

Development of a Low-Cost Laparoscope

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Cover picture: Exploded view of low-cost laparoscope. (Own image)

Development of a Low-Cost Laparoscope

THESIS

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Summary

Laparoscopic surgery significantly improves patient outcomes by reducing infection rates, post-operative pain, and recovery times compared to traditional open surgery. However, in low- and middle-income countries, the widespread adoption of laparoscopy remains severely restricted by the prohibitive costs, fragile optical infrastructure, and continuous power supply demands of conventional laparoscopic tower systems.

This thesis presents the design, development, and validation of a low-cost, USB laparoscope intended as a direct replacement for commercial laparoscopes in routine surgical procedures. Adopting a human-centered, context-driven design methodology, functional requirements were formulated through literature review, live surgical observations, and semi-structured interviews with healthcare professionals experienced in low-resource settings. These evaluations established that device robustness, ease of reprocessing, and local repairability outweigh surgical versatility and incremental cost variations.

In the preliminary phase, four low-cost off-the-shelf CMOS camera modules were quantitatively benchmarked against state-of-the-art commercial laparoscopes across standard ISO optical metrics. While commercial reference systems demonstrated wider diagonal fields of view and superior low-light robustness, the low-cost CMOS modules exhibited lower color reproduction errors and significantly reduced geometric barrel distortion. The 2-megapixel GC2755 sensor was selected for prototype integration due to its superior sharpness at close operational working distances and its compact physical dimensions, which uniquely permitted a fixed 30° viewing angle offset within a 12 mm outer diameter shaft.

The final prototype incorporates a rigid, in-shaft distal housing with isolated LED channels, an acrylic optical window, and a modular, two-part PETG handle featuring an O-ring seal, brass cable gland, and tactile orientation indicator. Manufactured at a total component cost of €45.53, the scope operates via a single USB connection to a standard laptop, eliminating the need for external light sources or processing units.

Mechanical characterization confirmed structural integrity under operational tension, bending, and torsional loads. Thermal testing verified that steady-state tip temperatures plateau at 38°C, remaining safely below the 48°C tissue-burn threshold while matching human body temperature, which offers potential anti-fogging benefits. Qualitative evaluation with six surgical professionals yielded a median System Usability Scale (SUS) score of 83.75, well above the 68 acceptability baseline. Surgeons unanimously confirmed that the prototype can be operated intuitively without retraining and possesses adequate optical fidelity for diagnostic and basic surgical interventions, though further enhancements in light dimming and dynamic testing are required for complex procedures.

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Chapter 1

Introduction

This chapter introduces the context of laparoscopic surgery. It first outlines the state of the art in high-income countries (HICs), then examines the current state of laparoscopy in low- and middle-income countries (LMICs) and the main barriers to its implementation. Previous work conducted on innovations that aim to bring the cost of laparoscopic surgery down is summarised. Finally, the goals of the project and the outline of this report are described.

1.1 Background of Laparoscopy

Medicine and healthcare aim to heal with minimal complications and to ensure patients' quick return to good health [1]. A current approach in modern medicine is the use of smaller incisions to perform conventional procedures. This field is called minimally invasive surgery, in which small incisions are created and instruments are inserted inside the body instead of opening the body widely to inspect or operate on tissue [2, 3].

When minimally invasive techniques are applied to the abdomen, the approach is referred to as laparoscopy [2, 4, 5]. Standard procedures such as appendectomy, tubal sterilization, and cholecystectomy (gallbladder removal) are now performed almost exclusively laparoscopically in much of the Western world [3, 6]. Laparoscopy reduces the invasiveness of surgery and is associated with faster recovery, better cosmetic results, and reduced postoperative pain compared with open surgery [2, 4, 5]. Figure 1.1 provides an illustration over the difference between laparoscopic and open surgery.

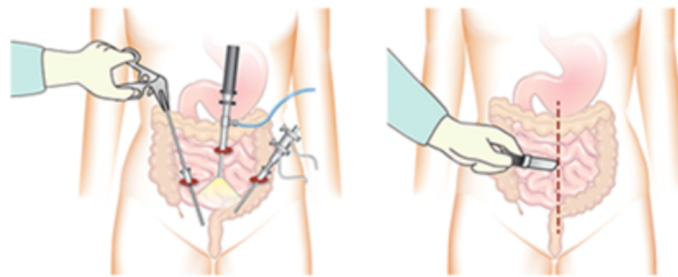


Figure 1.1: Laparoscopic (left) versus open surgery (right) [7]

To perform laparoscopic surgery, an operating space in the abdominal cavity must first be created to permit inspection and manipulation of the tissue [2, 8]. This is commonly achieved by inserting a tube-like instrument through the abdominal wall that pumps carbon dioxide gas into the cavity, which internally inflates the abdomen [2, 4, 8]. Special tube-like ports, or trocars, are used as sealed passageways for instruments to enter the abdominal cavity while preventing the gas from escaping [2, 4, 8]. A laparoscope, typically consisting of a camera head and a slender scope, is connected to a light source and inserted through one of the trocars, providing the surgeon with

a view of the abdominal cavity. Additional trocars allow the introduction of instruments such as grippers and cutters to perform the surgical procedure.

The light source, image processing, regulation of the body's gas pressure, and image display are usually combined in a large installation known as a laparoscopic tower (Figure 1.2). The initial purchasing cost of such a tower can exceed 100,000 dollars and it requires considerable energy to operate, which makes it expensive and not always feasible in resource-constrained settings [9, 10, 11]. Among these components, the illumination and imaging systems constitute the bulk of the cost and are also the most delicate and susceptible to damage when subjected to impacts or bending [12, 13].

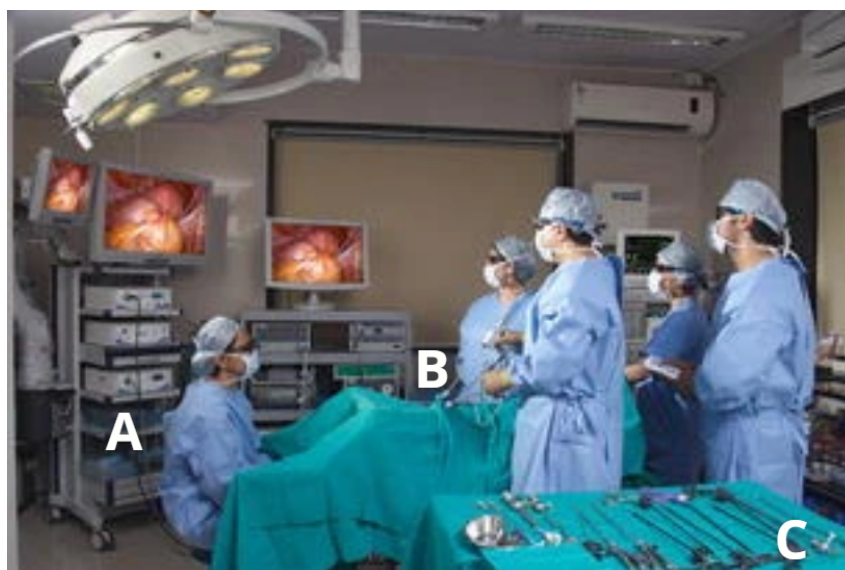


Figure 1.2: Basic laparoscopic surgery setting with laparoscopic tower (A), laparoscope entering the patient (B) and surgical instruments (C) [14]

1.2 Laparoscopy in LMICs

Laparoscopic surgery has become the standard of care in high-income countries (HICs) for many common procedures, due to its lower infection rates [15], reduced postoperative pain [16], faster recovery, and shorter hospital stays [17]. These advantages could be even more relevant for health systems in low- and middle-income countries (LMICs), where hospital beds are scarce, postoperative infections are common, and early return to work is crucial for household survival [16]. For this reason, global initiatives such as the Lancet Commission on Global Surgery and the World Health Organization's programmes for essential and emergency surgical care have recognised minimally invasive surgery as an important component of efforts to improve surgical access and outcomes worldwide [18].

