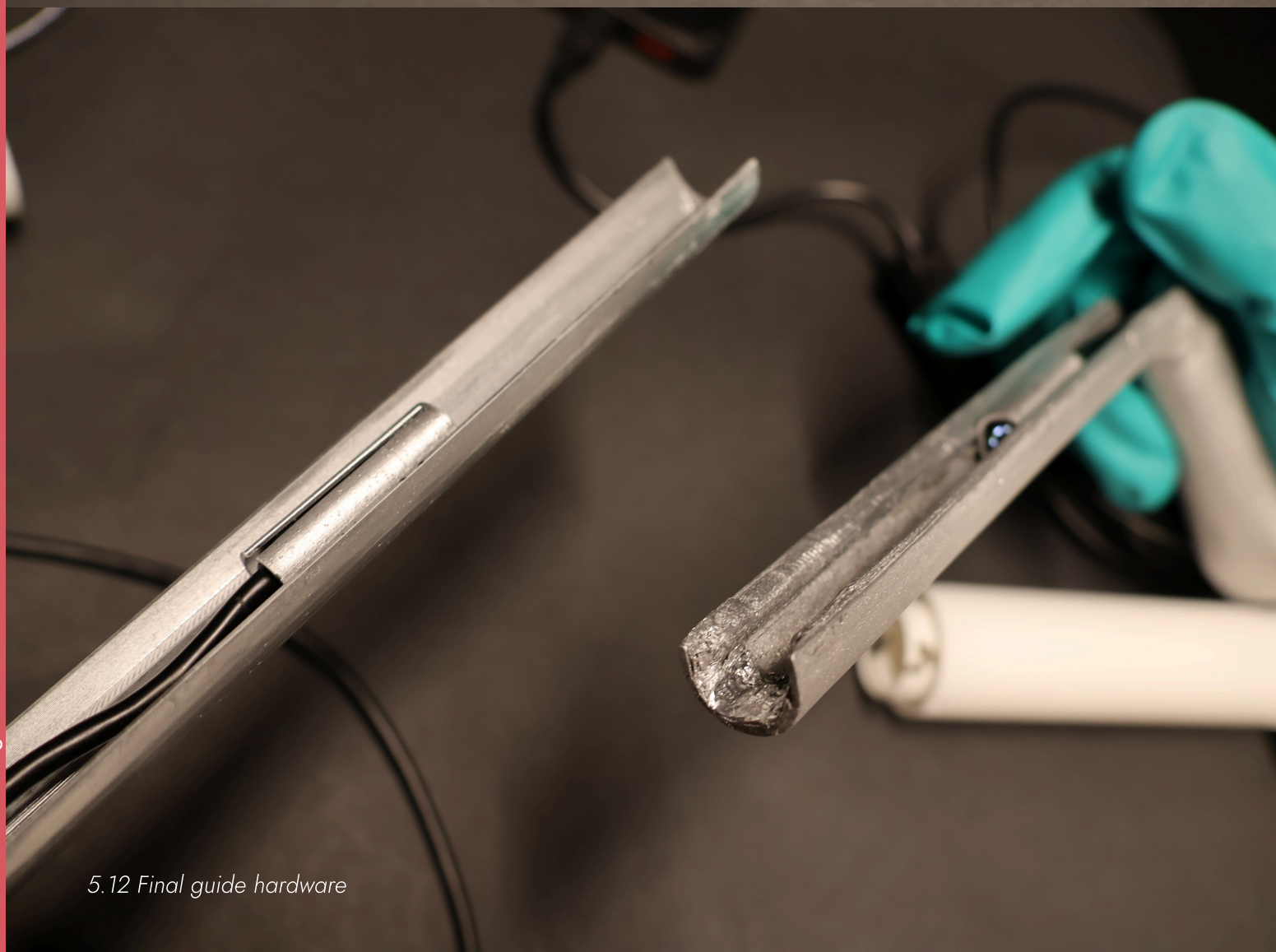
3. *Welding the 2 half pipes parts together to form the guide*



5. *Metal epoxy for the guides wouldn't be needed if this part were extruded in high-volume production.*



5.11 Guide hardware prototype evolution



5.12 Final guide hardware

Chapter 6: AI Model design and training

This chapter details the design and training of the Artificial Intelligence (AI) model that serves as the core of the diagnostic system. The guiding philosophy is to position the AI not as a replacement for clinical expertise, but as a collaborative diagnostic support tool that works alongside healthcare professionals. It is designed to function as a "digital colleague," providing consistent and objective evaluations to assist non-specialist providers in low-resource settings.

The following sections will explore the complementary strengths of AI's pixel-based vision and human contextual understanding. We will cover the specific architectural choices, justifying the selection of the appropriate neural network model, making it suitable for deployment on low-cost hardware.

6. AI Model design and training

6.1 The Role Of AI In Cervical Screening

In this thesis, AI is positioned as a diagnostic support tool that works in collaboration with healthcare professionals rather than replacing them. The system functions as a digital colleague, providing consistent and objective evaluations of cervical images to assist non-specialist providers in low-resource settings. The tool itself relies on the expertise of the healthcare professionals to identify and capture the relevant regions for the diagnosis.

At the core of this system is a Convolutional Neural Network (CNN), a deep learning algorithm inspired by the visual processing architecture of biological systems. CNNs have revolutionised computer vision, enabling automated image classification with unprecedented accuracy (Kim et al., 2022). Their ability to learn hierarchical visual patterns makes them particularly suitable for medical imaging tasks where subtle visual cues must be detected reliably.

The system outputs probability scores along with the diagnoses, along with heatmaps to encourage clinicians to understand the AI's recommendations rather than accept them, alongside their clinical assessment and patient context.

6.2 AI Vs. Human Vision In Medicine

AI and humans process information in a very fundamentally different manner. These differences and similarities if any are explored and the advantages and disadvantages of each type of 'vision' is explored.

6.2.1 AI's pixel vision

AI processes images as numerical grids of pixel values, analysing patterns in colour, texture, and intensity with mathematical precision. Unlike human vision, AI can independently extract features from different colour channels (red, green, blue). These colours combine in various ratios to form digital images. It is able to learn to prioritise the most diagnostically relevant information from each channel (Figure 6.1). This capability enables AI to enhance contrast and detect subtle features, such as textural differences or vascular patterns, that may indicate pathology (Sellors J, 2003).

This approach offers some unique advantages: AI can detect slight variations in colour intensity that might be imperceptible to the human eye and maintain consistent performance regardless of viewing conditions or operator fatigue.

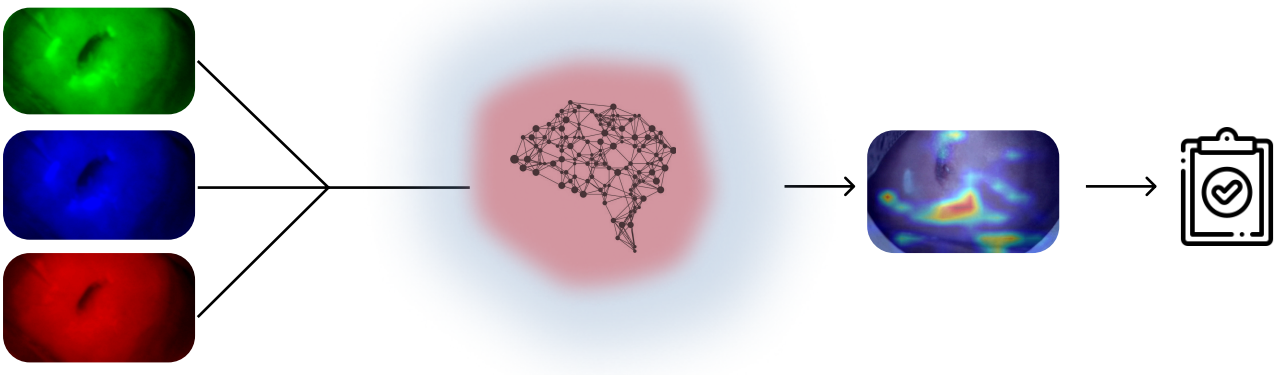


Figure 6.1: High level overview of how AI see's the world

6.2.2 Human vision

Human diagnosticians bring contextual awareness, clinical experience, and anatomical understanding to image interpretation. Clinicians integrate visual findings with patient-history, clinical symptoms, and their accumulated knowledge to make diagnostic decisions. As one interviewed doctor noted, experienced clinicians can often make accurate diagnoses even from lower-quality images due to their contextual understanding and pattern recognition skills, which are developed through years of practice.

To enhance their visual assessment, clinicians often employ additional tools such as green light filters to improve vascular pattern visibility and contrast enhancement (Zhiyun Xue et al., 2022). Clinical practice varies in screening approaches – while some doctors prefer VIA (acetic acid) testing, others favour VILI (Lugol's iodine), and many use both methods for cross-verification (Spijk.M, 2024). The choice often depends on available compounds at the clinic and individual practitioner preferences based on their training and experience.

However, this expertise is not universally available. Healthcare workers without extensive training in cervical pathology may struggle to distinguish between benign inflammation and precancerous lesions (Interview with Dr. Milkias, 2025), highlighting the potential value of AI as a diagnostic support tool.



Figure 6.2: Cervical Cancer Explanation with Dr Conrad of GIC Space(M.Hofstede,2024)

6.3 Training the AI System

Training a neural network for cervical screening involves feeding it large quantities of labelled images, cervical photographs annotated as VIA Positive, VIA Negative, or Suspicious for Cancer. The network consists of interconnected nodes with adjustable weights and biases that determine how image data flows through the system.

The training process works through iterative refinement:

1. Input Processing: The AI receives a cervical image and processes it through multiple layers.
2. Feature Extraction: Early layers detect basic features like edges and textures.
3. Pattern Recognition: Deeper layers combine these features to recognize complex patterns.
4. Classification: The final layers produce probability scores for each diagnostic category.
5. Error Correction: A function called the loss function measures prediction accuracy, and the network adjusts its parameters to improve performance.

This process repeats across thousands of images and multiple training epochs, gradually improving the model's ability to distinguish between normal and abnormal cervical findings.

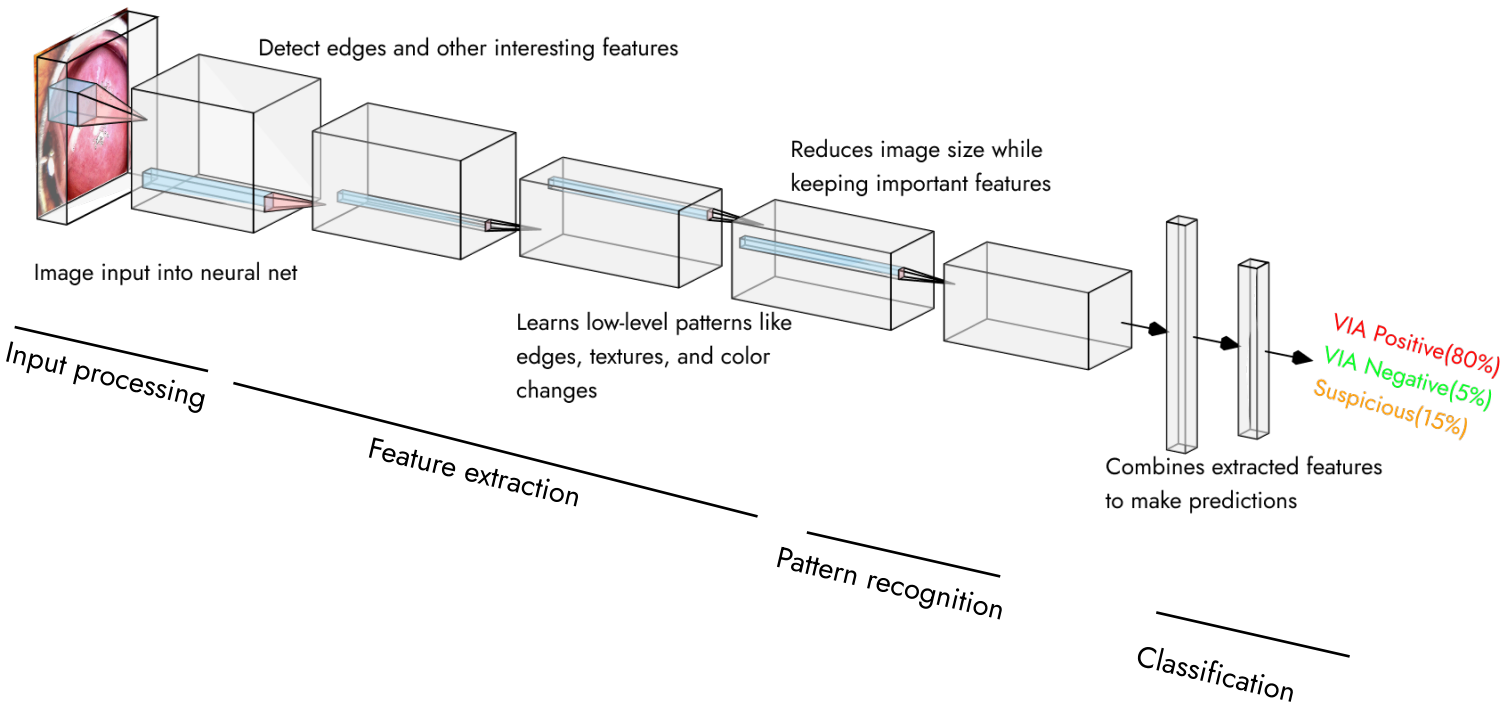


Figure 6.3: AI learning process

6.4 Model Architecture And Design Choices

The specific architectural choices, justifying the selection of the EfficientNet model for its balance of high performance and computational efficiency, making it suitable for deployment on low-cost hardware

6.4.1 Choice of AI model: EfficientNet

EfficientNet was chosen as the base CNN architecture for several key reasons:

1. Strong Medical Imaging Performance: In benchmark studies, including prior work by Spijk (2023) at TU Delft, EfficientNet variants (B0–B2) demonstrated superior or comparable performance to heavier models, even on small-scale medical datasets.
2. Computational Efficiency: Given deployment requirements in low-resource settings, EfficientNet's computational efficiency is important for quick processing on less powerful processors like the one in the Raspberry Pi 4 used in this project(Figure 6.4).
3. Robust Generalization: The model can train and adapt to new data with limited training, with training strategies.

6.4.2 Model Variant Selection

Various EfficientNet variants (B0-B4) were evaluated on the dataset.(Figure 6.5)(Appendix A4) EfficientNet-B0 was ultimately selected as it achieved the best accuracy while being the most time-efficient. Since the system is intended for deployment on hardware without heavy computational capabilities, quick turnaround time is essential for healthcare workers.

6.4.3 Colour Processing Capabilities

Unlike human clinicians who may rely on specific filtering techniques to enhance visibility, AI systems can autonomously extract relevant features from different colour channels. Research by Sato et al. (2018) found that in AI applications, the total number of training images played a more significant role in improving accuracy than categorising images based on green filter presence or absence. This suggests that deep neural networks can learn to prioritise useful features from raw colour data without requiring pre-filtered inputs.

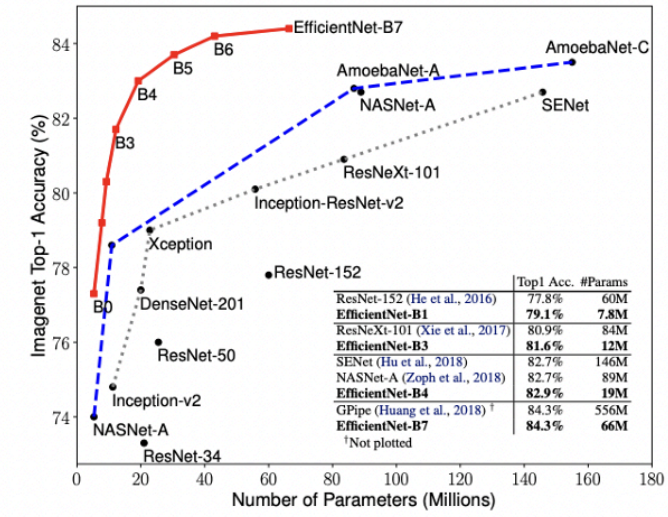


Figure 6.4: EfficientNet vs other architectures (Tan & Le, 2019).