Despite this potential, laparoscopy remains underutilised in many LMICs. While there are notable success stories, such as the implementation of laparoscopy in Botswana, where it has demonstrated significant social and economic benefits [19, 17], widespread adoption is still limited.

Previous systematic reviews have identified several barriers to the uptake of laparoscopic surgery [20, 21]. The most frequently mentioned challenges are the cost, availability and maintainability of equipment, unreliable infrastructure (including electrical power outages and access to medical-grade CO₂), and a shortage of sufficiently trained personnel [20, 21, 22].

1.3 Laparoscopic Surgery Innovations

Academic groups and start-ups have explored alternative, lower-cost solutions aimed at reducing reliance on the laparoscopic tower, continuous power supply, and specialised infrastructure. Examples of this are RAIS abdominal wall lift device [23], the ReadyView Laparoscope [24] and the FlexMod laparoscope [25].

The RAIS-device [23] is a metal spiral that can be subsequently inserted and retracted to lift the patients abdominal wall. This creates space to perform laparoscopic surgery and eliminates the need to inflate the the abdomen with CO₂. A schematic illustration of the device can be seen in Figure 1.3. This innovation has been proven to be effective and safe, and is already used in real surgeries in rural India.

The ReadyView laparoscope [24] aims to eliminate the laparoscopic tower by using a commercially available smartphone camera that can be connected to a laptop with a USB cable. It uses LED lights for illumination as a replacement for the expensive and fragile fibre optics used in conventional laparoscopes. The Readyview laparoscope can be seen in Figure 1.3.

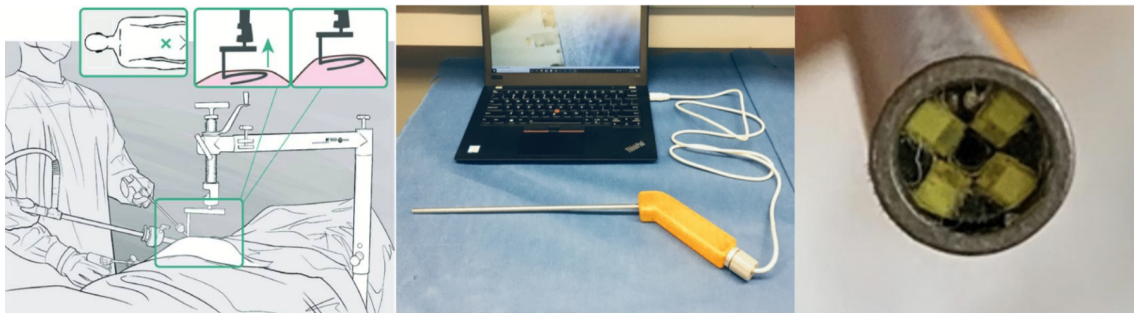


Figure 1.3: RAIS abdominal wall lifting device (left)[23] and ReadyView laparoscope (middle and right)[24]

For the design of the FlexMod laparoscope [25], a comparative analysis was performed of several low-cost imaging systems against two commercial laparoscopic camera systems used in a Dutch hospital. After the selection of a camera that had similar performance to the commercial laparoscopes, a design of a modular laparoscope was made that could be made into two different configurations using interchangeable parts:

- Standard gas laparoscopy scope with a flexible chip-on-the-tip section that can be straightened to pass through a trocar and then released to a fixed 30° viewing angle. Parts for this configuration are indicated by the letter A in Figure 1.4.
- Gasless laparoscopy scope with a chip-on-the-tip that is statically bent at 30° and can enter directly through the abdominal entry point, without the use of a trocar. This configuration is indicated in Figure 1.4 with the letter B. The design was meant to be used in combination with the previously mentioned RAIS-device [23].

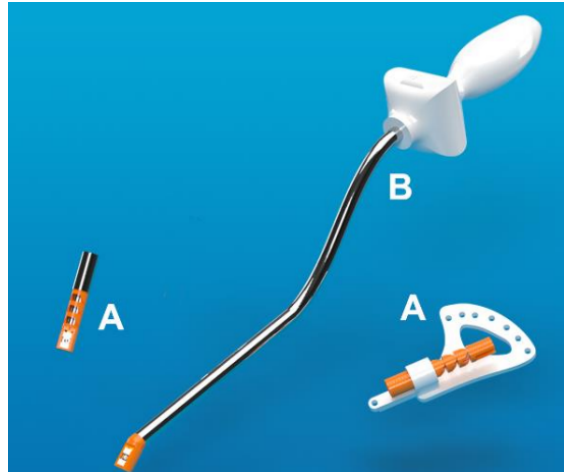


Figure 1.4: FlexMod laparoscope [25]; a modular laparoscope design with parts for a steerable tip design for gas laparoscopy (A) and a static configuration for gasless laparoscopy (B).

These low-cost solutions still have important limitations. Designs like the RAIS-device [23] and ReadyView laparoscope [24] deviate substantially from state-of-the-art laparoscopic equipment, which constrains their direct replacement potential. A lot of additional training would be necessary for their adoption.

The ReadyView laparoscope, while it offers great cost-effectiveness, still got complaints from surgeons about the image quality [24]. The viewing angle of 0° is also not ideal for most common laparoscopic surgeries.

The FlexMod laparoscope showed great potential in theory, but turned out to be not as effective in practice [25]. The bending mechanism turned out to have too much friction to be usable. It also proved to be too big of a challenge to make the steerable as well as the static design sterilisable.

1.4 Goals of this project

From literature, it becomes clear that laparoscopy can offer great benefits in low-resource settings. However, there still remain significant barriers to the uptake of this practice. To tackle the barriers of costs, dependency on constant electricity and necessity of additional training, the goal of this thesis is:

”The design of a low-cost USB laparoscope that is usable as a direct replacement for a commercial laparoscope.”

To get to this goal, this thesis focuses on the following steps in the process of designing a low-cost laparoscope:

1. **Identification of a low-cost imaging system:** Benchmark low-cost imaging systems performance against commercial laparoscope systems using empirical data from and the test setup of the FlexMod design process to find a suitable imaging system.
2. **Defining functional requirements and performance criteria:** Combine findings from literature and interviews with surgeons that have experience in low-resource settings into a comprehensive set of functional requirements and performance criteria.
3. **Develop a low-cost laparoscope:** Design and produce a prototype low-cost laparoscope.

4. **Validate:** Determine whether the development of the prototype is successful using objective mechanical tests and a subjective test with surgeons.

1.5 Report Outline

The report is structured into two parts; first the benchmarking of low-cost imaging systems against commercial laparoscopes and subsequently the design process and validation of a low-cost laparoscope prototype.

The first part consists of two chapters. Chapter 2 describes the materials and methods used to test the performance of selected low-cost imaging systems. Chapter 3 presents the results that followed from these tests.

The second part also consists of two chapters. Chapter 4 describes the whole design process from defining the functional requirements to the final prototype. Chapter 5 presents the tests that were used to evaluate the performance and usability of the prototype and their results.

To round off the report, a discussion and conclusion on both parts will be provided.

Chapter 2

Methods for Comparing Image Quality of Cameras

To assess whether low-cost imaging systems can provide clinically usable image quality for laparoscopy, this chapter describes how four low-cost imaging systems were experimentally benchmarked against two commercial laparoscopes. This chapter first details the imaging systems under evaluation, alongside the software and hardware infrastructure utilized for testing. Subsequently, the experimental testing workflow is explained. Finally, the chapter defines the objective imaging metrics used to quantify performance: field of view (FOV), sharpness, color accuracy, tone response and noise, and geometric distortions.

2.1 Imaging systems

This study compares two commercial laparoscope systems currently used at BovenIJ Hospital, Amsterdam, with four low-cost imaging system in order to evaluate their suitability for a low-cost laparoscope. The reference commercial systems represent both state-of-the-art and older-generation clinical imaging, providing a realistic baseline for performance in current practice.

The commercial laparoscopes use a Karl Storz 26003AA 10 mm slender scope connected to a Stryker 1688 and Olympus OTV S7 image processor respectively. These setups will be referred to as the Stryker and Olympus.

The low-cost systems consist of compact endoscopic camera modules with fixed optics, processing pipelines and LED's. An overview of all evaluated sensors, their supplied specifications and manufacturer details is provided in Table 2.1.

Sensor name	Stryker 1688 AIM 4k	Olympus OTV S7 Urology	OV5693	GC5035_10mm	GC5035_7mm	GC2755
diameter (mm)	10.0	10.0	12.6	10.0	7.0	7.0
Type of sensor	Three chip CMOS	CMOS	CMOS	CMOS	CMOS	CMOS
Resolution options (pixels)	3840×2160 to 1920×1080	768×504	2592×1944 to 1280×720	2592×1944 to 1280×720	2592×1944 to 1280×720	1920×1080 to 1280×720
Max Frame Rate (fps)	60	60	60	30	30	30
Resolution tested (pixels)	1920×1080	768×504	2592×1944	2592×1944	2592×1944	1920×1080
Field of view (deg)	Depends on scope	Depends on scope	76.9	76.9	86.0	80.0
Cost (€)	25,000	10,000	21,19	21,99	13,65	18,19
Focus	Automatic	Automatic	Automatic	Automatic	Fixed	Fixed
Manufacturer info	Stryker Instruments, Kalamazoo, Michigan, USA	Olympus Medical Systems, Tokyo, Japan	Shenzen Chuangjing Electronics Co., Shenzen, Guangdong, China	Shenzen Weinan electronics Co., Shenzen, Guangdong, China	Shenzhen Huashi Chengjin Technology Co., Ltd., Shenzen, Guangdong, China	Luohe Hongqun Supply Chain Co., Ltd., Luohe, Henan, China

Table 2.1: Overview of evaluated imaging systems and supplied specifications.

2.2 Software

Several software tools were required for the image quality tests.

First, Resolume Avenue 6 [26] was used to capture images from the low-cost systems via USB at the native resolution of the imaging system.

Second, Imatest [27] was utilized in combination with physical charts to determine the performance of the imaging systems. Imatest is an industry-standard, professional camera testing software. A detailed description of how this software operates is provided in Section 2.4.

Finally, Microsoft Excel [28] was used to store and analyze the data retrieved from Imatest.

2.3 Test Setup

To evaluate the imaging metrics, the cameras must capture pictures of physical test chart under strictly controlled conditions. Any variance in lighting angle, distance, or target planarity would introduce errors and invalidate the comparison between systems. Therefore, a specialized test setup was engineered to isolate these variables.

The setup consists of a rigid frame enclosed by a box to block all ambient light. The test charts were held in place by magnets on a piece of sheet metal to ensure they were perfectly straight. To prevent chart resolution from limiting the measurements, original vector files of the Imatest charts were obtained and combined into two composite targets. These targets were printed using a high-quality, colour-calibrated printer at 1200 dpi to support accurate sharpness, colour, and tone measurements across all systems. The low-cost camera tests were conducted in the TU Delft MISIT lab, while the commercial laparoscopes were evaluated at BovenIJ Hospital, using the same test setup. Pictures of the setup can be seen in Figure 2.1.

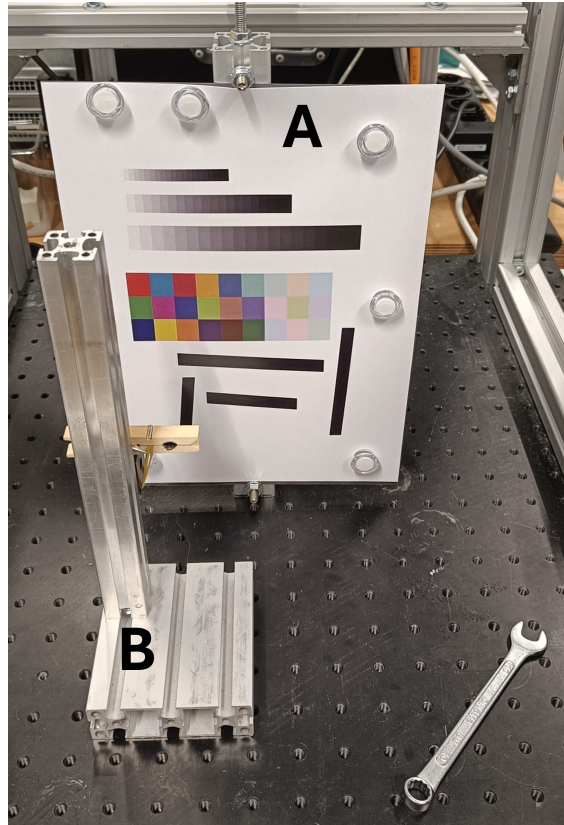


Figure 2.1: Image quality test setup showing the chart holder mounted with multiple test charts (A) and an adjustable mounting clamp for the imaging systems (B).

2.4 Test Description

The tests consisted of the following steps:

1. **Position chart and imaging system:** Make sure the imaging system is located in front of the centre of the chart and at the desired distance. Also ensure the chart is straight.
2. **Capture image:** Put the box over the setup to block out all external light. Capture an image of the chart using the Resolume Avenue 6 software. Make sure the capturing settings are set to the native resolution of the imaging system.
3. **Upload to Imatest:** Upload the captured image into the Imatest environment. If the software does not automatically recognize the chart, select it manually. The software will now compare the uploaded image to a reference embedded in the software. The differences between the uploaded image and the reference determine the results of the image quality test. The software presents these results automatically. The measured metrics and the charts that they are tested with are detailed further in Section 2.5.
4. **Export Data:** The results presented by the Imatest software are exported into Microsoft Excel tables for further analysis.
5. Repeat step 2, 3 and 4 with the different imaging systems.
6. Repeat step 1-5 with the different charts.