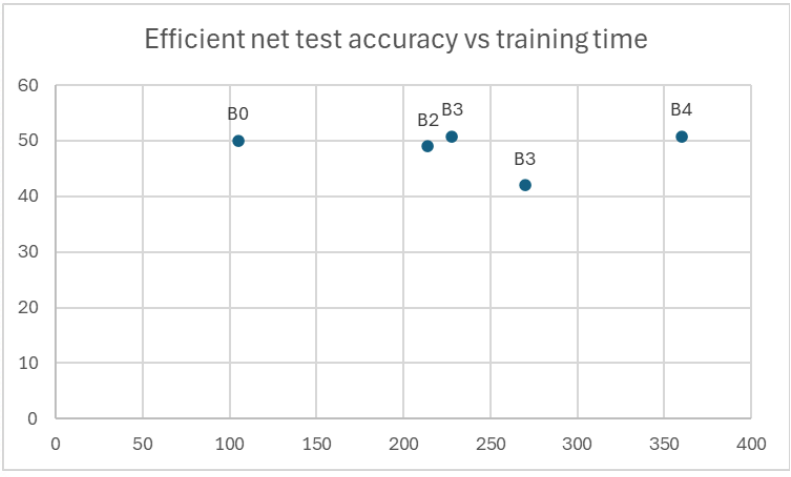


Figure 6.5:Efficient net b1-b4 comparison over 15 epochs on the Mobile ODT dataset(Accuracy vs time(s))

6.6 Addressing Limited Data: Transfer Learning

Typical CNN-based learning requires at least 1000+ images per class (Warden, 2017). However, the current dataset contained only around 200 images, which could be expanded to roughly 800 through data augmentation techniques, such as flipping and rotating. This remains insufficient for training a CNN from scratch without significant risk of overfitting. Overfitting is a phenomenon that occurs when a machine learning model learns or matches the training data too closely, leading to poor performance on new, unseen data (Overfitting, n.d.). This necessitates alternative approaches to training the system.

To compensate for the limited availability of annotated cervical images, transfer learning was employed. Transfer learning utilises a trained model's knowledge to learn on a new dataset, aiming to improve learning in the target domain by leveraging knowledge from a source domain (Marques et al., 2022).

As part of this project pre-trained CNN architectures (such as EfficientNet-B0), initially trained on the ImageNet dataset which consists of images of generic objects, were fine-tuned for the specific task of classifying cervical images into VIA Negative, VIA Positive, and Suspected Cancer categories. The ImageNet-trained model can already identify low-level features, such as edges, texture and shape. The ability to extract these features from an image is transferable to medical imaging applications.
There are seveeral benefits to transfer learning (Murel & Kavlakoglu, 2025), rather can starting from scratch:

- Reduced Training Time: Fine-tuning pre-trained models requires significantly lesser time than training from scratch, since the model already 'knows' to look for certain patterns.
- Smaller dataset: Pre-trained models can capture general features, enabling better performance on smaller, specialized datasets.
- Lower Computational Cost: Fine-tuning requires less GPU memory and fewer training iterations.

6.6.1 Multi-Stage Transfer Learning Strategy

To address the challenge of a limited training dataset, a standard single-step fine-tuning process proved insufficient. Instead, a more robust multi-stage transfer learning strategy was devised and implemented. This approach was selected because it leverages the core benefits of transfer learning, such as reduced training time, lower computational costs, and improved performance on smaller, specialised datasets, while adding a critical layer of contextual learning.

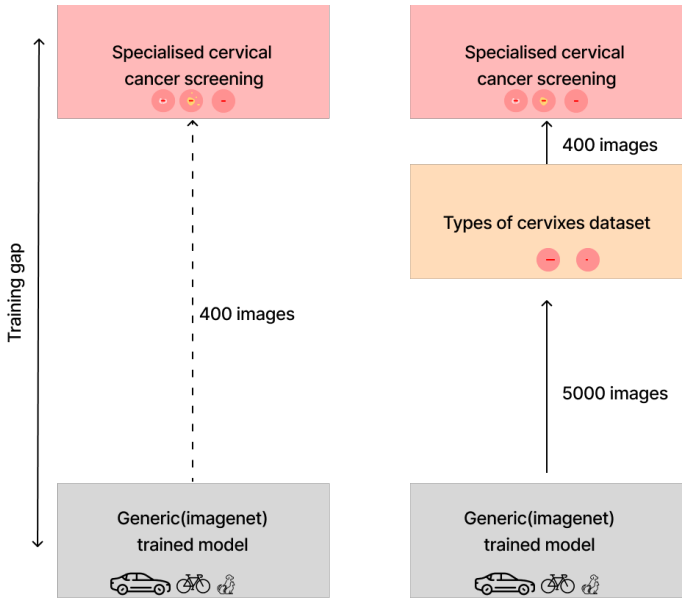


Figure 6.6: Graphic showing the training gap and the need for a multi-stage approach

The training stages are on the right to give a comprehensive overview of what is taking place in that phase, and on the left there are more implementation details.

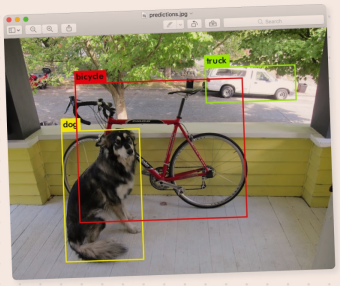
Stage 1: Domain Adaptation on Cervical Anatomy

The first stage aimed to bridge the large conceptual gap between the generic objects in the ImageNet dataset and the specific domain of medical imaging. The goal was to teach the model the fundamental features of cervical anatomy before asking it to make a diagnosis.

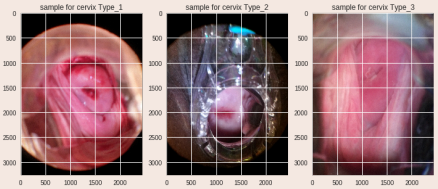
To achieve this, a pretrained EfficientNet-B0 model was fine-tuned on a large, general dataset of approximately 4,000 cervical images from the Mobile ODT dataset. The training in this stage was configured to allow for maximum adaptation: all layers of the network were left trainable, and extensive data augmentation (rotation, flips, zoom) was used alongside a categorical cross-entropy loss function and the Adam optimizer. This process adapted the model's feature detectors from generic patterns to cervix-relevant ones, like organic textures, shapes, and colours.

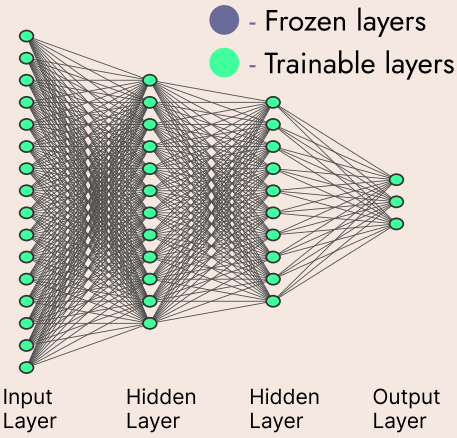
Figure 6.7: Steps for multistage training

Step 1: Start with an efficientNet which is trained on generic data(imagenet)



Step 2: Tune the neural network to classify cervixes with the large 'types of cervixes' dataset (Mobile ODT), allowing the whole network to morph and change to learn the new data



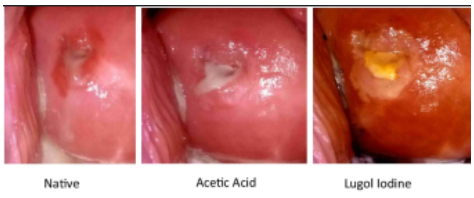


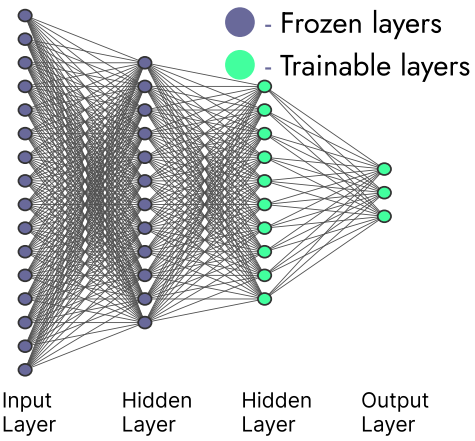
Stage 2: Fine-Tuning for Diagnostic Classification

Once the model had learned to "see" a cervix, the second stage specialized its knowledge for the diagnostic task. The model from Stage 1 was fine-tuned on the smaller, specific dataset of ~300-400 images, which were classified into three categories: VIA Negative, VIA Positive, and Suspected Cancer.

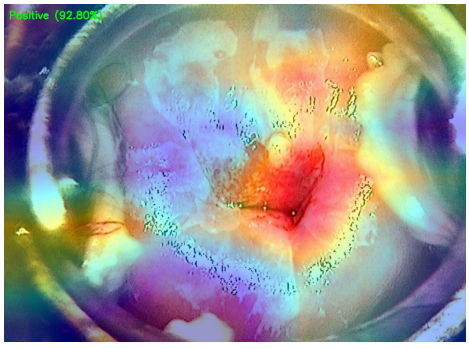
Given the limited size of this diagnostic dataset, a more targeted training approach was required to prevent overfitting. The model's lower layers, which had already learned the essential anatomical features in Stage 1, were frozen. Only the top layers were retrained, allowing the model to adapt its high-level reasoning for diagnostic classification while preserving its foundational knowledge. Data augmentation was again applied to increase the effective volume of the training data.

Step 3: Freeze half the network so that the features it has learnt earlier are retained while it continues to learn what tumours undergoing VIA and VILI look like learning to classify VIA positive, negative and suspicious using the IARC dataset





Step 4: Load the model in the program and run classifier based on real-time captured images. The heatmaps should help clinicians understand the AI's decision



6.7 Performance, Interpretability, And Validation Of The Strategy

The success of the multi-stage strategy was validated not just by accuracy metrics, but by a crucial enhancement in the model's interpretability and clinical relevance. Building on the foundational model from previous research, this project aimed to improve not only its accuracy but also its clinical trustworthiness.

The initial single-stage model from prior work achieved a promising accuracy of over 70%—surpassing the WHO's 60% sensitivity benchmark for manual VIA. However, as part of this project's deeper analysis, its interpretability was examined using Grad-CAM visualisations, which revealed a significant flaw. As shown in Figure 6.8 a(left), the model was focusing on irrelevant areas, such as the metallic jaws of the speculum, rather than the clinically important cervical tissue. This meant that despite its high accuracy score, its decision-making process was clinically invalid and could lead to dangerous misdiagnoses, a conclusion supported by its low confidence score of 44.9% on that prediction.

The multi-stage approach was specifically designed to correct this fundamental error. The results, shown in Figure 6.8 (right), demonstrate its effectiveness. The new model's Grad-CAM heatmap shows its attention correctly centred on the cervical tissue, ignoring the speculum. This improved focus translated directly into a more confident and trustworthy diagnosis, with the confidence score for the same image rising to 96.3%. The confusion matrix for the new model also reflects a more robust classification performance. This process emphasised the vital lesson that for medical AI, high accuracy is meaningless if the model is not focusing on the correct clinical features. The two-stage strategy was therefore validated as essential for creating a model that is not only accurate but also clinically relevant and trustworthy.

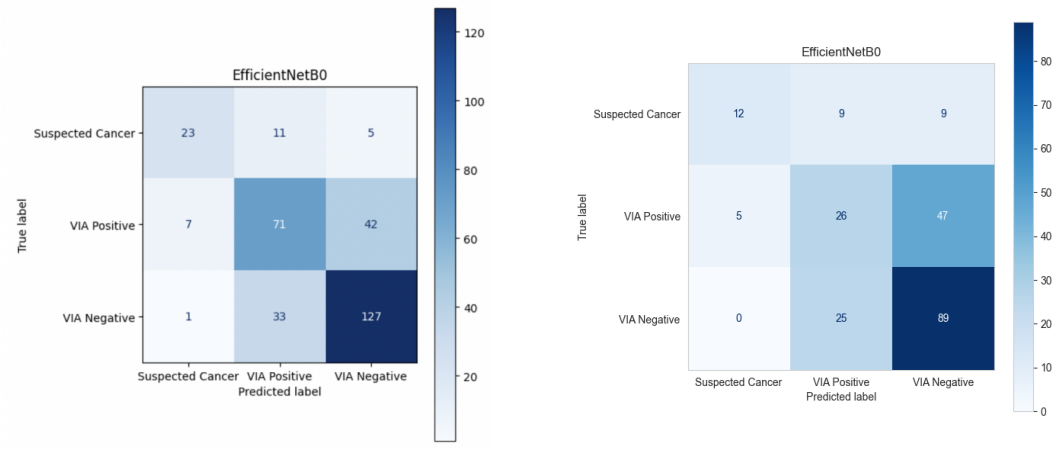


Figure 6.7: Previous results(left) vs new model's results

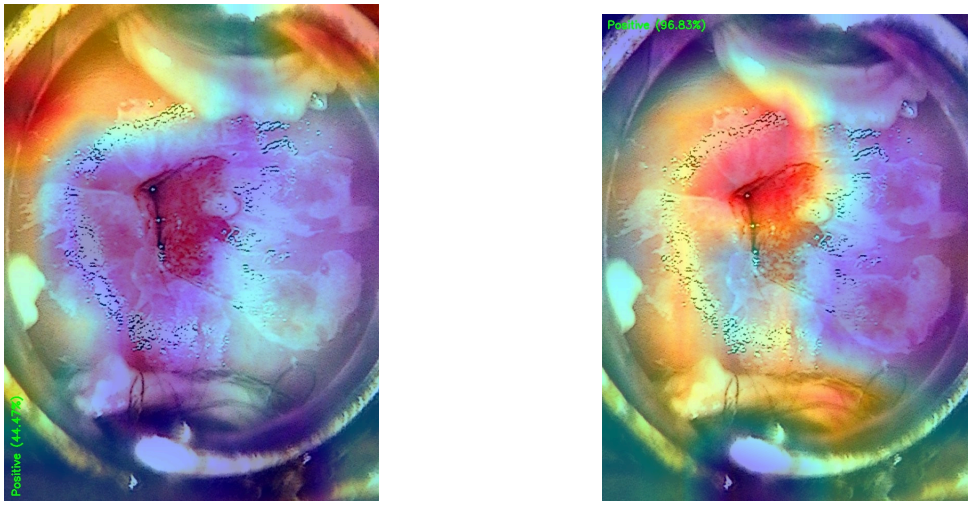


Figure 6.8: Previous results(left) with heatmap showing outer areas and lower confidence score vs new model's results focussing on the cervix and higher confidence score

Chapter 7: Integrated system

The preceding chapters have described the systematic design and validation of the core subsystems: the optical setup for glare-free imaging (Chapter 4), the durable and user-focused hardware guide (Chapter 5),and the reliable AI model (Chapter 6). While each component was optimised separately, the success of this project depends on their seamless integration into a unified, effective clinical tool.

This chapter presents the culmination of these efforts: the fully integrated, AI-assisted cervical imaging system. It explains how the mechanical, optical, electronic, and software elements are assembled into a functional, point-of-care device. We will first provide an overview of the final system architecture and then describe the complete clinical workflow, from initial setup to AI-assisted diagnosis. Finally, this chapter shares the results of the final validation tests with an OBGYN specialist, offering valuable, real-world feedback on the prototype's usability, ergonomics, and potential for clinical adoption. This marks the final technical step before the overall project evaluation in the following chapter.

7. Integrated system

7.1 System Integration Overview

The final cervical imaging system integrates mechanical, optical, electronic, and AI components into a unified system for screening. This chapter details how subsystems developed and tested in earlier chapters were brought together into a deployable unit.

The integrated system consists of:

Hardware Components:

· C-Spec speculum (unmodified standard design)
· Removable mechanical guide rail
· Stainless steel camera housing with biocompatible finish
· USB endoscopic camera (1280x960 resolution, integrated LED ring)
· Cross-polarisation filter assembly (glued to camera)

Electronics and Processing:

· Raspberry Pi 4B
· Custom software interface
· Portable power supply
· USB-C cable

Software and AI:

· Real-time image capture utility with quality assessment
· Focus sharpness feedback with visual indicators
· EfficientNet-B0 AI classifier
· Result display with GradCAM heatmaps and confidence scoring
· Offline operation capability with local data storage

These components together support a point-of-care cervical screening workflow.