A flow chart of these test steps showing what software is used in each step can be seen in Figure 2.2.

The testing approach is aligned with ISO 19264 principles for imaging performance evaluation, complemented with metrics and procedures drawn from Imatest documentation and relevant standards used in optical and imaging characterization, including ISO 8600 [29] and ISO 12233 [30].

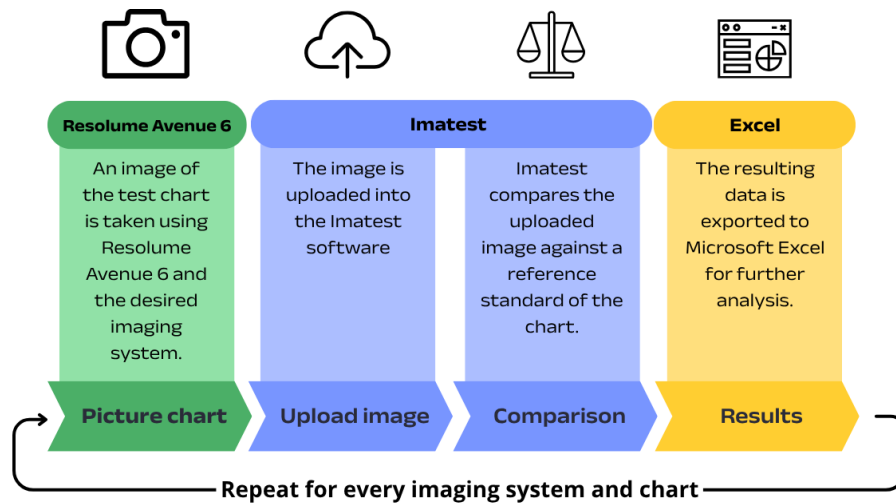


Figure 2.2: Visual representation of the workflow of the image quality testing.

2.5 Test Metrics and Charts

2.5.1 FOV

The FOV is tested to validate the vendor's claims. The test is performed by capturing an image in the native aspect ratio of the sensor. A printed 16:9 and 4:3 rectangle of 240x135 and 200x150 mm are used for the respective ratios, as shown in Figure 2.3. The sensor is centered at the rectangle and then moved backward until the rectangle is at the image's border. Based on the tangential relation, the FOV can be determined in horizontal, vertical, and diagonal degrees, as in ISO 8600-3 [29].

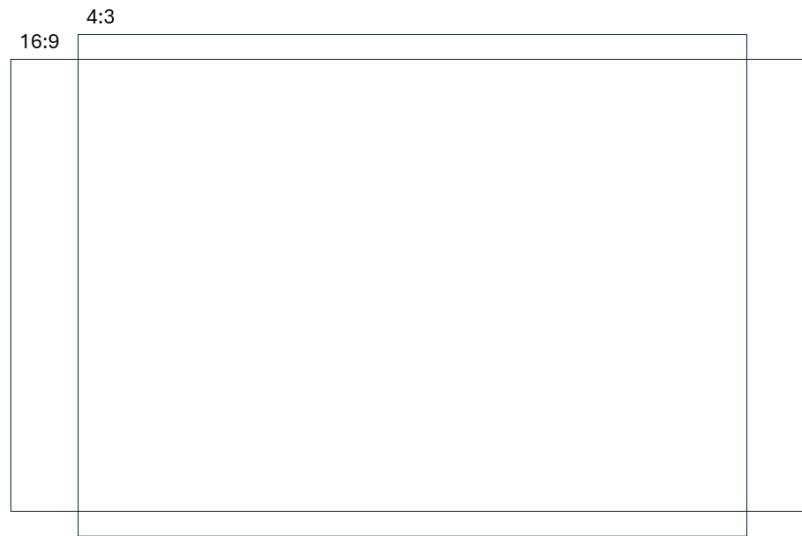


Figure 2.3: Rectangles chart to test field-of-view. (own image)

2.5.2 Sharpness

Sharpness is seen as the most important factor for image quality [31]. This aspect is objectively measured using contrast's modulation transfer function (MTF) and the 10-90% rise distance at 100mm and 50mm working distances. The industry standard for imaging sharpness is the MTF50 value, which indicates the frequency of black and white cycles that fit per pixel while maintaining 50 percent of the initial contrast [32, 33]. This metric, expressed in cycles per pixel, facilitates comparison across systems with varying resolutions [33]. The 10-90% rise distance measures the number of pixels between 10 and 90 percent of the contrast.

Imaging systems with higher resolution, greater MTF, and a shorter rise distance between edges will be perceived as having sharper images [34].

The images produced by the assessed imaging systems are not raw and, therefore, are subject to processing and compression into specific formats by manufacturers. This process potentially allows for corrections or alterations to the image through software, a common practice that can impact the analysis. Most often, sharpening techniques, which enhance contrast around edges, are employed, thereby increasing the MTF50 frequency and the perceived quality of the image [31, 35]. This sharpening effect is quantified using the peak MTF value, where a value of 1 represents normal contrast, and values above 1 indicate the presence of sharpening [35].

Commercial laparoscopes are equipped with image enhancement modes that amplify these postprocessing effects. However, these enhancements do not necessarily reflect the intrinsic quality of the imaging systems [35]. When these modes are fully activated, the contrast could be amplified up to three times the original. These sharpening algorithms typically show greater efficacy on straight lines and high-contrast edges. Therefore, both linear and nonlinear sharpness tests are conducted to assess sharpness. Based on slanted edges and wedges, these tests adhere to the guidelines set forth in ISO 12233 [31, 36]. The wedge and slanted edge charts used in the tests are shown in Figure 2.4.

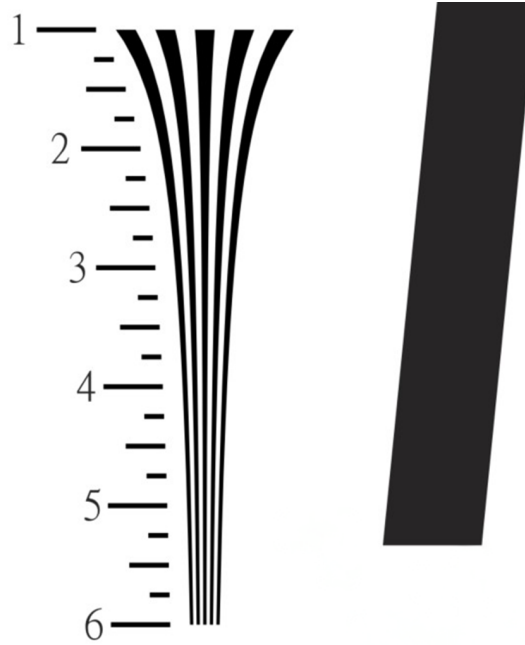


Figure 2.4: Wedge (left) and slanted edge (right) charts to test sharpness. [37]

2.5.3 Colour

In the field of imaging, colour accuracy can be assessed quantitatively using the ΔE and ΔC metrics. These metrics describe deviations in colour and luminance between a target and its captured image. Specifically, ΔE measures the overall perceptual colour difference, which is a combination of colourfulness and luminance difference. ΔC focuses on chroma (colourfulness) deviation only. [38]

For colour analysis, the Universal Test Target (UTT) colour test chart is employed (Figure 2.5). For comparability, the widely used Adobe RGB colour space is selected as the reference standard. [38]



Figure 2.5: UTT Colour chart to test colour reproduction performance. [37]

2.5.4 Tone response and noise

The tone and noise characteristics of imaging systems are evaluated using the Kodak Q-13 chart, focusing on exposure error, gamma, contrast, and noise [39]. It is shown in Figure 2.6.

Exposure error is defined such that a value of 0 indicates ideal exposure. Negative values signify underexposure (a darker image than the reference), while positive values indicate overexposure. Exposure is commonly expressed in f-stops, where the f-number is defined as the ratio of the lens focal length to the entrance pupil diameter, and therefore relates inversely to the amount of light reaching the image sensor.

The gamma value describes the relationship between pixel value and scene (or chart) luminance, i.e., the mapping between input exposure and output signal brightness. A gamma of 1 corresponds to a linear tone response, whereas values below 1 indicate a brighter rendering of darker tones (lifting shadows) to separate more tones in low-luminance regions. [40]

The contrast ratio is determined by comparing the difference between the chart's white background and black lines, and indicates how distinctly black and white tones can be separated. [40]

Finally, pixel noise is assessed as variation/error in the measured tone or colour of pixels. It is commonly expressed using signal-to-noise ratio (SNR) and a colour-difference metric (often reported as a percentage). An image is considered clear if $\text{SNR} > 1$ (equivalently, > 0 dB). This clarity is tested across a range of normalized exposures (e.g., from the darkest tone up to the brightest tone), as indicated with C in Figure 2. [41]



Figure 2.6: Kodak Q-13 chart to test tone response and noise. [37]

2.5.5 Distortions

Distortion is evaluated using a checkerboard test chart (indicated with a D in Figure 2). The chart is designed to span the full field of view, enabling comparison between physically straight lines on the chart and their representation in the captured image. [42]

The assessment follows the SMIA TV distortion approach, which aggregates barrel distortion, pincushion distortion, perspective distortion, and chromatic aberration into a single distortion value expressed as a percentage. The maximum barrel distortion can be determined by identifying the radius (or image region) with the most pronounced horizontal and vertical deviation, providing an overall measure of barrel distortion present in the image. [42]

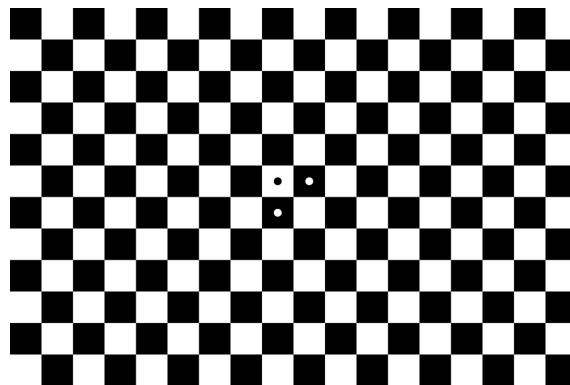


Figure 2.7: Checkerboard chart to test distortion. [37]

Chapter 3

Results of Image Quality Tests

This chapter presents the quantitative results of the imaging system tests. Four off-the-shelf imaging systems were benchmarked against two commercial laparoscopic systems using the standardized procedures described in Chapter 2. Performance is reported across the key imaging metrics used throughout this study: field of view, sharpness, colour accuracy, tone response and noise, and geometric distortion. The results are shown in the corresponding tables, enabling a direct, metric-by-metric comparison between the low-cost candidates and the clinical reference systems. The chapter concludes with a short summary and explanation of what the results mean for the rest of the project.

3.1 FOV

As summarized in Table 3.1, the measurements show that all low-cost imaging systems were broadly consistent with their advertised field of view (FOV). The reference laparoscope systems (Stryker and Olympus) achieved a diagonal FOV of approximately 91° , reflecting state-of-the-art optical performance. In addition, the GC2755 sensor showed a more pronounced horizontal–vertical difference due to its native resolution, being 1920x1080. The other sensors exhibited a smaller discrepancy between horizontal and vertical FOV components because of their respective native resolution, being 2592x1944.

For field of view, no off-the-shelf module exceeds the wide diagonal FOV measured for the reference laparoscopes. The low-cost cameras remain in the range of roughly 74° to 83° diagonal FOV, whereas both reference systems measure about 91° diagonal.

Metric	Stryker	Olympus	OV5693	GC5035_10mm	GC5035_7mm	GC2755
Advertised FOV diag (deg)	wide view	wide view	76.9	76.9	86.0	80.0
Measured FOV diag (deg)	91.0	91.0	74.3	75.0	82.7	80.0
Measured FOV hor (deg)	75.0	62.4	62.4	63.1	70.3	72.4
Measured FOV vertl (deg)	52.0	48.9	48.9	49.4	55.7	44.7

Table 3.1: Measured field of view (FOV) per imaging system

3.2 Sharpness

The sharpness assessment was performed at two working distances, 100 mm and 50 mm. For each distance, two targets were evaluated: a wedge and a slanted edge. From these measurements, MTF characteristics were obtained and summarized using peak MTF, MTF50, and the 10–90% rise distance. The results are reported in Table 3.2.

A clear difference in image processing is visible from the peak MTF values. The commercial reference systems show stronger sharpening, most notably for the Stryker system at 100 mm with a peak MTF of 1.44. The off-the-shelf modules generally remain close to unity, indicating limited sharpening, except for the GC5035_7mm at 100 mm which reaches 1.30.

Based on wedge MTF50 at 100 mm, the OV5693 achieves the highest score among the low-cost cameras, followed closely by the GC5035_10mm, while the GC2755 scores lowest. At 50 mm, the OV5693 and GC5035_10mm remain similar, the GC5035_7mm decreases, and the GC2755 improves substantially compared to its 100 mm performance, as shown in Table 3.2.

The 10–90% rise distance provides a complementary indicator of perceived edge sharpness. At 100 mm, the OV5693 and GC5035_10mm show short rise distances of roughly 1–2 pixels, while the GC2755 exhibits a much larger rise distance, indicating a significantly blurrier edge transition. At 50 mm, the GC2755 improves markedly, whereas the OV5693 and GC5035 variants show larger rise distances than at 100 mm, consistent with the increased difficulty of maintaining sharp focus at shorter working distance.

Overall, several low-cost modules match or outperform the reference systems on objective sharpness metrics. At 100 mm, OV5693 achieves a higher wedge-based MTF50 than both reference systems, and GC5035_10mm exceeds Olympus on the same metric. OV5693 and GC5035_10mm also show shorter edge-transition distances than both Stryker and Olympus at 100 mm.

At 50 mm, GC2755 yields the highest wedge-based MTF50 of all systems and all low-cost modules show shorter rise distances than both reference systems. The results highlight that measured sharpness depends strongly on both working distance and in-camera processing, with the commercial systems achieving high apparent sharpness primarily through stronger sharpening, while the low-cost modules rely more on intrinsic optical and sensor performance.