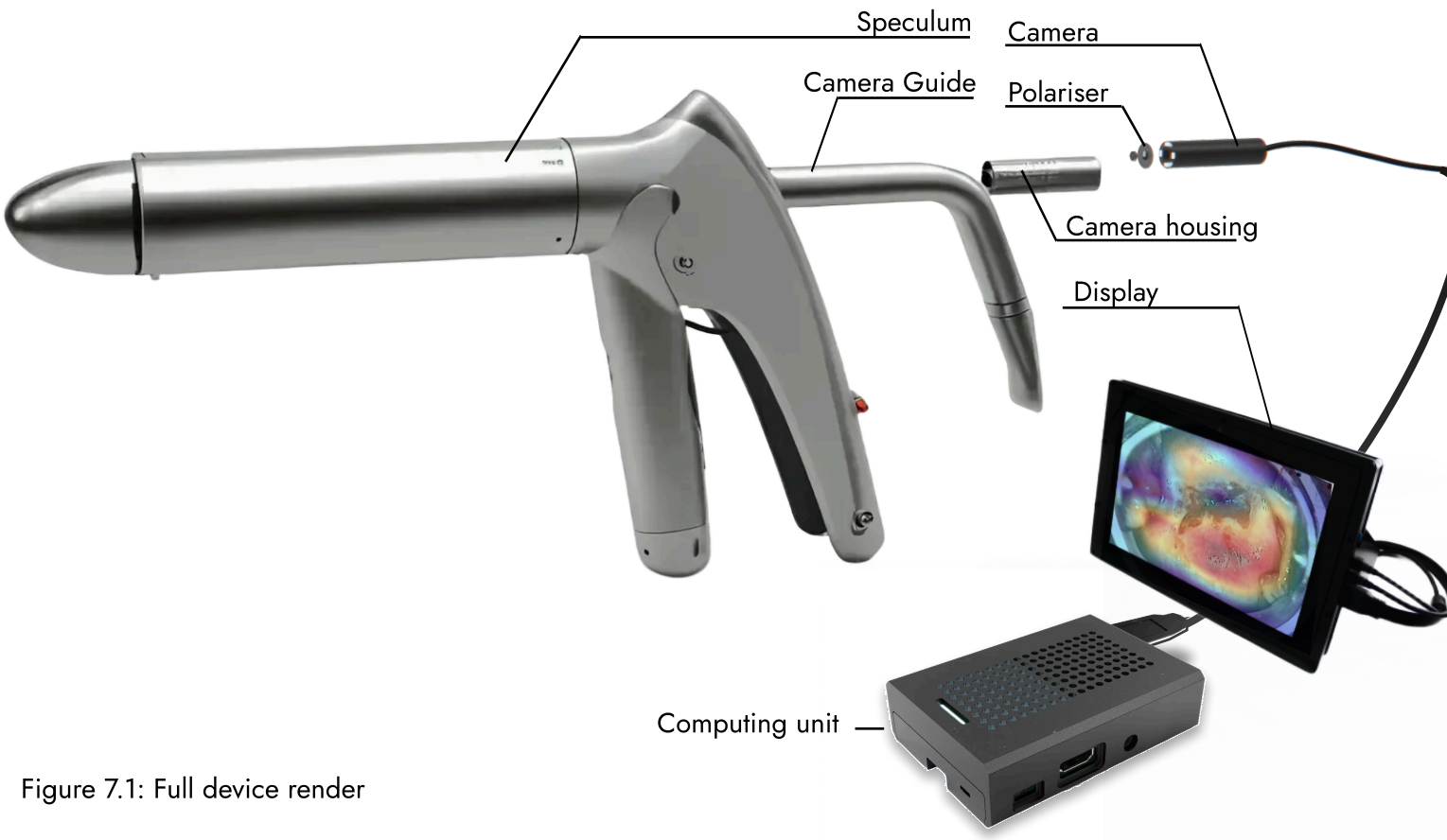
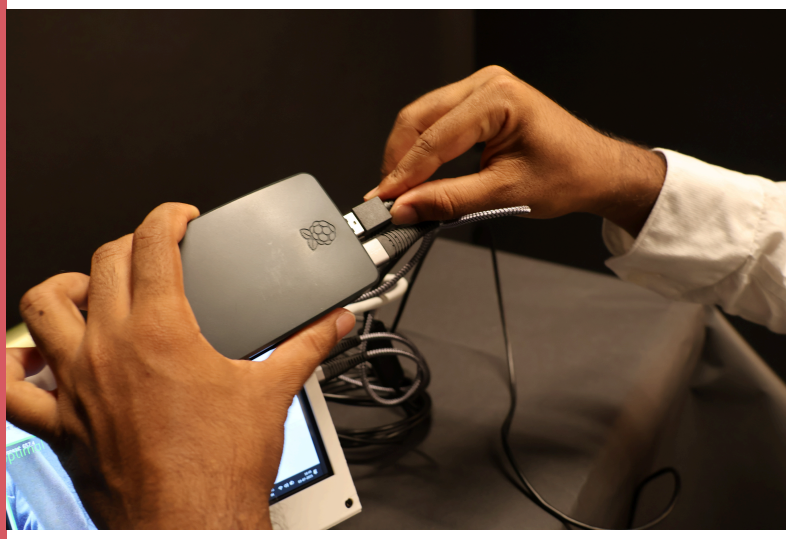
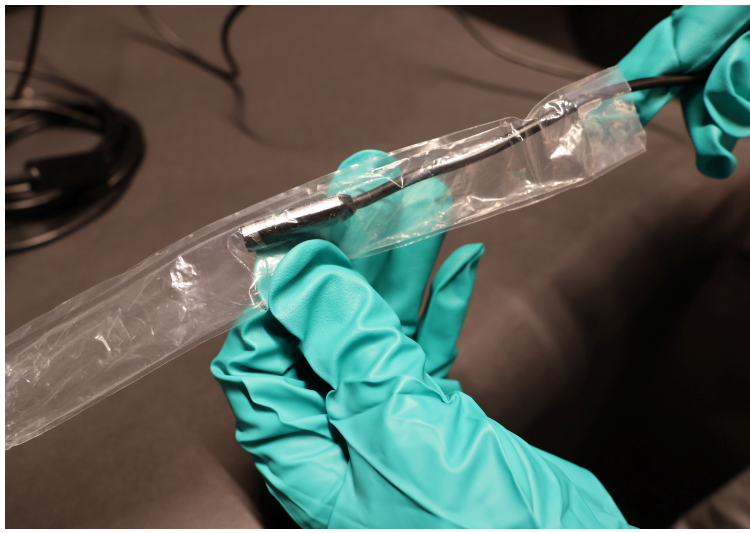


Figure 7.1: Full device render

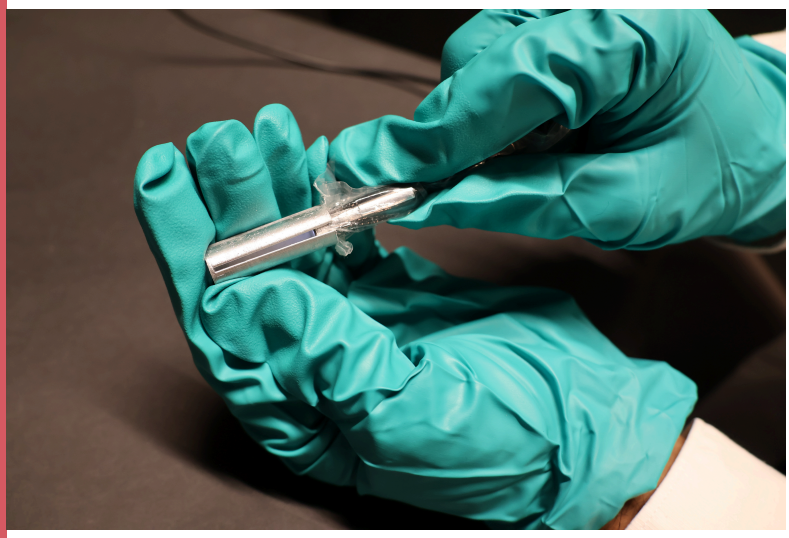
Figure 7.2 Steps for preparation of device (can be done prior to patient arrival)



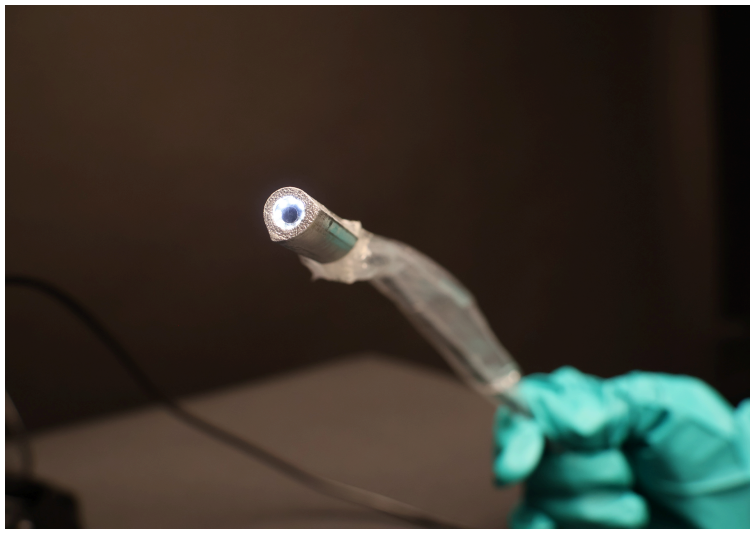
1. Plug in the device to battery backup and power



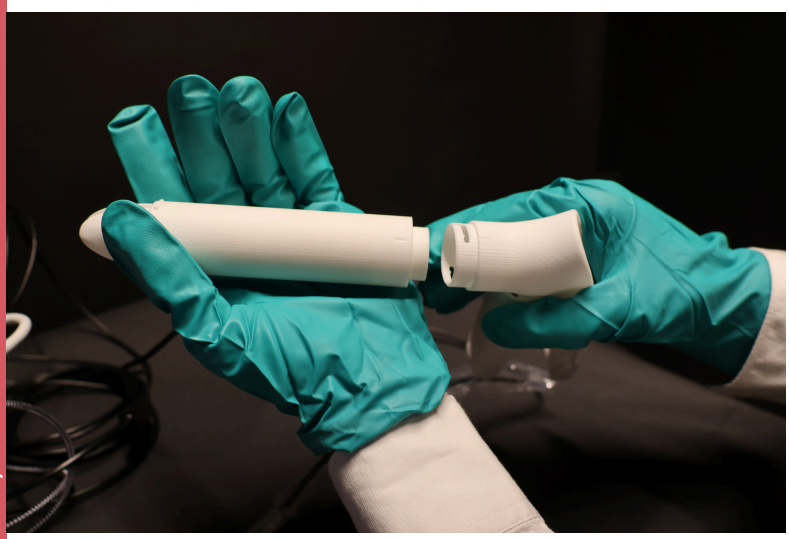
2. Insert camera into sterile plastic sheath



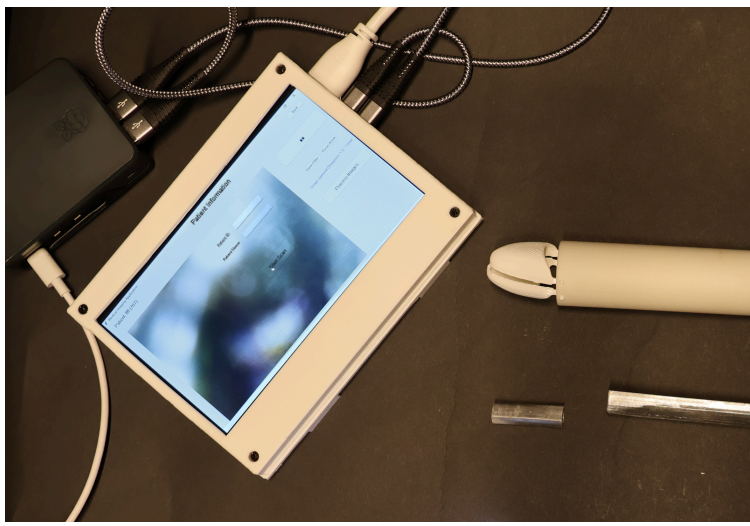
3. Insert the camera and the protective covering into the camera case



4. The fully assembled camera system turned on should be as shown with the plastic firm against the lens



5. Assemble the C-spec speculum



6. Enter patient information before scan

Figure 7.3 Steps for usage of device



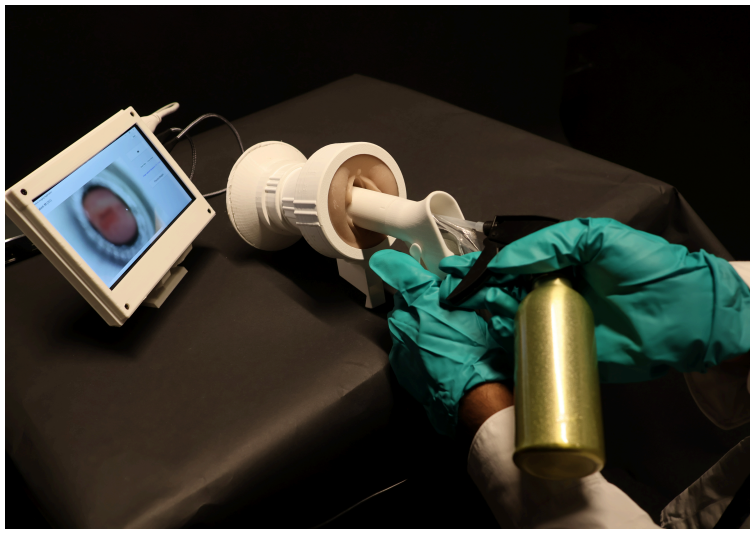
1. Insert the C-Spec in the patient and squeeze the handle when it is completely inside



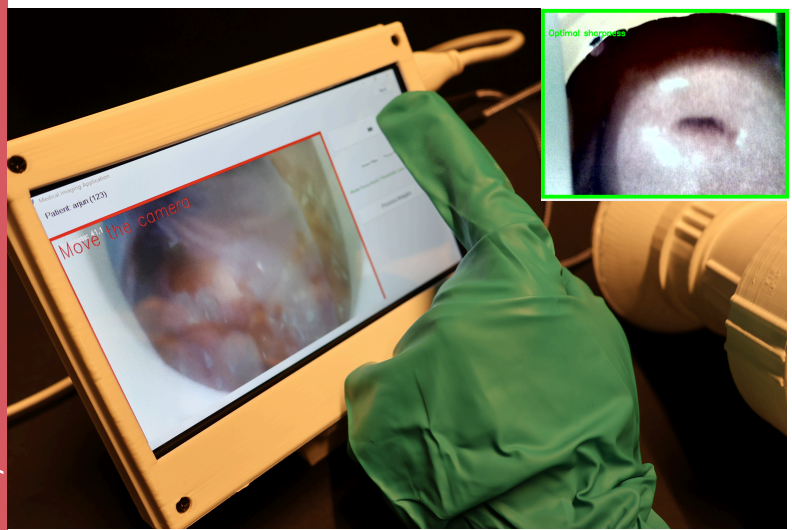
2. Insert camera guide into speculum



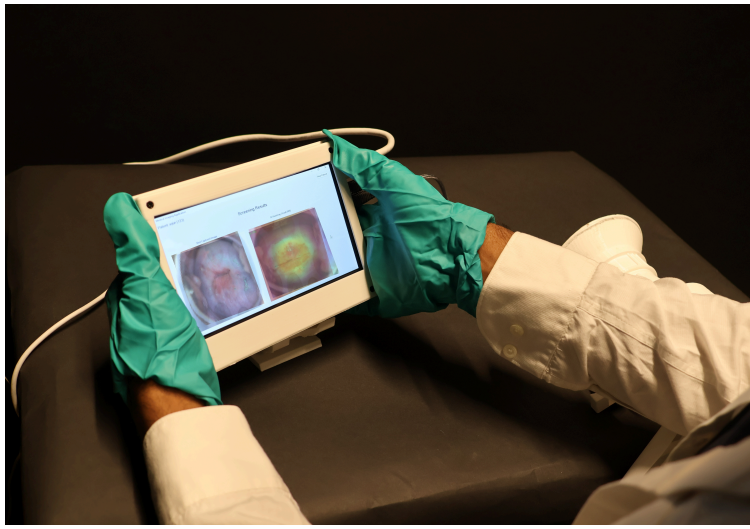
3. Insert the camera(with casing) into the guide and slide in until the cervix is visible



4. Clean the cervix if necessary and spray the cervix with ascetic acid or dab with Lugol's iodine



5. Move the camera until optimal image is obtained(top corner) as per the software guidance system and click pictures using mouse/touch



6. View results with confidence score and reasoning in 10-seconds after screening completion

7.2 Software: The Bridge Between AI And Hardware

The software acts as the bridge that integrates the hardware, the AI, and the clinician into a single cohesive system. It functions as the brain of the device, designed to handle two critical tasks in parallel: providing real-time focus assistance to the user and running the AI diagnostic model upon capture.

Screen 1: Patient Information

The clinical workflow begins at the "Patient Information" screen (Figure 7.4). This simple entry form requires the clinician to input a unique Patient ID and Patient Name. This crucial first step ensures that all captured images and diagnostic results from the session are correctly logged and associated with the right individual, maintaining data integrity. Once the information is entered, the clinician proceeds by clicking "Start Scan."

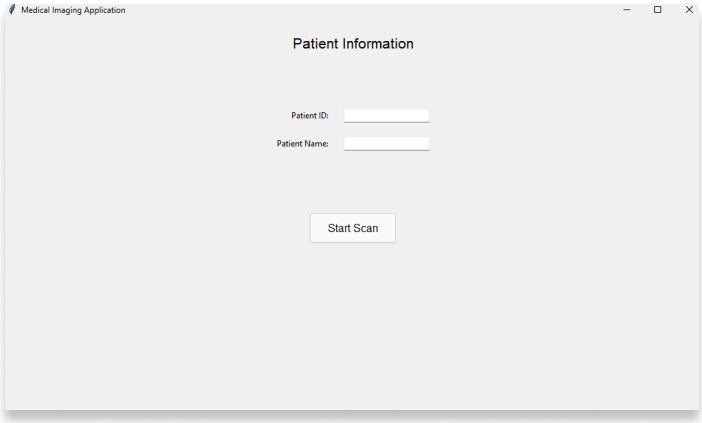


Figure 7.4 - The initial patient data entry screen

Screen 2: Image Capture and Real-Time Guidance

The second screen is the primary interaction hub for the clinician (Figure 7.5). It features a large live video feed from the endoscope, allowing the user to position the camera. To the right of the feed are the main controls:

- A large capture icon to take a picture which is easy to operate with gloves too.
- The Focus Assist toggle, which activates the real-time sharpness feedback via a colored border around the video feed.
- A Green Filter toggle for enhanced visualization of vascular patterns if needed.
- A status indicator confirming when the camera is ready.

The clinician uses the hardware guide to move the camera until the Focus Assist border turns green, indicating optimal sharpness, and then presses the capture button. After capturing one or more images, they click "Process Images" to initiate the AI analysis.

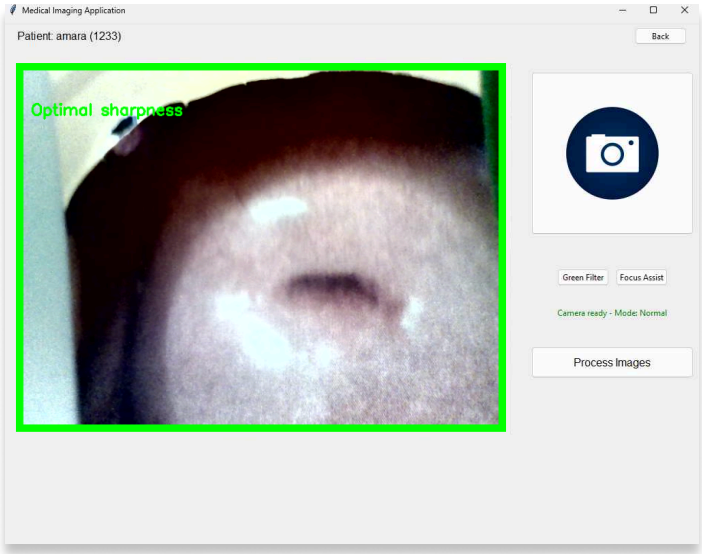


Figure 7.5 - The main image capture interface with real-time feedback controls.



(clockwise) Green, red and blue border feedback images



Screen 3: Screening Results and Interpretation

The final screen presents the diagnostic results in a clear, side-by-side format designed for easy interpretation (Figure 7.6).

- On the left, the Best Captured Image is displayed for clinical review.
- On the right, the AI Heatmap (Grad-CAM) overlay is shown, visualizing the areas the model focused on to make its decision.

Below the images, the final Diagnosis and the model's Confidence percentage are displayed in large, unambiguous text. This screen provides all the necessary information for the clinician to make a confident assessment, integrating their own expertise with the AI's findings. A "New Patient" button allows the user to easily return to the start of the workflow.

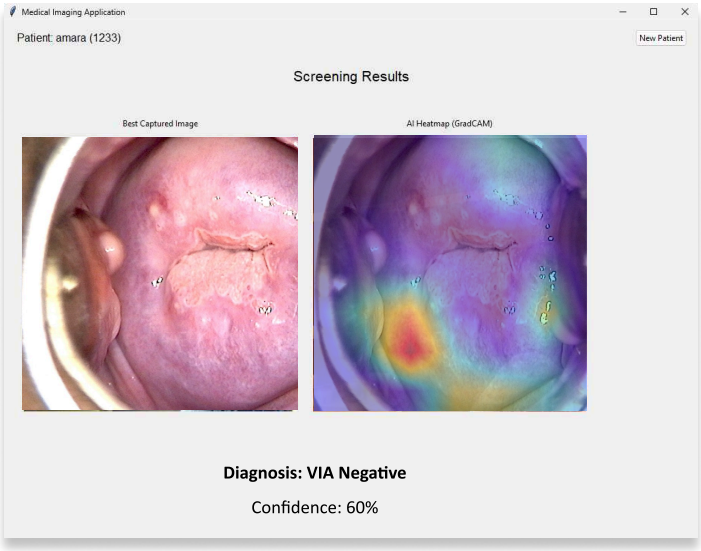


Figure 7.6 - The final results screen, designed for clear interpretation.

7.3 Final Validation Testing With An OBGYN Specialist

To validate the entire integrated system, a final testing session was conducted with an experienced OBGYN specialist from LUMC. Following the experimentation protocol (Appendix A6), the session was designed as a semi-structured interview and usability test.
The primary goals were to assess user trust in the AI, the usability of the hardware, the perceived image quality, and the system's overall fit into a clinical workflow. The following analysis is structured thematically based on the specialist's feedback.

Hardware Ergonomics and Handling

The specialist confirmed that the standard clinical workflow involves two-handed operation: one hand to manipulate the speculum and the other for the instrument. The system was found to be compatible with this workflow.

"You hold the speculum with one hand and you hold your camera with the other one. So you always have one hand on the speculum, and one here."
This observation validated the need for a simple, accessible capture button on the screen, as the operator's hands would be occupied with the hardware.

The Camera Guide

The guide rail was perceived as a helpful feature for maintaining orientation and preventing accidental contact with the cervix. However, the specialist noted that for detailed examinations, their focus was on the screen, not the physical guide.
"Without the guide to hold the thing in place it does not stay down and I need to hands, so I will always need a second person to help me click the image "
This helped validate the need for a guide

A second key insight was the desire for a dual-mode system. While the guide provides stability for standard image capture, the specialist expressed a need to operate in a "free-hand" mode for more complex cases.
"I may want to take it out and look around the corners without the guide. It is still a good primary option to have the guide, but this could also be a secondary mode."

This confirms that the removable nature of the guide is a critical feature, offering both standardization for novice users and flexibility for experts.

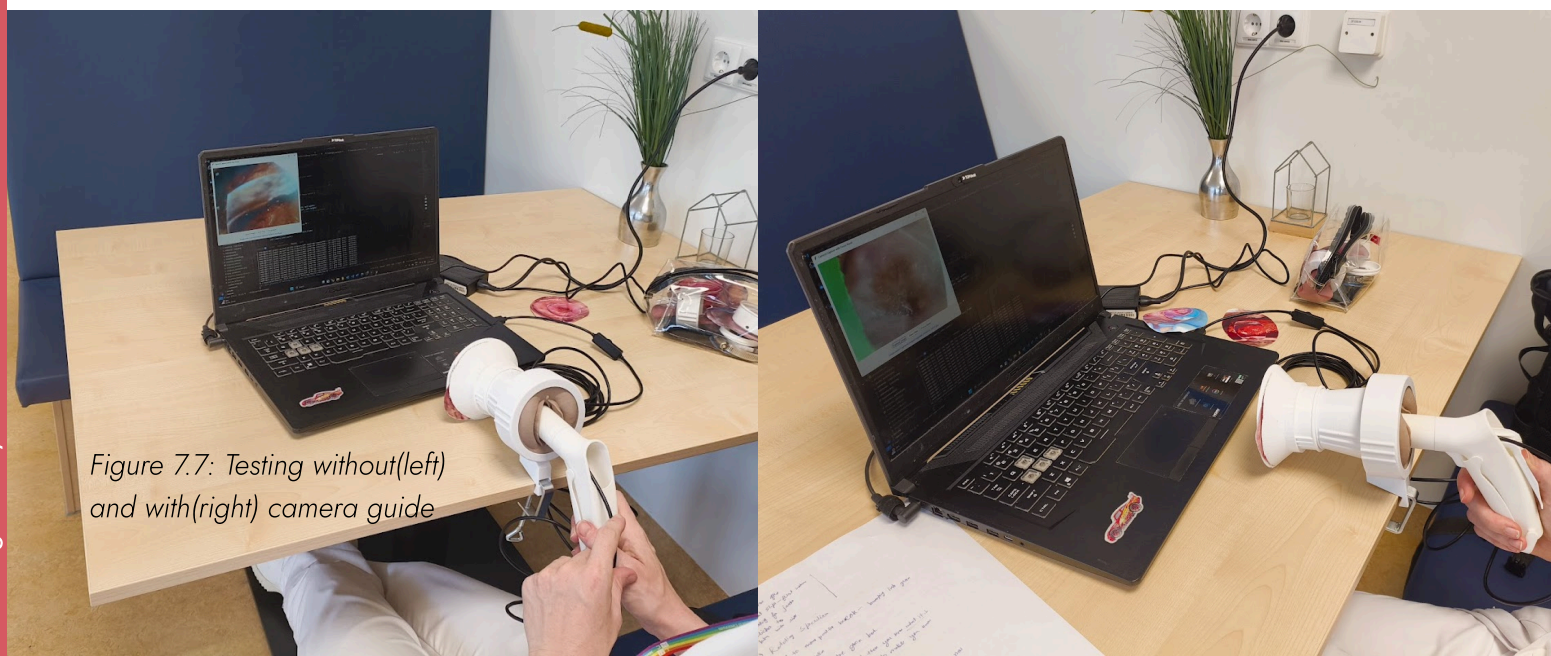


Figure 7.7: Testing without(left) and with(right) camera guide

Optical System: Validating Glare Reduction

The cross-polarization filter was validated as a crucial innovation. The specialist immediately noted the problem of glare with the unfiltered camera, stating the reflection was "very dominant" and "annoying." When testing the polarized version, the improvement was clear:

"This is much better without the reflection... you don't have the reflection now, yeah, I would probably now save this image and use it"

This qualitative feedback confirms that the cross-polarization system directly addresses a major barrier to acquiring high-quality images, meeting a primary design objective.

Software Feedback: The Sharpness Assist

The real-time feedback system sparked significant discussion. The specialist found the initial version, which displayed numerical sharpness scores, to be confusing: "it shows a lot of different numbers." They strongly endorsed the concept of using a simple color-coded system (red/green) for users in the field.

The testing also uncovered a flaw in the algorithm's logic. The specialist noted that a wide overview shot, while useful clinically, might be less "sharp" than a close-up, yet the system would incorrectly flag it as a poor image.

"This looks a bit far away to me, but it still gives 'good' because the overview is OK. But if you really want to see what's happening, you actually want to go that close."

This highlights a critical area for future work: developing a more context-aware feedback system that can differentiate between poor focus and intentional overview shots.

Psychologically helpful: The image sharpness assistance helped the doctors be sure that they were clicking good images, however it was found from the comparable image sharpness data(Figure 7.8) that they instinctively could click good images which were diagnostic worthy and didn't

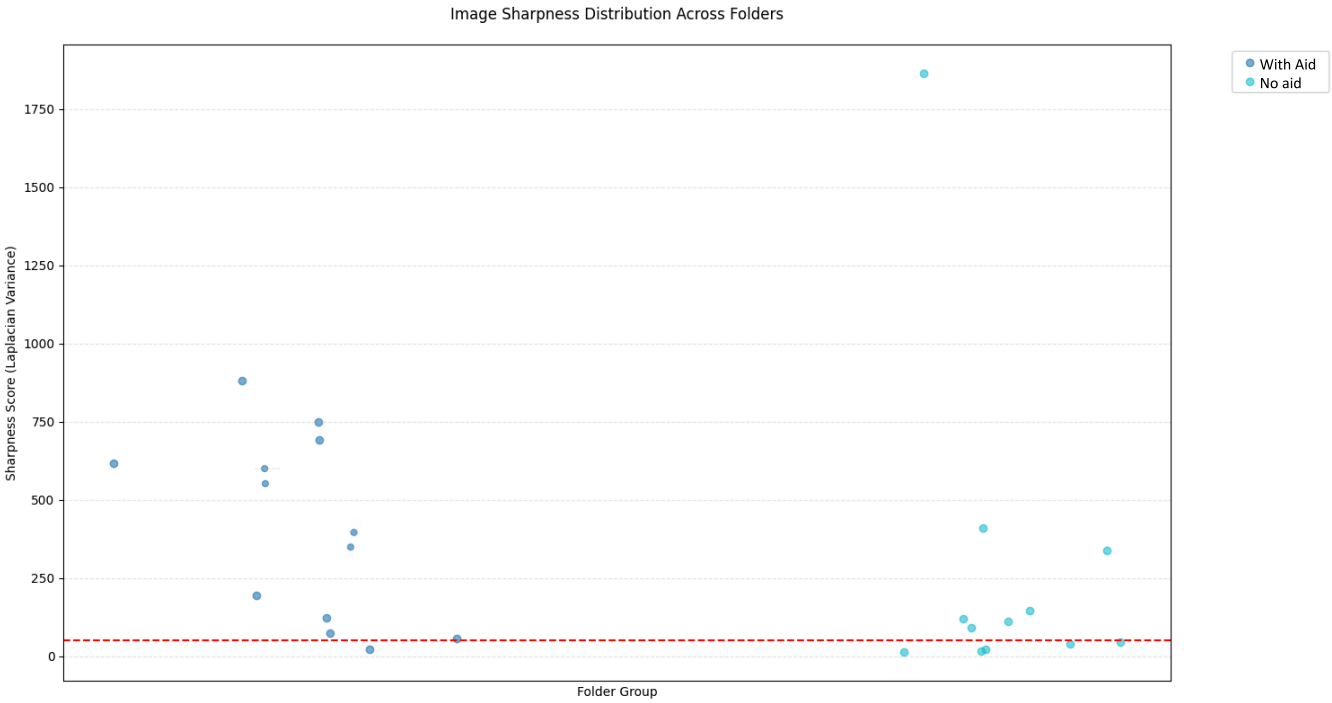


Figure 7.8: Image Sharpness for with aid and without(each dot represents an image)

Workflow and Consumables:
Perhaps the most critical feedback concerned the system's reliance on a consumable plastic sheath for the camera. Drawing on experience from other medical device implementations, the specialist identified this as a major potential barrier to adoption in LMICs.

"If you have a plastic thing which has to go over it as well, that is a problem, they may say we don't have the plastic, so we will not use it, or they will try to use it without the plastic itself."

This insight, reinforced by observations from another LUMC doctor regarding the unsustainability of single-use plastic specula(Figure 7.9, 7.10), makes the issue of consumables from a minor consideration to a primary design challenge for future iterations.
In summary, the validation session was successful. It confirmed that the integrated system is functional and that its core innovations, particularly the glare reduction and guided imaging are clinically valuable. Most importantly, it provided invaluable, actionable feedback that will be essential for refining the prototype into a truly deployable clinical tool.



Figure 7.9: Fully assembled camera

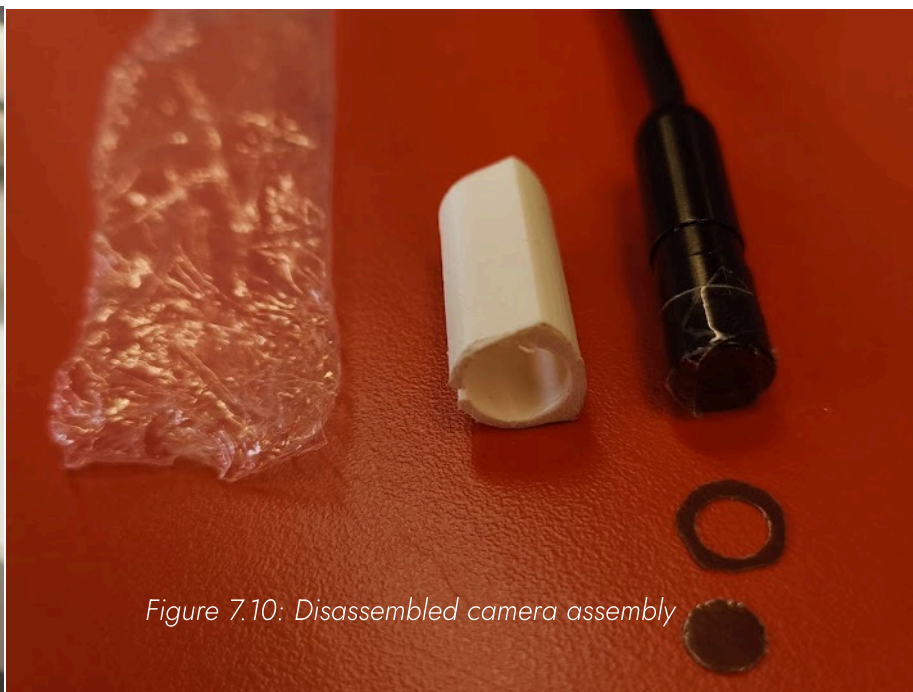
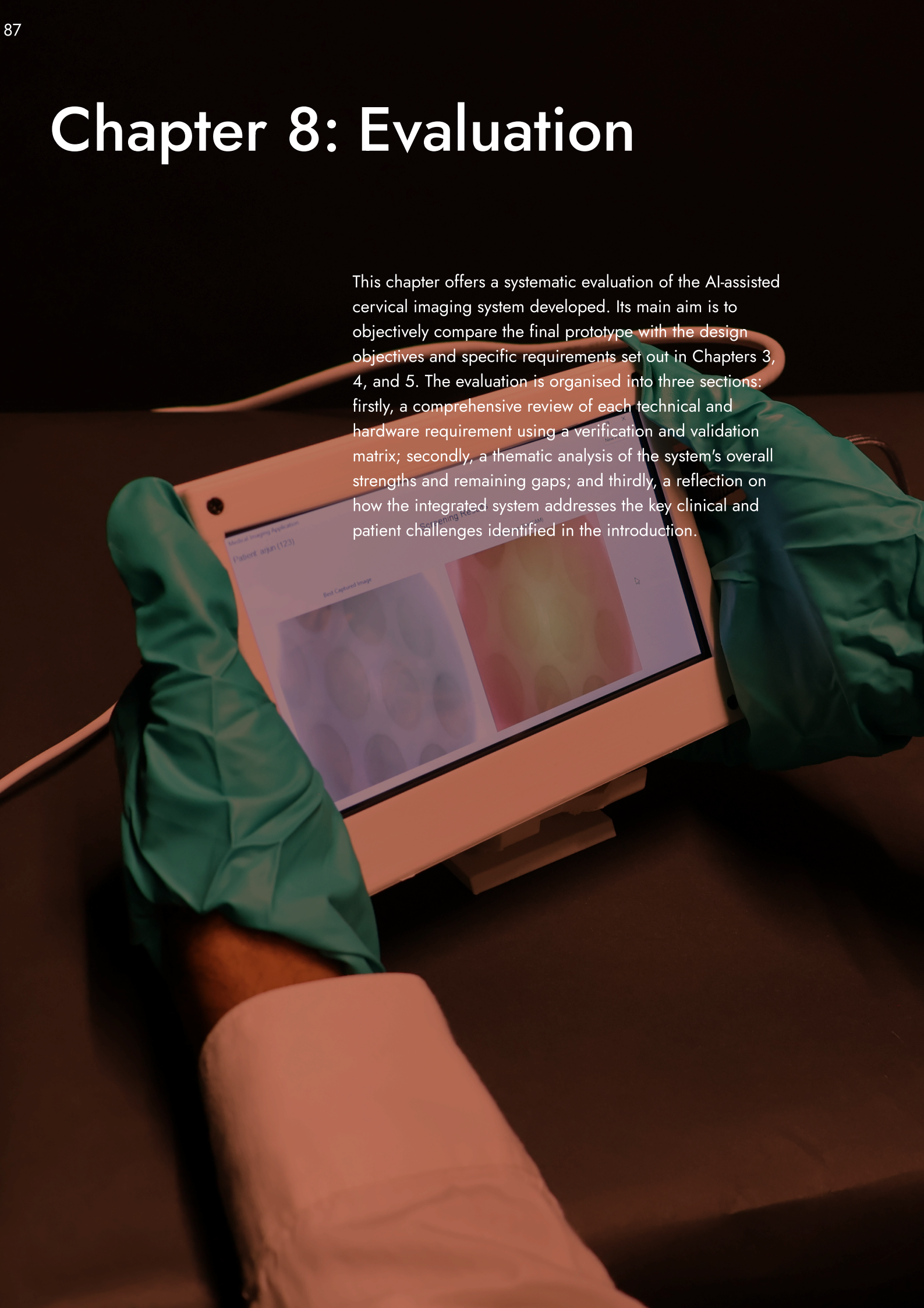