Metric	Stryker	Olympus	OV5693	GC5035_10mm	GC5035_7mm	GC2755
100mm						
MTF peak	1.4	1.0	1.1	1.00	1.3	1.0
MTF50 wedge [cy/px]	0.2	0.1	0.2	0.2	0.1	0.1
MTF50 slanted edge [LW/PH]	0.2	0.1	0.3	0.3	0.3	0.1
10–90% rise distance [px]	1.7	5.2	1.2	1.4	1.8	11.6
50mm						
MTF peak	1.2	1.0	1.0	1.0	1.0	1.0
MTF50 wedge [cy/px]	0.1	0.1	0.1	0.1	0.1	0.2
MTF50 slanted edge [LW/PH]	0.1	0.1	0.3	0.2	0.2	0.4
10–90% rise distance [px]	4.7	5.8	2.2	2.1	2.8	1.7

Table 3.2: Sharpness metrics at 100 and 50 mm working distances

3.3 Colour

The colour test evaluates colour reproduction and white balancing using the ΔE and ΔC metrics. Mean and maximum errors for each imaging system are summarized in Table 3.3. Overall, the OV5693 achieves the lowest mean and maximum colour errors among the low-cost cameras, and it also outperforms both commercial reference systems on these metrics. The GC5035_10mm follows as the second-best low-cost option, while the GC5035_7mm shows the largest errors across the off-the-shelf cameras.

ΔE : The overall colour difference, captured by ΔE , indicates that the OV5693 reproduces the test-chart colours most accurately, with the lowest mean and maximum deviations. The GC2755 performs comparably to the GC5035_10mm in mean error but exhibits a higher maximum error, suggesting that some colours are reproduced with larger outliers. Both reference laparoscopes score higher mean and maximum ΔE values than the OV5693, indicating larger overall colour deviations under the tested settings.

ΔC : The chroma deviation, quantified by ΔC , shows a similar ranking. The OV5693 again yields the smallest mean and maximum chroma errors, followed by the GC5035_10mm. The

GC2755 and GC5035_7mm exhibit substantially larger ΔC values, indicating less consistent colour saturation reproduction. The commercial systems show elevated chroma errors as well, with the Olympus system producing the highest ΔC values in this dataset.

Taken together, the results in Table 3.3 suggest that all evaluated low-cost cameras outperform both reference systems in mean and maximum ΔE and ΔC , indicating smaller overall colour deviations and improved chroma reproduction under the tested conditions. The OV5693 provides the most faithful colour and saturation reproduction among the evaluated candidates for the low-cost system.

Metric	Stryker	Olympus	OV5693	GC5035_10mm	GC5035_7mm	GC2755
ΔE mean	31.6	37.6	18.5	27.7	33.0	25.6
ΔE max	54.3	71.3	35.0	45.9	63.0	54.0
ΔC mean	21.0	25.7	12.5	16.1	27.8	22.1
ΔC max	49.5	63.7	30.2	35.5	56.8	52.1

Table 3.3: Colour accuracy metrics per imaging system

3.4 Tone Response and Noise

The Kodak Q-13 target test evaluates tone response and noise using four metrics: exposure error, gamma, mean pixel noise, and the exposure level at which $\text{SNR} > 1$. The results are summarized in Table 3.4 and provide a quantitative comparison of tonal reproduction and noise performance across the off-the-shelf cameras and the two laparoscope reference systems.

Exposure error shows clear differences in exposure calibration. The GC5035_7mm is closest to ideal exposure with an error of 0.08 f-stops, followed by the Olympus system at 0.28 f-stops. The OV5693 and GC5035_10mm show moderate overexposure with errors of 0.48 and 0.40 f-stops, while the Stryker system exhibits the largest positive exposure error at 0.94 f-stops. The GC2755 is underexposed with an error of -1.11 f-stops.

Gamma values indicate that the off-the-shelf cameras apply a stronger tone lift than the laparoscopes. The GC5035_10mm and GC5035_7mm yield the highest gamma values at 0.70 and 0.67, with the OV5693 at 0.60. The Stryker and Olympus systems are lower at 0.39 and 0.47, and the GC2755 is lowest at 0.30.

Mean pixel noise differs strongly between candidates. The Olympus system produces the lowest mean pixel noise at 0.71%, followed by the GC5035_7mm at 0.80% and the Stryker system at 1.10%. The GC2755 is higher at 2.05%, while OV5693 and GC5035_10mm show substantially larger mean pixel noise at 11.23% and 7.42%.

Low-light robustness, expressed by the exposure level where $\text{SNR} > 1$, is best for the Stryker system at -9.75 stops. All off-the-shelf modules maintain $\text{SNR} > 1$ down to roughly -5 stops, which is clearly better than the Olympus system at -1.22 stops, but not as robust as Stryker.

In summary, the GC5035_7mm outperforms both laparoscopes on exposure accuracy. For low-light performance, all off-the-shelf cameras outperform the Olympus system, while none outperform the Stryker system. In mean pixel noise, no off-the-shelf camera outperforms Olympus, and the GC5035_7mm is the closest low-cost alternative.

Metric	Stryker	Olympus	OV5693	GC5035_10mm	GC5035_7mm	GC2755
Exposure error [f-stops]	0.9	0.3	0.5	0.4	0.1	-1.1
Gamma	0.4	0.5	0.6	0.7	0.7	0.3
Pixel noise mean [%]	1.1	0.7	11.2	7.4	0.8	2.1
Exposure at SNR > 1 [stops]	-9.8	-1.2	-5.0	-5.3	-5.3	-5.0

Table 3.4: Tone response and noise metrics per imaging system

3.5 Distortion

The checkerboard test assesses geometric distortion in each imaging system. Distortion is reported as a single SMIA TV distortion value, which captures the combined effect of barrel and pincushion distortion together with other geometric deviations. The results are summarized in Table 3.5.

Across all evaluated systems, the off-the-shelf camera modules exhibit a smaller magnitude of SMIA TV distortion than both laparoscope reference systems. The OV5693 shows the lowest distortion with a value of -0.90%, followed by the GC5035_10mm and GC5035_7mm at -1.80%. The GC2755 is slightly higher at -2.68%. In comparison, the Stryker 1688 and Olympus OTV S7 show larger distortions of -3.7% and -4.9%, respectively.

In summary, all low-cost camera modules outperform both Stryker and Olympus on SMIA TV distortion in this dataset, indicating straighter line reproduction and reduced geometric deformation under the tested conditions.

Metric	Stryker	Olympus	OV5693	GC5035_10mm	GC5035_7mm	GC2755
SMIA TV distortion [%]	-3.7	-4.9	-0.9	-1.8	-1.8	-2.7

Table 3.5: Geometric distortion (SMIA TV) per imaging system

3.6 Summary

This chapter presented a quantitative benchmark evaluation of four low-cost imaging systems against two established commercial laparoscopes. A comprehensive, metric-by-metric comparison is compiled in Table 3.6, where the performance of each low-cost imaging system is color-coded relative to the commercial standards.