Figure 7.10: Disassembled camera assembly

Chapter 8: Evaluation



This chapter offers a systematic evaluation of the AI-assisted cervical imaging system developed. Its main aim is to objectively compare the final prototype with the design objectives and specific requirements set out in Chapters 3, 4, and 5. The evaluation is organised into three sections: firstly, a comprehensive review of each technical and hardware requirement using a verification and validation matrix; secondly, a thematic analysis of the system's overall strengths and remaining gaps; and thirdly, a reflection on how the integrated system addresses the key clinical and patient challenges identified in the introduction.

8. Evaluation

8.1 Requirements Review

A Verification and Validation (V&V) matrix was used to formally assess the project's outcomes against its predefined requirements. This method provides clear traceability from project goals to final results.

Imaging and System Performance Requirements

The following table evaluates the system's performance against the imaging and software requirements (IM1-IM12).

Table 8.1: Must have - image requirements

Code	Requirement Summary	Evaluation Method	Evidence/Results	Assessment	Comments
IM1	Reduce specular glare to <10% of ROI	Qualitative and quantitative analysis of images taken with and without the cross-polariser setup on a reflective oral cavity surface, a clinically approved analogue for this test.	The cross-polariser nearly eliminated specular reflections, dramatically improving diagnostic visibility. This was confirmed visually during the specialist validation session ("This is much better without the reflection").	Met	The low-cost polariser film was highly effective and represents a core contribution to image quality.
IM2	Sharp focus from 30–80 mm	The endoscope camera was tested on the CLOE phantom setup at varying distances, with sharpness measured using the real-time Laplacian algorithm.	The 8mm borescope maintained a high Laplacian score (>80) within this range, successfully covering the typical anatomical depth of the cervix.	Met	The camera's native depth of field was sufficient for the application.
IM3	Minimize motion blur (< 2px shift)	The hardware guide rail was tested for stability during simulated use. The real-time sharpness algorithm was benchmarked to detect and prevent capture during motion.	The guide rail provided significant stability. The sharpness algorithm successfully flagged blurry frames, preventing the capture of images with significant motion artefacts.	Met	The system effectively mitigates motion blur but does not eliminate it. The primary solution was software-based (sharpness feedback), which relies on user compliance.
IM4	Illumination ≥ 1500 lux; ISO kept < 800	A lux sensor was used in the CLOE phantom setup to measure illumination at the target plane. Camera settings were analyzed to confirm ISO levels.	The integrated LED ring provided illumination exceeding 1600 lux at a 40mm distance, allowing the camera to operate at an ISO of 400, well below the 800 limit.	Met	The off-the-shelf endoscope's lighting was sufficient.
IM5	Resolution ≥ 1280×720 px (HD)	The specifications of the selected USB endoscope were verified, and captured images were confirmed to be at the native resolution.	The selected camera module has a native resolution of 1280x960 pixels, exceeding the minimum HD requirement.	Met	The resolution is adequate for detecting fine textural changes.
IM6	±10% illumination variance across cervix	Image analysis was performed on captures from the phantom setup to measure luminance uniformity across the central region of interest.	This keeps varying based on several factors like the angle at which the camera is towards a wet surface etc, and could not be measured reliably	Unknown	While generally uniform, minor hotspots were still present due to the proximity of the light source. It remains to be measured with certainty that the light is sufficiently uniform.

Table 8.2: Nice to have - image requirements

Code	Requirement Summary	Evaluation Method	Evidence/Results	Assessment	Comments
IM7	Field of view ≥ 70° diagonal	The manufacturer's specifications for the selected endoscope were confirmed.	The chosen endoscope has a 70° diagonal field of view as per its technical data sheet.	Met	This FOV was confirmed by the OBGYN specialist to be sufficient for capturing the entire transformation zone in most cases.
IM8	Preserve over 90% of captured image	The final hardware design was analyzed to measure how much of the camera's field of view was obstructed by the polariser or housing.	The custom-cut polariser and housing resulted in a minimal obstruction, preserving approximately all of the original image frame.	Met	The design successfully integrated the necessary optical modifications without significantly compromising the diagnostic view.
IM9	Provide real-time sharpness/blur feedback	The software interface was tested during the usability session with the OBGYN specialist to assess the clarity and effectiveness of the color-coded feedback system.	The specialist confirmed the feedback was intuitive ("It helps me know what is a good image"). The red/blue/green border system was easily understood.	Met	The quality feedback loop was validated as a key feature for supporting non-specialist users.
IM10	Clinician view must show RGB; AI may use normalized inputs	The software architecture was inspected to confirm that the clinician-facing display shows the direct camera feed, while the AI model's input pipeline includes a separate normalization step.	The user interface was confirmed to display the full-color RGB image. The AI pre-processing script shows normalization is applied before inference.	Met	This dual approach ensures clinical interpretability for the user while optimizing the input for the AI model.
IM11	Total capture + processing time < 5 seconds	The system workflow was timed on the Raspberry Pi 4 prototype, measuring the duration from the final capture command to the display of the AI classification result.	Average processing time was measured at approximately 10-15 seconds for a batch of images	Unmet	
		Software timestamps were used to measure the latency between the button press event and the frame acquisition callback in the custom capture	The average latency was measured at approximately 150-200 ms for rasberry pi 4,		The low latency ensures the captured image reflects the moment the clinician identified as optimal. However, the clicking mechanism itself plays a role, and the image could be shaky if the physician is not able to click easily

Table 8.2: Hardware requirements

Code	Requirement Summary	Evaluation Method	Evidence/Results	Assessment	Comments
HW1	No on-lens condensation at 100% relative humidity	Tested in a simulated high-humidity environment using the CLOE phantom setup.	No condensation was observed on the lens during the 5-minute simulated procedure.	Met	The camera's plastic lens prevented condensation
HW2	Tool-free attachment	Timed assembly/disassembly of the guide rail and camera housing with the C-Spec during the usability testing session.	The OBGYN specialist found the system "quite easy and smooth to use". Assembly was consistently under 30 seconds.	Met	The simple friction-fit design was validated as clinically appropriate and efficient.
HW3	Defined patient-contact constraint and camera range	The mechanical design of the guide rail was inspected, and its function was observed during usability testing.	The guide rail provides a clear travel range of 40mm, and a mechanical stop prevents the camera from advancing beyond the speculum's end.	Met	This safety feature was effective and appreciated by the clinician.
HW4	Camera must not contact patient tissue	The system was designed to be used with a disposable plastic sheath over the camera, and the guide rail provides a physical barrier.	The design inherently prevents the camera electronics from making direct contact. The specialist noted the importance of the plastic sheath.	Met	The design meets this critical safety requirement, though it introduces a dependency on a consumable item.
HW5	Construction must survive 1,000 use cycles	This was not physically tested. The assessment is based on material selection (316L stainless steel) and design principles.	The robust, monolithic design and use of medical-grade stainless steel strongly suggest high durability.	Not Met (Untested)	Full lifecycle testing was beyond the scope of this project. However, the design is based on established principles for durable medical devices.
HW6	Smooth, cleanable surface geometry	The final hardware prototype was inspected for crevices and surface finish. The design was reviewed with the specialist regarding cleaning protocols.	The electropolished finish and lack of sharp internal corners or crevices make the guide rail and housing easy to wipe down with alcohol.	Met	The design is compatible with standard cleaning and disinfection methods used in LMICs.
HW7	Integrated access for swabs or acetic acid spray	The cross-sectional area of the speculum with the guide rail installed was measured and visually assessed during usability testing.	The off-center design of the guide rail preserves a large, unobstructed channel for the insertion of swabs or other instruments.	Met	This was a critical design trade-off that was successfully implemented.
HW8	Self-centering or alignment aid for image framing	The function of the guide rail in ensuring consistent camera orientation was evaluated during the usability test.	The guide rail was praised for helping with orientation ("The guide definitely helps"). It provides consistent, repeatable alignment.	Met	This "nice-to-have" feature was successfully implemented and validated as highly useful.
HW9	Locking or friction-based positioning	The system was assessed during usability testing for its ability to hold the camera's position, enabling one-handed operation.	The 10-degree angled rails provide a firm friction hold. However, the design does not feature a hard "locking" mechanism.	Partially Met	The friction hold is sufficient for stable one-handed operation, but a true locking feature could be a future improvement.
HW10	Preferably monolithic or low part count	The final design consists of 3 main components: the guide rail and the camera housing, the C-spec itself	The design attempts to minimizes complexity, with only three reusable parts needing to be managed and sterilized by the user.It also has the additional 4th plastic piece	Unmet	The final system had several parts and it would be nice to make this simple system even simpler and ensure an almost monilithic system without too many dependencies

8.2 Strengths And Gaps

This section provides a thematic analysis of the project's successes and limitations, moving beyond individual requirements to assess the system as a whole.

8.2.1 Image Quality and Optical System

- **Strength**: The cross-polarisation system is the project's most significant technical innovation. It successfully solves the critical and pervasive issue of specular glare using a low-cost, easily replicable method. This directly improves the quality of data for both the AI model and human review, which is fundamental to the system's value proposition.
- **Gap**: The compact design, with the light source and lens in close proximity, occasionally produces minor polarization artefacts (e.g., color fringing). Furthermore, testing revealed that a dirty or smudged lens can significantly degrade image quality, highlighting the critical importance of a strict cleaning protocol in the field. The polariser film's susceptibility to scratching also highlights a key area for future work: developing a more robust, field-replaceable filter assembly to ensure long-term image quality and system maintainability.

8.2.2 Hardware Design and Usability

- **Strength**: The final removable guide rail is an elegant solution that successfully balances multiple competing requirements: it provides stability and repeatable orientation, is easy to clean, preserves instrument access, and is simple to manufacture. Direct feedback from the OBGYN specialist confirmed its ergonomic benefits and intuitive workflow.
- **Strength**: The system design demonstrates significant flexibility. While the removable guide rail provides stability and standardization for training or routine cases, it can be easily removed, allowing experienced clinicians to operate in a "free-hand" mode for inspecting complex cases or unusual anatomy. This dual-mode capability maximizes its utility across different user skill levels.
- **Gap**: The system is fundamentally designed to integrate with the C-Spec speculum. As noted by Dr. Milkias, this specific instrument is not the standard in many clinical settings like Ethiopia. This dependency on a non-standard speculum represents a significant adoption barrier, as it may require additional training and a departure from established clinical workflows.
- **Gap:** The specialist raised a critical concern about the system's dependency on a consumable plastic sheath for the camera. In resource-constrained settings with fragile supply chains, this dependency is a major vulnerability that could be a significant barrier to adoption.

8.2.3 AI Model and Software Interface

- **Strength**: The multi-stage transfer learning strategy was highly effective. By first adapting the model to the general domain of cervical anatomy before fine-tuning it for diagnostic classification, the model's focus (as shown by Grad-CAM maps) shifted to more clinically relevant regions, improving its trustworthiness.
- **Strength**: The real-time sharpness feedback system was validated as a valuable and intuitive tool. It directly empowers non-specialist users to capture high-quality, diagnosis-ready images, which is essential for the system's intended use case.
- **Gap**: The sharpness algorithm, while effective, can provide misleading feedback in certain contexts, such as when a clinician is intentionally capturing a wider overview shot from a distance. The feedback logic could be refined in the future to be more context-aware.

8.3 System Reflection

The ultimate measure of this system's success is its potential to transform the patient journey. This evaluation reflects on how the integrated system holistically addresses the barriers of distance, cost, and diagnostic uncertainty faced by women like Amara, as illustrated in Chapter 2.

The system directly confronts the barriers of distance and cost by meeting its <€200(Refer Appendix A7) design target, making it a potentially feasible alternative to expensive colposcopes in secondary care settings. This affordability could empower local workers and reduce the need for long, expensive referral journeys, though further contextual research is needed to validate this assumption.

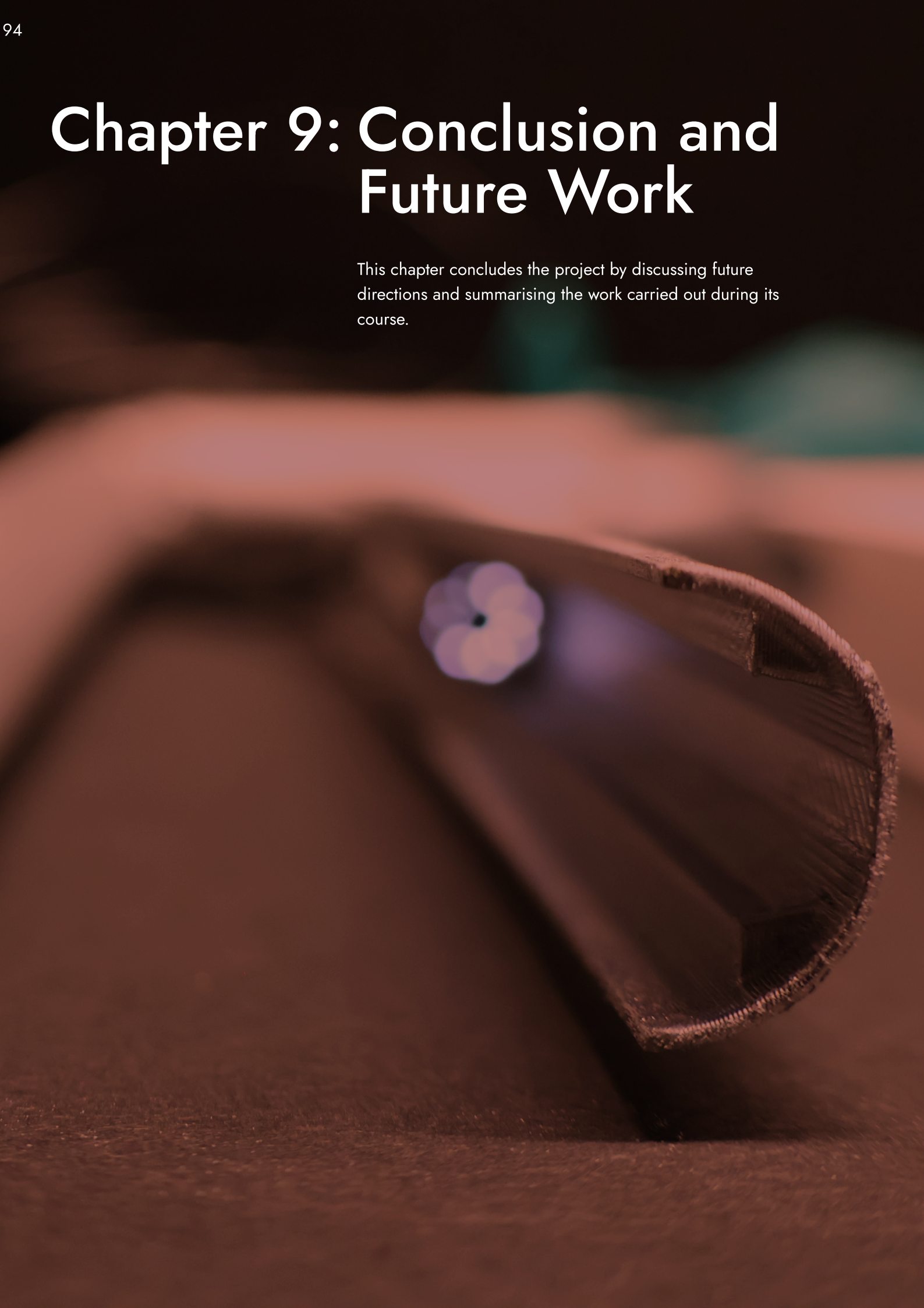
It also addresses diagnostic uncertainty by standardizing the image capture process through consistent, polarized lighting and a hardware guide. While the AI's diagnostic accuracy is currently limited by the available dataset, the system's primary immediate value is as a high-quality data collection platform. Its accessibility can facilitate the large-scale data collection needed to build a more reliable predictive model in the future.

Finally, the system reduces treatment delays by enabling a "screen-and-refer-with-confidence" model. Even when local treatment options like LEEP are unavailable, an immediate, confident diagnosis allows for faster and more accurate referrals, a significant improvement over the current standard of care.

Despite these strengths, the system is not yet a complete solution. The evaluation has highlighted critical vulnerabilities—such as the dependency on a consumable sheath, the lack of formal clinical trials, and the need for a full production and training plan—that must be addressed in future work.

Chapter 9: Conclusion and Future Work

This chapter concludes the project by discussing future directions and summarising the work carried out during its course.



9. Conclusion and Future Work

This thesis set out to demonstrate the feasibility of creating a usable, robust, and AI-supported cervical imaging device for low-resource settings. This final chapter summarizes the key contributions of the project and outlines the necessary future work required to transition this promising prototype into a scalable, impactful clinical tool.

9.1 Conclusion

This project successfully developed an integrated, AI-assisted cervical imaging system that addresses the core challenges of cost, usability, and diagnostic quality. The key contributions include:

- **A Novel Low-Cost Glare Reduction System:** A cross-polarisation filter system was developed and validated, effectively solving the critical issue of specular glare using affordable, off-the-shelf components.
- **A Clinically-Informed Hardware Guide:** The removable, dual-mode hardware guide provides stability for novice users and flexibility for experts, while ensuring patient safety and maintaining access for clinical instruments.
- **A Trustworthy AI Strategy:** A multi-stage transfer learning approach was validated as essential for developing a clinically relevant AI. By initially training the model to recognise cervical anatomy, its focus was appropriately shifted to diagnostic features, ensuring trustworthy recommendations and fostering collaboration by demonstrating the model's reasoning.
- **An Integrated, Affordable System:** The final prototype, with a bill of materials under the €200 target, demonstrates a viable, low-cost alternative to traditional colposcopes, positioning it as an accessible tool for decentralized screening.

Ultimately, this work provides a validated technical foundation for a system that can transform the patient journey. It offers a clear pathway to move from a multi-week, multi-hundred-kilometer diagnostic ordeal to a confident, localised clinical decision, bringing timely and effective care closer to the women who need it.

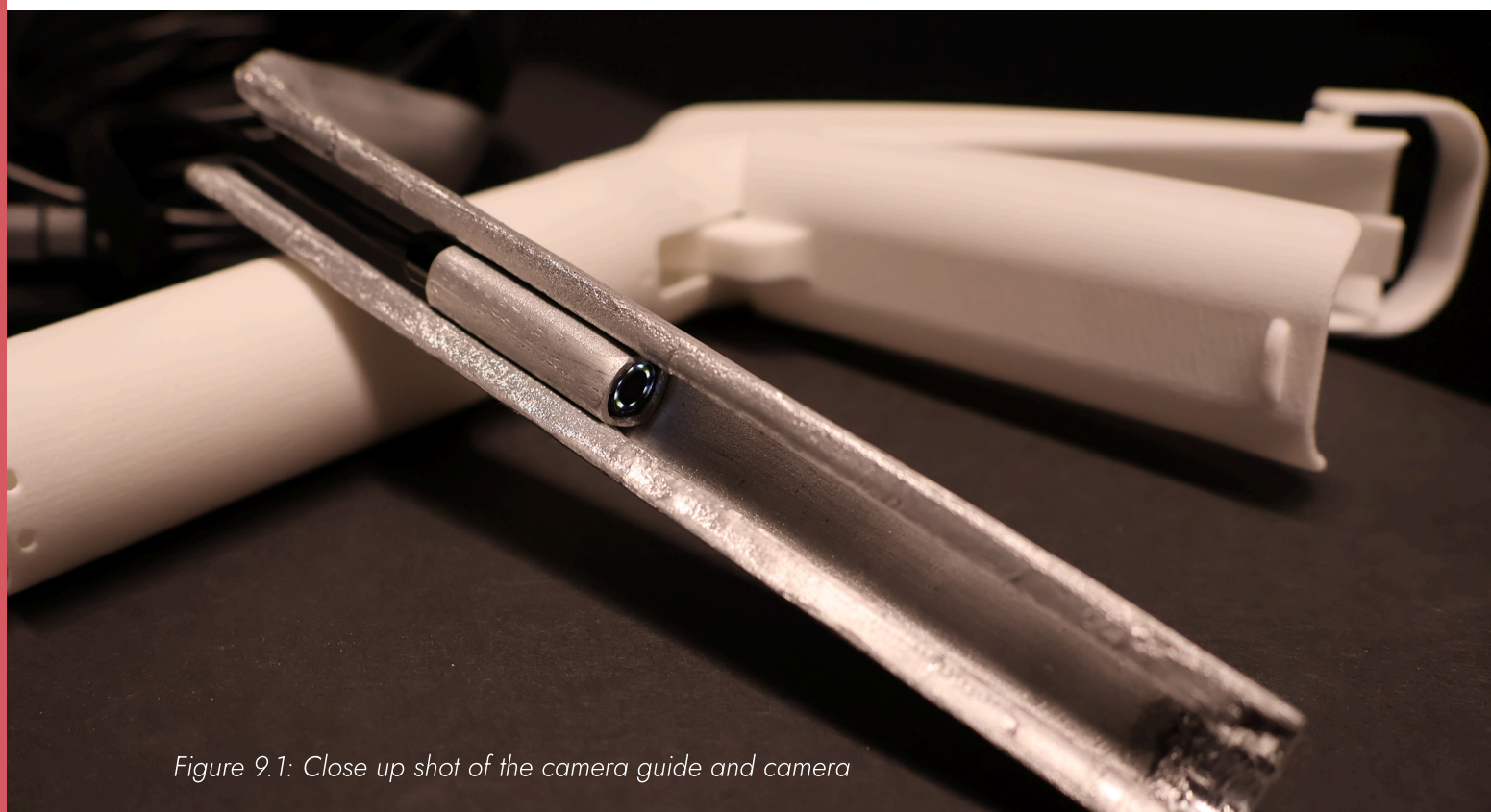


Figure 9.1: Close up shot of the camera guide and camera

9.2 Future Work And Development Directions

While this thesis has successfully demonstrated a proof-of-concept, several opportunities exist to enhance its performance, usability, and scalability. The following directions outline a roadmap for future research and development.

- **Enhancing AI Model Robustness through Data Collection:** The AI model's current performance is limited by the dataset size. This next phase should be led by an AI/ML specialist who can build upon the trustworthy foundation established in this thesis. The most critical future work is to initiate a multi-center data collection study. Establishing collaborations with local healthcare providers in Ethiopia and Cameroon is essential to build a large, diverse, and well-annotated dataset of thousands of images, ensuring representation of varied anatomical and pathological conditions. Given that higher accuracy figures have been reported in academic literature, achieving a clinically deployable level of sensitivity and diagnostic accuracy is a feasible and crucial goal.
- **Hardware Maturation and Production Readiness:** The current hardware prototype needs to be optimized for manufacturing and rigorously tested. This includes refining components for manufacturability, performing accelerated corrosion testing on the stainless steel parts to ensure long-term durability in humid clinical environments, and validating the sterilisation protocols for all reusable components. Furthermore, the design should be iterated to simplify assembly and reduce the number of parts even further if possible.
- **Longitudinal Usability and Clinical Validation:** The system must undergo more extensive validation. This includes formal clinical trials to compare its diagnostic accuracy against the gold standard (colposcopy and biopsy-confirmed histology). Concurrently, long-term usability testing should be conducted with a broader range of providers, including nurses and health extension workers, to assess adoption over time within the context and gather iterative feedback to create an ideal, user-centered product.

- **System-Level Deployment Strategy:** Looking much beyond the device itself, a successful implementation requires a broader strategy. This includes developing a comprehensive training curriculum with simple, visual guides for non-specialist users, creating a local manufacturing and supply chain plan to ensure sustainability, and conducting a formal health economics study to validate the system's cost-effectiveness within the Ethiopian healthcare system.

By systematically addressing these areas, this project can evolve from a prototype to a scalable solution that creates an impact in the space of cervical cancer screening for women in resource-constrained settings.

Chapter 10: Personal Reflection

At the outset of this thesis, I documented my motivations, strengths, ambitions, and perceived struggles. Now, at its conclusion, it is valuable to revisit those initial thoughts to reflect on my personal and professional growth throughout this journey. The following provides a candid assessment of how my initial expectations and self-perceptions were challenged, confirmed, and ultimately shaped by the practical realities of the project.

Motivation and Ambition: Bridging Design and Engineering

My stated ambition was to "deliver a meaningful, tangible solution" that embodied both my design and engineering capabilities. Looking back, I can see how my approach to problem-solving has evolved. My engineering background was crucial for the technical deep-dives into optics and AI, but it was my design education that constantly pushed me to ask "Why?", "For whom?", and to rigorously test my assumptions. This was particularly evident in the hardware design. My engineering instincts might have led to an over-optimised, complex solution for the camera guide. The design process, however, guided me towards the elegant simplicity of the final removable rail. This evolution was perhaps the most integral to my growth as a designer during this project. I had to focus only on what was most appropriate and effective for the user, even if the final product appeared simple or looked as though less work went into it to a third person. This shift was heavily influenced by insights from my coursework in designing for emerging markets, which shaped my priorities and taught me not to make assumptions about the context. This created a healthy tension: the need to validate every decision versus the need to make quick, gut-based choices to maintain momentum, testing them later to prove their validity.

My strengths and how they were tested

I identified persistence as a key strength, and this project tested it in ways I didn't anticipate. The most challenging aspect for me was the AI development. As someone more comfortable with tangible code and hardware, grappling with the abstract nature of a neural network that "had a mind of its own" was a significant hurdle. The process of troubleshooting the AI model's focus was a multi-week effort of iterative testing, not just to fix it, but to truly understand why it made certain decisions. This persistence, though taxing, was what ultimately led to the more robust multi-stage training strategy.

This experience also shaped a core working principle that I will carry forward: "From Theory, to Practice, to People." In conversations with my mentors, I developed a cycle to avoid getting stuck: begin with a literature study, and when that is saturated, get my hands dirty with practical building and prototyping. With something tangible built, I could then approach experts for feedback. Their suggestions would, in turn, send me back to the literature and to the workshop to build something better. This iterative loop became the engine that drove the entire project.

I was fortunate to have access to expert clinicians and AI specialists. Their insights were invaluable and fundamentally altered the project's trajectory. At the same time, the experience underscored the immense value of this resource, and I often wished I had even more access to their guidance. It solidified my understanding that for medical device design, the end-user is not just a source of requirements, but an essential co-design partner.

Struggles and Growth: Confronting My Own Process

Reflecting on my self-identified struggles has been the most insightful part of this process.

- **Scope Creep and Personal Limits:** My fear of scope creep was well-founded. My passion for this work often means I get carried away by multiple interesting and challenging ideas. This project was one of the more demanding I have undertaken, and there were several times I felt stretched too thin by tackling too many interconnected challenges at once. This struggle, however, forced me to refocus and confirmed that my skills are best utilised in system integration—connecting disparate parts like hardware, optics, and AI into a cohesive whole. The experience tested me in several ways, pushing me to my limits, but it also underscored the importance of the "In Scope" and "Out of Scope" lists defined in Chapter 1. They became an essential tool for saying "no" to interesting tangents in order to deliver a complete system. Despite the challenges, I am happy with the final outcome and the resilience I developed in the process.
- **Documentation**: My initial plan to document my work daily was challenging to maintain, leading to a chaotic process and multiple revisions of this report. It was the hardest part of the project for me and served as a critical lesson: a designer's role is not just to process complex information, but to be able to convey those thoughts clearly. I have come to understand that meticulous documentation is not an administrative burden, but a core design skill—one that I have worked to hone in this final revision and will carry into my professional work.
- **Voicing Expectations:** I requested regular check-ins with my mentors, and this proved to be immensely helpful. The weekly meetings created a consistent rhythm and provided a forum where I felt comfortable asking for the specific, constructive feedback I needed. These regular interactions helped me become more confident in articulating my needs and challenges, directly addressing a weakness I had identified.

In conclusion, this thesis was as much a project in self-management as it was in design and engineering. It provided a structured environment to confront my weaknesses, validate my strengths, and ultimately deliver a project that I feel truly represents my ambition to create tangible, meaningful technology.

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Appendix

A1. Project Brief

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME

Complete all fields and indicate which master(s) you are in

Family name	Gopkumar	7608	
Initials			
Given name	Arjun		
Student number	5951968		

IDE master(s)	IPD	✔	Dfl		SPD	
2nd non-IDE master					
Individual programme *(date of approval)*					
Medisign					
HPM					

SUPERVISORY TEAM

Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Prof.dr.ir. J.C. Diehl	dept./section	SDE
mentor	Ir. S.M Persaud	dept./section	SDE
2nd mentor			
client:	Karlheinz Samenjo		
city:	Delft	country:	Netherlands
optional comments	Prof. J.C. Diehl and Stefan Persaud, from the same department, bring distinct expertise to the project. J.C focuses on inclusive and sustainable healthcare, while Stefan specializes in embodiment design and hardware integration. Their skills make for a well rounded mentor team.		

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Jan-Carel Diehl

Digitally signed by Jan-Carel Diehl
Date: 2025.01.21 14:51:58 +01'00'

Name JC Diehl Date 21 Jan 2025 Signature

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total _____ EC

Of which, taking conditional requirements into account, can be part of the exam programme _____ EC

★	**YES**	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

L. Boot Digitaal ondertekend door L. Boot Datum: 2025.03.18 12:50:41 +01'00'

Name Lisette Boot Date 18 mrt 2025 Signature _____

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Monique von Morgen Digitally signed by Monique von Morgen Date: 2025.03.19 11:32:21 +01'00'

Name Monique von Morgen Date 19 Mar 2025 Signature _____

Personal Project Brief – IDE Master Graduation Project

Name student Arjun Gopkumar **Student number** 5,951,968

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title **Developing a low-cost endoscope for AI enhanced cervical cancer screening**

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The project addresses cervical cancer screening in rural, low-resource settings, such as Cameroon, where the shortage of specialists affects timely and accurate diagnoses. Traditional tools like colposcopes are often inaccessible due to their cost and logistical challenges. Even with the tools in place, doctors with adequate training and experience in diagnosis may be absent. This project builds on prior research at TU Delft by developing an experimental setup to optimize imaging quality for AI-based detection of cervical cancer. The ultimate goal is to transition from prototyping to a working device that can be tested in a clinical setting.

Key stakeholders include healthcare providers, patients, hospitals, and the client, Karlheinz Samenjo. Providers need affordable, reliable tools that function within limited infrastructure, while patients benefit from early, non-invasive diagnostics that reduce delays and improve outcomes. Public health organizations seek scalable solutions to address diagnostic gaps in such settings.

Opportunities include using off-the-shelf components to develop cost-effective and replicable systems while leveraging AI to improve diagnostic consistency. However, challenges remain, including insufficient training data for AI, constraints on high-cost or specialized hardware, and the need for validation in clinical contexts. Engaging stakeholders --AI experts, doctors, and end-users --throughout the process will be critical to refining the device and ensuring its efficacy in real-world applications.