The empirical dataset demonstrates that the low-cost imaging systems achieve optical performance parity with, and in distinct domains exceed, the clinical baselines under uniform test conditions. Specifically, the low-cost systems consistently exhibited lower color reproduction errors (ΔE and ΔC) and superior geometric linearity, yielding significantly reduced geometric distortion compared to both the Stryker and Olympus imaging systems. While trade-offs were quantified regarding absolute diagonal field of view and low-light signal robustness, the baseline clarity remained sufficient.

The technical deficit observed for the 2-megapixel GC2755 module at the extreme 100 mm working distance remains structurally acceptable, as standard laparoscopic camera manipulation occurs at significantly closer operational distances [43] where the sensor achieved optimal resolution. Consequently, the quantitative findings confirm that all four evaluated low-cost imaging systems are thoroughly viable and usable for integration into the development phase of a low-cost laparoscope.

Metric	Unit	Stryker 1688	Olympus OTV	OV5693	GC5035_10mm	GC5035_7mm	GC2755
Field of View							
Advertised FOV diagonal	deg	wide view	wide view	76.9	76.9	86.0	80.0
Measured FOV diagonal	deg	91.0	91.0	74.3	75.0	82.7	80.0
Measured FOV horizontal	deg	75	62.4	63.1	70.3	72.4	72.4
Measured FOV vertical	deg	52	48.9	49.4	55.7	44.7	44.5
Sharpness (Wedge + Slanted-edge) at two distances							
50mm							
MTF peak (wedge+edge)	–	1.2	1.0	1.0	1.0	1.0	1.00
MTF50 (wedge)	cy/pix	0.1	0.1	0.1	0.1	0.1	0.2
MTF50 (slanted edge)	LW/PH	0.1	0.1	0.3	0.2	0.2	0.4
10–90% rise distance	pixels	4.7	5.8	2.2	2.1	2.8	1.7
100mm							
MTF peak (wedge-edge)	–	1.4	1.0	1.1	1.0	1.3	1.0
MTF50 (wedge)	cy/pix	0.2	0.1	0.2	0.2	0.1	0.1
MTF50 (slanted edge)	LW/PH	0.2	0.1	0.3	0.3	0.3	0.1
10–90% rise distance	pixels	1.7	5.2	1.2	1.4	1.8	11.6
Color (Colorcheck)							
DeltaE mean	–	31.6	37.6	18.5	27.7	33.0	25.6
DeltaE max	–	54.3	71.3	35.0	45.9	63.0	54.0
DeltaC mean	–	21.0	25.7	12.5	16.1	27.8	22.1
DeltaC max	–	49.5	63.7	30.2	35.5	56.8	52.1
Tone and Noise (Kodak Q-13)							
Exposure error	-fstops	0.9	0.3	0.5	0.4	0.1	1.1
Gamma (estimated)	–	0.4	0.5	0.6	0.7	0.7	0.3
Pixel noise mean	%	1.1	0.7	11.2	7.4	0.8	2.1
Exposure at SNR > 1	fstops	9.8	1.2	5.0	5.3	5.3	5.0
Peak SNR	dB	19.8	21.0	18.9	18.5	20.8	21.0
Distortion (Checkerboard)							
SMIA TV distortion	%	-3.7	-4.9	-0.9	-1.8	-1.8	-2.7

Table 3.6: Overview of low-cost imaging system analysis. Green indicates better performance than commercial laparoscope, yellow indicates similar performance and red indicates worse performance.

Chapter 4

Design Phase

This chapter describes the full design process of a low-cost laparoscope design process. It starts with a description of the design methodologies used. Afterwards functional requirements are formulated, which are used to generate multiple concept solutions. Subsequently the concepts are compared and rated using a multicriteria analysis approach. The best concept is selected and further perfected in the final design section. The chapter concludes with an extensive assembly instruction of the final prototype.

4.1 Design Methodology

This thesis adopts a design methodology that combines principles from the “Delft Design Guide: Perspectives, models, approaches, methods”, “TU Delft- The Mechanical Engineering Design Process”, and the “Roadmap for the design of surgical equipment for Safe Surgery Worldwide” [44, 45]

In both design methods, the first step is to formulate the need based on context and problem analysis. This initial step has already been completed and are presented in Chapter 1. The information outlined and gathered in that chapter will also be utilised for the subsequent steps in this chapter. The following are the next steps in this project:

1. **Functional Requirements:** The functional requirements are synthesized out of findings from literature, viewing several live laparoscopic surgeries in the Netherlands and interviews with surgeons who have performed laparoscopic surgeries in low-resource settings.
2. **Concepts:** Multiple concepts are thought out and prototypes will be made, consisting of different solutions for the remaining functional requirements.
3. **Multicriteria Analysis:** The concepts are graded based on a multicriteria analysis. The criteria are also formed and rated in collaboration with surgeons that perform surgeries in low-resource settings.
4. **Final Design:** From the results of the multicriteria analysis a final design is chosen, worked out into further detail and a prototype is built.
5. **Validation:** This part will be described in Chapter 5. The chapter will be split in two parts; Mechanical tests to see objectively if the functional requirements have been met and a usability test with surgeons to gain qualitative insights on usability from experts that work in this field.

4.2 Functional Requirements

The first step in the design phase consists of formulating functional requirements that are necessary for the low-cost laparoscope to work in low-resource settings. To ensure no important details were overlooked, this set of requirements was made in collaboration with surgeons that operate in such

environments. The resulting list can be found in Table 4.1. Notes taken during the interviews can be found in Appendix A. The requirements that the surgeons emphasized on are noted with a *.

The interviews were performed with approval of the TU Delft Human Resource Ethics Committee (HREC).

Requirement	Unit	Description
Cost*	< €200	The laparoscope's purchasing price must not exceed € 200 to ensure affordability.
Consumables	0	The design must eliminate the need for consumables such as drapes.
Imaging System	-	The imaging system must deliver comparable performance as the state-of-the-art laparoscope.
Shaft Length	300mm	The distance from the tip to the handle must be enough to reach the entire abdominal region.
Shaft diameter*	< 12mm	The shaft must fit through commercially available trocars for gas laparoscopy.
Illumination	-	Illumination must provide sufficient light to distinguish anatomical differences in training phantom.
Weight Specification	1kg	Total mass must not exceed state-of-the-art values.
Disinfection*	-	All materials must withstand High-Level Disinfection (HLD) agents such as Cidex OPA and Glutaraldehyde. The scope should also be cleanable with an autoclave.
Viewing offset*	30°	A 30° viewing angle offset relative to the shaft is required for optimal viewing and direct transfer of conventional laparoscopic skills.
Temperature	48°C	All parts of the device temperature must stay below temperatures where sustained contact can cause burns [46].
Power Supply*	USB	The device should be powered by USB to eliminate the dependency on constant electricity

* Direct result from interviews with healthcare professionals.

Table 4.1: Functional requirements for the low-cost laparoscope

4.3 Concepts

The design strategy is constrained by the selection of one of the off-the-shelf camera modules evaluated in the preliminary phase of this study. This selection inherently satisfies multiple functional requirements. Consequently, the primary functional requirement that permits alternative technical solutions is the execution of the 30° viewing angle offset. The following section describes 4 concepts that were considered to achieve this configuration.