→ *space available for images / figures on next page*

introduction (continued): space for images



image / figure 1 Concept for ergonomic gynoscope(AED 2024) - the final outcome of the thesis will be a working prototype



image / figure 2 Eduscope optical rig - inital experiments will be based on a similar platform

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The lack of accessible and reliable cervical cancer screening tools in low-resource settings, such as Cameroon, results in delayed and inaccurate diagnoses. This project aims to address this problem by optimizing imaging quality for AI-based detection, focusing on creating a cost-effective, scalable solution. Existing tools like colposcopes are prohibitively expensive, while current prototypes lack stability, consistent image quality, and provisions for easy sterilization or reuse. Within the 100-day timeframe, the project will focus on developing an experimental setup to achieve optimal imaging. Key challenges include ensuring consistent clarity, stabilization, and adequate illumination while simulating real-world conditions such as humidity and fluid presence. These efforts will pave the way for integrating these improvements into a functional endoscopic device.
This solution could allow non-specialists to capture high-quality images for AI-based diagnostics, improving diagnostic accuracy and alleviating the systemic burden. Leveraging off-the-shelf components enhances feasibility, scalability, and affordability, which are critical for deployment in low-resource settings. The project creates added value for patients, healthcare providers, and public health organizations by reducing barriers to early detection and improving access to life-saving care.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a **prototype of a low-cost endoscope** to **create a reliable, cost-effective cervical cancer diagnostic aid for non-specialist healthcare professionals in low-resource settings**.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will follow a research-through-design approach, emphasizing iterative experimental prototyping to explore and optimize imaging quality. The process begins with mapping the environmental and technical variables affecting image clarity and consistency, such as lighting, humidity, and fluid presence. This will inform the development of an experimental setup to simulate real-world conditions.

Using co-creation sessions with AI experts, the imaging setup will be fine-tuned to ensure alignment with the requirements for accurate AI-based detection. This will be followed by contextual interviews with healthcare professionals to refine specifications and usability aspects.

The final phase involves concept realization, translating the learnings from experimentation and co-creation into a functional prototype. The prototype will undergo iterative evaluation loops to ensure feasibility, usability, and scalability in low-resource medical contexts.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	17 Jan 2025
Mid-term evaluation	14 Mar 2025
Green light meeting	14 May 2025
Graduation ceremony	11 Jun 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I am drawn to this project due to my passion for developing solutions that have a direct impact on lives, especially in the medical device field. My motivation is to combine my engineering expertise with my design education to create an affordable cervical cancer diagnostic tool for low-resource settings. By solving real-world problems, I aim to improve healthcare accessibility and outcomes for underserved populations.
I also wish to deepen my understanding of design methodologies, prototyping, and testing, while refining my ability to work within constraints such as budget and infrastructure. Ultimately, I seek to demonstrate my ability to deliver technically sound practical solutions within emerging markets contexts.
Some learning ambitions I have include:

1. Developing a deeper understanding of low-cost medical device design, focusing on optimizing existing technologies for resource-constrained environments.
2. Combining engineering knowledge with product design, using signal/image processing and CAD modelling to create a tangible product.

Learning how to design for user groups that are different from myself --particularly in the context of female health, a sensitive area I am passionate about and believe requires more attention.

A2. Other approaches explored

Mobile phone colposcope

One of the approaches was to try and use a smartphone with a telephoto lens(*Figure A.1, A.2).* This approach helps maintain a sterile field, as the camera remains outside areas requiring strict sterility. Additionally, the lenses could be relatively inexpensive, as they can be made from epoxy (Breaking Taps, 2021). A potential advantage of using a mobile phone colposcope is that the AI software could run directly on the phone, integrating both the camera and processing power into a single device. Modern smartphones offer high-resolution, photorealistic images, making them a viable optical tool.

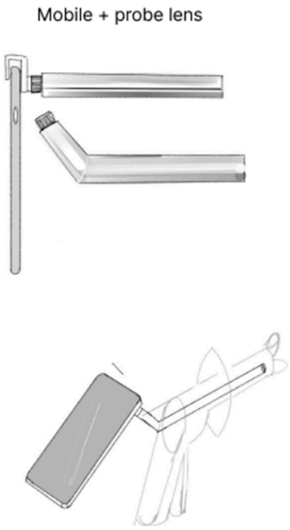


Figure A.1: Concept sketch



Figure A.2: Mobile phone clip-on lenses(Amazon.nl,2025)

However, the rapid evolution of smartphone technology presents significant challenges. Past experiences, such as those from the long-running Stichtoscope project, highlight the difficulties of relying on smartphones due to their varying sizes, shapes, cameras, and operating systems. A similar problem was run into by the Mobile ODT team who in the end created a smartphone-like device to be compatible with their hardware architecture*(Figure A.3)*.

As these devices continue to change, software must be frequently updated and adapted to remain functional, adding to long-term maintenance concerns.



Figure A.3: Mobile ODT older concept(Left) vs new concept with custom phone(right)(MobileODT, 2024)

Speculum free endoscopy

One of the design approaches explored was inspired by modern gastric endoscopes. However, a key concern was identified: instead of prioritizing cutting-edge performance that may lead to early obsolescence, the focus should be on repairability and long-term usability. Ensuring that the equipment remains functional over time is more beneficial than designing a really good but short-lived device.

This approach was considered because avoiding the use of a speculum could allow the device to inspect the vaginal walls in addition to the cervix. Once inside, an angled lens attachment(Figure A.5) —similar to a dentist's mirror—could enable a broader field of view (Figure A.4). However, repeated use could lead to damage, such as minor cracks or the accumulation of tape and debris (*Figure A.6)*. Ensuring a highly durable endoscope would be expensive and impractical for the intended context. Additionally, incorporating complex technologies such as optical fibers or high-precision optical endoscopes would require specialized expertise for repairs, making them unviable options.



Figure A.4: Dental insepction

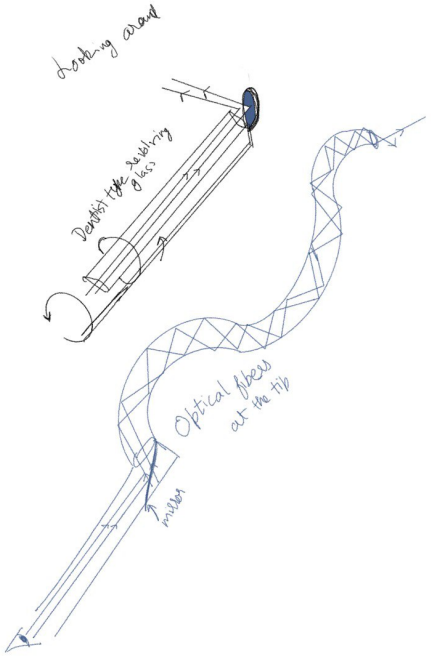


Figure A.5: Concept sketch

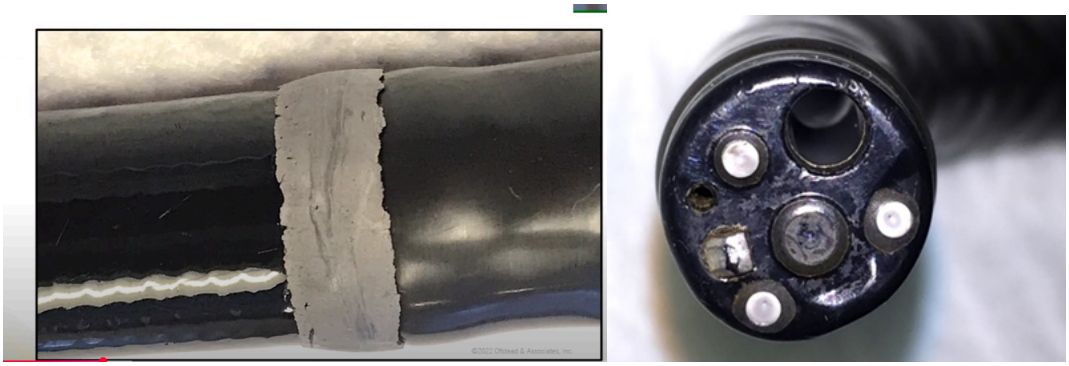


Figure A.6: Damaged upper GI endoscope, damage on tape of endoscope (site for biofilm formation)(Ofstead Insights, 2022)

Early Concept 1:

Full length shield (Figure A.7,A.8)

Pros:

1. Could accommodate protective lenses or other items like diffusers, if necessary, diffusers were later dismissed
2. Plastic shielding could easily be inserted

Cons:

3. It was flimsy and could break quickly, it bent around a lot
4. No directionality - this is not important for the AI but is important for the human while navigating

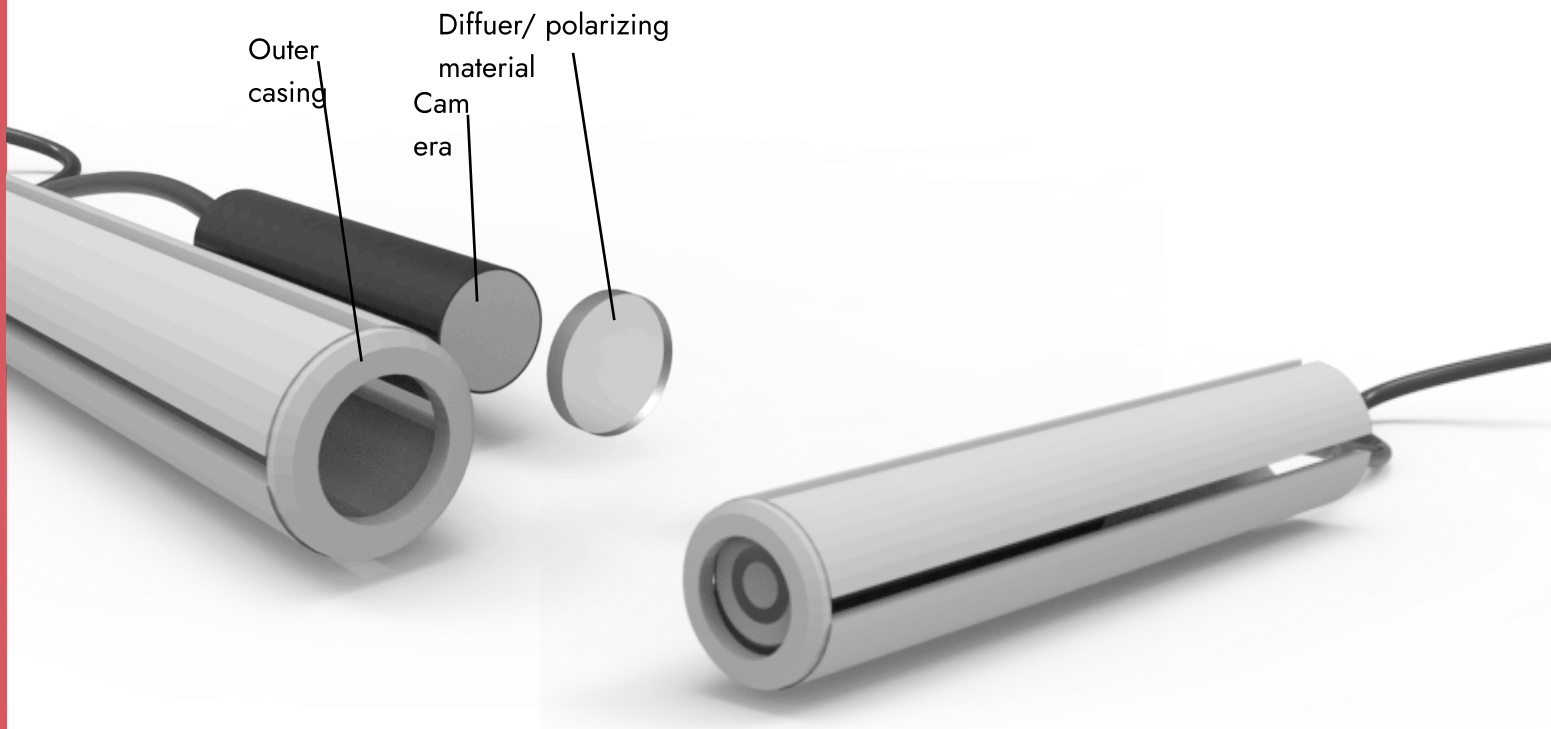


Figure A.7: Concept 1 renders



Figure A.8: Concept 1 demonstrating addition of a sterile thin plastic cover

Early Concept 2:
Guided slider*(Figure A.9)*

Pros:
1. Directional inserts, no tolerance cuts making it more sturdy
2. Positioning the camera directly in the middle. This was a problem identified with the original camera channel for the C-spec.

Cons:
1. It does not work with the existing C-spec since there has to be an additional channel for directionality
2. It could have tight tolerances and make it difficult for manufacturing
3. It needs to be pushed via the wire which could over-time make it become less effective

These prototypes need to be explored further to ensure that it is intuitive and usable by the medical professionals and fits into their sterilisation procedures. Since the outermost part touching the human body is the C-spec and not the camera body itself, it might be sufficient to just wipe the camera down as was done with other similar products(Asiedu et al., 2020)

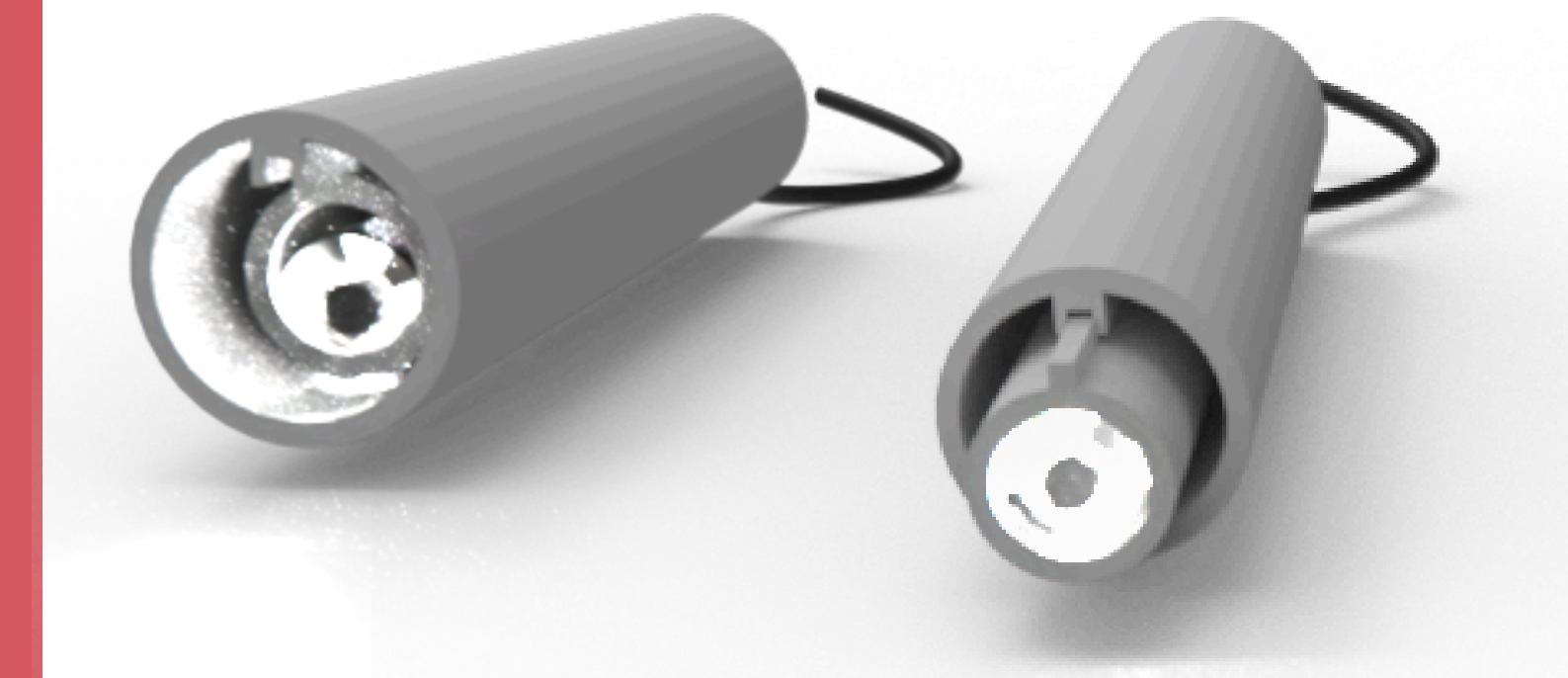


Figure A.9: Concept 2 renders

A3. Requirements derived from IEC Standards

The endoscope/borescope camera is one which is purchased online or can be easily available and that is quite convenient in terms of sourcing, the cost of such an endoscope could range from 20(Endoscoop Camera - Inspectiecamera - Camera - Telefoon - 2 Meter | Bol, n.d.) to more expensive ones upto 200 euros(Industriële Endoscoop 1080P 4.3 360° 8.5 32G 2M, n.d.) and could be cheaper with appropriate sourcing. This is already a fraction of the cost of a colposcope which can cost 8,500 euros. A key advantage of using an endoscope is that it does not require a specialist to operate, making it suitable for resource-constrained settings. Additionally, due to its affordability, damaged or malfunctioning endoscopes can be replaced without significant financial loss.

To ensure that the selected endoscope meets the necessary standards for medical imaging, an initial investigation was conducted into the International Electrotechnical Commission (IEC) standards for medical endoscopes. This below table is a list of requirements in order of priority

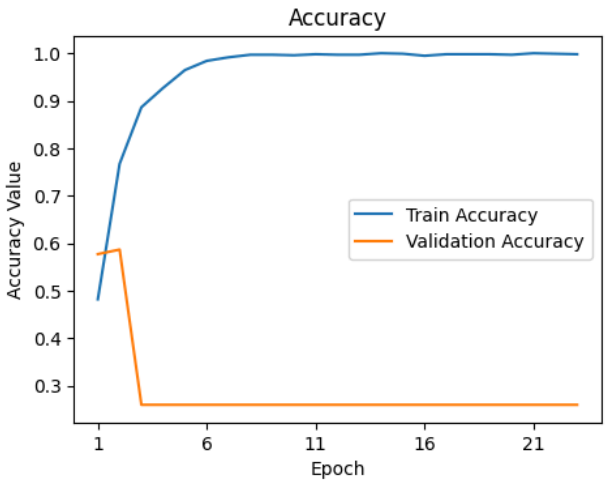
Category	Requirement	Applicable part
General	Compliance with ISO 8600-1, Ridgid endoscope	Endoscope + C-spec
Design	Smooth surfaces, no cracks or pores	C-spec
Insertion Portion	For gynaecological use, this should be minimized for patient comfort while maintaining functionality. If used without the speculum, otherwise it is constrained by the speculum diameter	Endoscope (if the length exceeds the C-spec)
Cleaning/Sterilization	Detailed usage, cleaning, and sterilization instructions	Endoscope + C-spec
Optical	Wide FOV (≥70°), high resolution, minimal distortion. This needs to be based on the camera choice for the endoscope	C-spec
Safety	Compliance with IEC 60601-2-18, ISO 10993-1, and ISO 14971	Endoscope + C-spec
Instrument Channel	This may or may not be needed	C-spec
Usability	Ergonomic design, intuitive controls	Endoscope
Marking	Clear, durable markings with model number, dimensions, and serial number	Endoscope + C-spec
Instruction Manual	To be developed along with the final concept	Endoscope + C-spec
Packaging	Protects device during storage and shipping	Outer packaging
Gynaecology-Specific	Fluid handling, patient comfort, compatibility with gynaecological procedures	C-spec

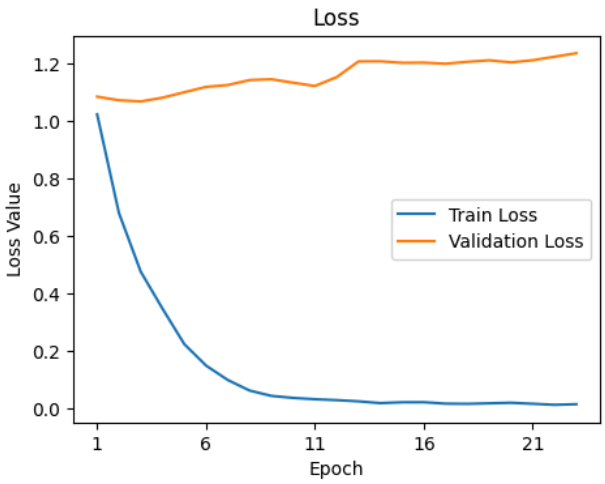
Table A.1 IEC derived requirements

A4. Training of different neural networks

Training of EfficientNet networks on Mobile ODT Dataset

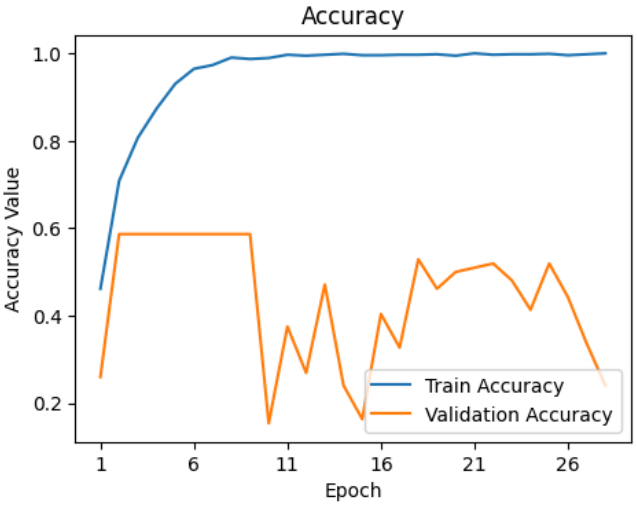
EfficientNet b3

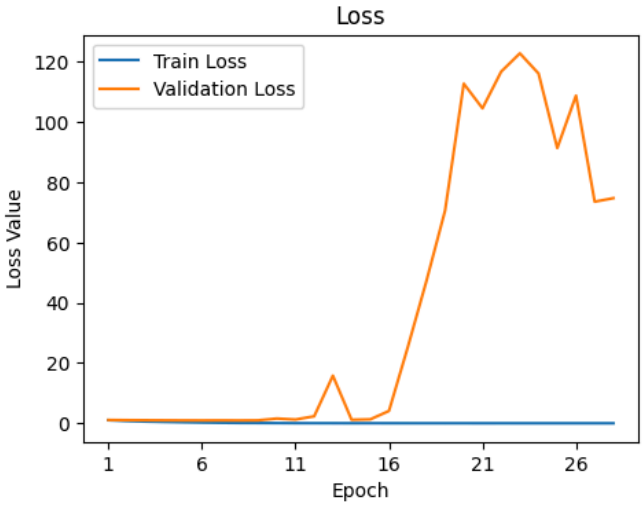




Model Accuracy in %	99.89
Test Accuracy in %	31.01
Test Loss in %	107.43
Time Taken To Train in Seconds	322.21

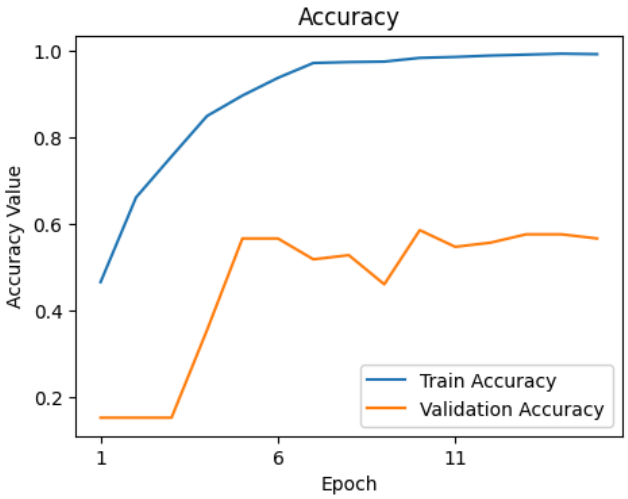
EfficientNet b2

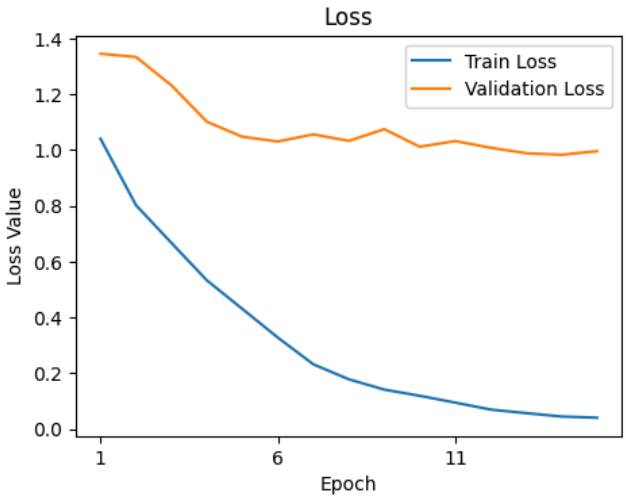




Model Accuracy in %	48.18
Test Accuracy in %	18.20
Test Loss in %	130.14
Time Taken To Train in Seconds	157.82

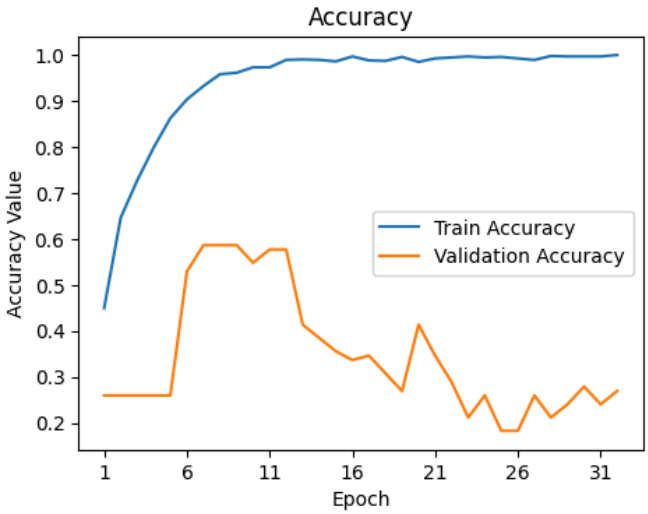
EfficientNet b1

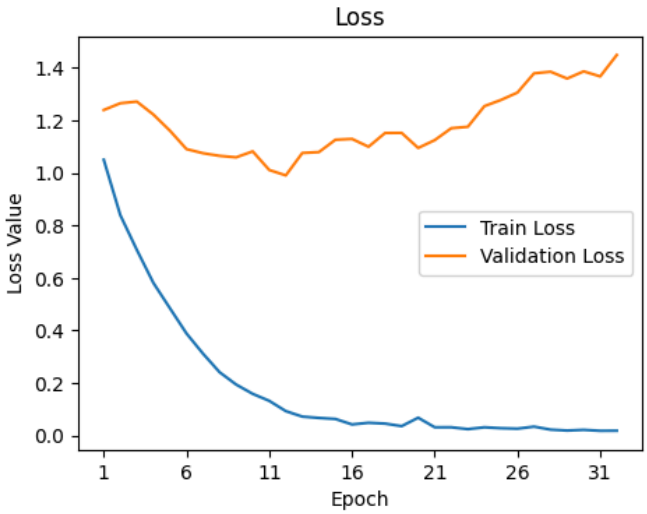




Model Accuracy in %	99.25
Test Accuracy in %	48.76
Test Loss in %	104.56
Time Taken To Train in Seconds	228.37

EfficientNet b0





Model Accuracy in %	98.93
Test Accuracy in %	50.56
Test Loss in %	102.90
Time Taken To Train in Seconds	151.54

A5. Image capture mechanism

Tests were conducted to determine the optimal image capture mechanism. The study aimed to compare clicking using a pedal and clicking using a button. The two different mechanisms were tested across sitting and standing with two participants (Figure A.10). Participants tested the mechanisms and rated their difficulty. The following are the results from the experiment conducted (Figure A.11).



Figure A.10:Testing procedure

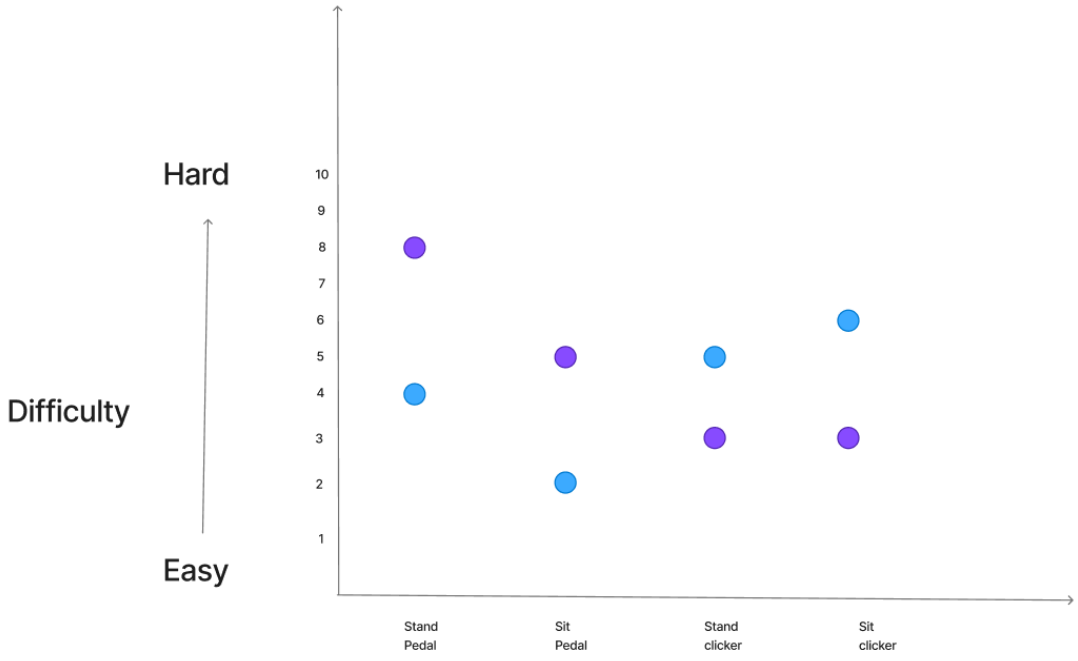


Figure A.11:Testing results

A6. Experimental test protocol

Experimental Proposal: Comparative Study to Evaluate Design Interventions for Cervical Imaging

1. Objective

To evaluate whether the proposed design interventions improve image quality (sharpness and clarity) during cervical imaging using a low-cost endoscopic setup. This will help determine the effectiveness of design changes in aiding users to capture clinically usable images.

2. Experimental Setup:

- Simulation Model: CLOE GTM gynecological training model with a modified back area for image insertion.
- Test Materials:
  - 5 printed cervix images inserted into the model
  - 1 custom 3D(silicon) cervix model for realistic imaging conditions
- Lighting Conditions: Constant lighting set to maximum brightness
- Speculum: Fixed tube-like speculum inserted consistently across trials

3. Experimental Conditions:

Condition A: Baseline (No Aid)

- The tube-like speculum is inserted.
- The endoscopic camera is inserted without any enhancements.
- The participant captures an image when they believe the cervix is in clear focus.
- This is repeated for all 5 cervix images and the 3D model.

Condition B: With Design Interventions

- Interventions include:
  - Polarising filter on the camera lens
  - Orientation guide-rail to help direct the camera correctly inside the vaginal canal
  - Real-time on-screen prompts when the image-processing feedback indicates a sharp image
- The participant is free to capture the image when they feel it is clear, now aided by the prompts and physical guides.

Figure A.10:Testing procedure

- This is repeated for the same 5 cervix images and 3D model.

4. Participants:

- (Ideally) 3-5 test users (e.g., medical trainees or clinicians familiar with vaginal examinations)
- Each participant completes both conditions to allow within-subject comparison, and this procedure is repeated twice per-user

5. Evaluation Criteria:

- Objective Measures:
  - Sharpness (measured via image gradient or Laplacian variance)
  - Focus accuracy (distance from optimal focal plane)
  - Presence of glare or overexposure
  - Age and experience of practioner
- Subjective Measures:
  - User confidence on whether the image is usable
  - Time taken to capture a satisfactory image

6. Outcome

To determine if the proposed interventions (polariser, camera guide, and AI prompts) significantly improve image quality and ease of use compared to the baseline method.

This can be quantitatively answered

7. Data Collection

- Images captured under each condition
- Timestamp for each capture
- User feedback forms post-trial

A7. Bill of Materials

Manufacturing and costs

Electronic subsystem

For the electronic subsystem since we are using primarily off the shelf components the cost estimation is straightforward and is under 200 euros for the most basic version of the device

Item	Description	Estimated Cost (EUR)	Source
Speculum	1	15	https://www.doctorshop.eu/Prodotti/surgery-CH/surgical-instruments-CH-6/instruments-for-gynecology-trousses-instrument-holder-CH-6-05/stainless-steel-cusco-speculum-small-100977
Guide (extruded + welded)	1	4.5	Aluminum tube extrusion + welding labor (local rates)https://shengenfab.com/sheet-metal-fabrication-cost
Camera housing	1	6	Stainless steel rolled tube; sheet-metal fabrication
Polarizers (pair)	1	2	PET film linear polarizer cut to size
Raspberry Pi 4 Model B (4GB)	Single-board computer for image processing and AI inference.	€ 88.50	https://elektronicavoorjou.nl/en/product/raspberry-pi-5-8gb/
USB Endoscopic Camera (8mm)	USB-connected borescope for cervical imaging.	€ 20.00	https://www.amazon.nl/s?k=usb+endoscope+8mm
Mini UPS Battery Backup	Portable power source for Raspberry Pi and peripherals.	€ 31.00	https://www.amazon.nl/Mini-UPS-batterijback-up-Intelligente-Ononderbroken-Beveiligingscamera-router-WiFi-computer/dp/B0CHMQ8GCG?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&psc=1&smid=A153HMXM6L7N91&gQT=1
USB Charger (5V, ≥2A output)	Device to recharge the battery bank.	€ 10.00	Bol.com
Total		€ 177.00	
Optional			
4.3 inch DSI touch display voor Raspberry Pi - 800x480	Touchscreen interface for real-time image preview and control.	€ 69.95	https://tweakers.net/pricewatch/467064/raspberry-pi-7-inch-touchscreen-display-zwart.html
With optional		€ 246.95	