4.3.1 Concept 1: In-shaft

The first concept implements a rigid architecture without moving parts, where the camera module is held permanently in place inside the distal tip of the shaft at a fixed 30° angle. Because the internal diameter of the shaft is only 10 mm, only the compact GC2755 camera module possesses dimensions compatible with this configuration. A 3D-printed PLA housing holds the camera

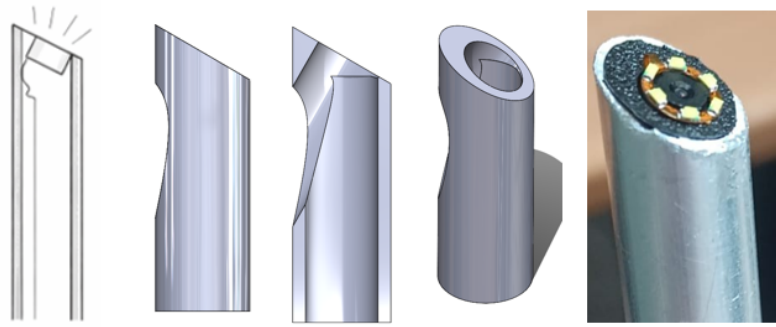


Figure 4.1: From left to right: concept drawing of Concept 1, side view of the designed housing, cross-section of the designed housing, different angle of the housing and prototype.

in place inside the shaft. Figure 4.1 shows a schematic drawing of this configuration alongside pictures of the designed housing and the final manufactured prototype.

4.3.2 Concept 2: Twister

The second concept utilizes an active mechanical mechanism where both the deployment to a 30° viewing orientation and the retraction to a 0° alignment are achieved via an actuated motion. The mechanism, shown in Figure 4.2, relies on axial rotation, comprising two independent tubular sections mated at a 15° cutting plane. When one segment is rotated by 180° relative to the adjacent section, the combined mating angles accumulate to form a definitive 30° structural offset. The mechanism is again made of 3D-printed PLA. In this concept, the camera module is seated straight within the distal section. Actuation is provided by a relatively stiff helical spring that attaches to bottom part of the distal end and goes all the way through the shaft. By rotating this spring, the distal end is rotated and all angles between 0 and 30 degrees can be achieved. The circular hole in the interface section and helical spring leave room for the USB-cable connect to the camera module.

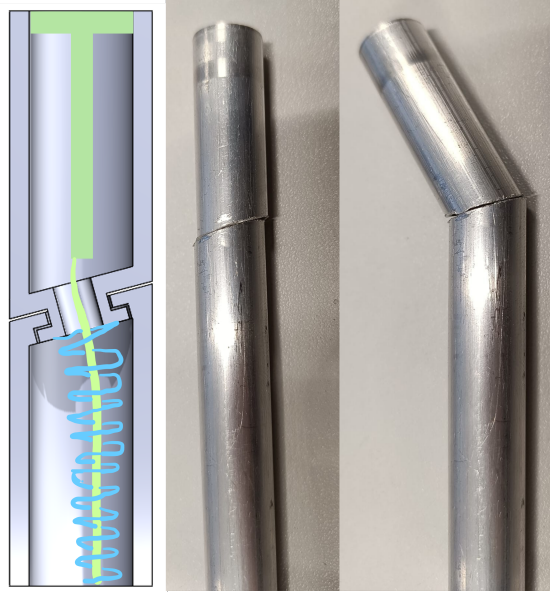


Figure 4.2: Left: cross-section of concept 2 showing the position of the imaging system (green) and the helical spring used to actuate the motion. Right: Pictures showing how the mechanism achieves 0° and 30° angles.

4.3.3 Concept 3: Tendon

Concept 3 combines active actuation with passive spring-back motion. The physical core of the mechanism consists of a continuous 3D-printed TPU helical spring incorporating an integrated rib that serves a dual purpose as an structural alignment guide and a routing channel for the internal USB cable. The mechanical articulation is actively controlled via a tendon routed along the opposite side of the structural rib. By pulling the tendon, the mechanism bends to the desired angle. A cross-sectional schematic detailing this mechanism is provided on the left side of Figure 4.3, with a prototype illustrated on the right. The camera module sits in a straight configuration in a shaft at the far side of the mechanism.

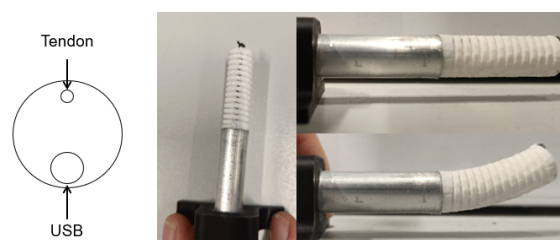


Figure 4.3: Concept 3: Tendon-driven bending mechanism. Left: Cross-sectional schematic of the bending mechanism showing the tendon routing and central passage for the USB cable. Right: Prototype illustrating the straight and actuated bending configurations obtained by pulling the tendon.

4.3.4 Concept 4: Passive

The fourth concept relies on a fully passive, elastic deformation principle. It incorporates a flexible section at the distal end of the shaft that maintains a natural 30° deflection angle when in mechanical equilibrium. When the instrument is structurally pushed through a straight surgical

trocar, the surrounding constraint forces the flexible segment to deform to a 0° alignment. Upon emerging from the distal exit port of the trocar into the intra-abdominal workspace, the elastic behaviour of the 3D printed TPU causes the tip to automatically return to its native 30° configuration. A cross-sectional drawing showing the position of the camera module in the mechanism and a kinematics simulation tracking this trocar transition sequence are documented in Figure 4.4.



Figure 4.4: Cross-section of concept 4 with camera module in green (left) and visual explanation of movement through a trocar in three steps (right)

4.4 Multicriteria Analysis

To determine which concept solution would be selected for the final laparoscope design, a formal Multicriteria Analysis (MCA) was executed. As with the formulation of the functional requirements, surgical professionals with direct operational experience in resource-constrained environments were consulted to determine the weighting distribution of each scoring parameter based on clinical field conditions. Notes of these meetings can be found in Appendix A. The criteria on which the concepts were evaluated are:

- **Robustness (Weight: 6):** The architecture should minimize structural vulnerability by eliminating fragile optical sub-components, internal rod-lenses, or delicate fiber-optic glass bundles.
- **Reprocessing Ease (Weight: 6):** The device assembly must ensure intuitive, reliable decontamination and high-level disinfection protocols, prioritizing geometric configurations that prevent fluid ingress and reassembly errors.
- **Repairability (Weight: 6):** The device must facilitate maintenance and component replacement within local healthcare facilities utilizing standard hand tools and non-specialized spare parts.
- **Cost (Weight: 4):** Manufacturing and purchasing costs should be minimized to guarantee economic viability and adoption potential.
- **Versatility in Surgery (Weight: 3):** The structural envelope and operational parameters of the scope must ensure adaptability across a diverse spectrum of laparoscopic interventions.

During the interviews, all three surgeons agreed that "the three R's" (Robustness, Reprocessing, and Repairability) represent the most critical performance criteria for low-resource clinical settings.

Robustness is paramount because operational environments in these target settings are often less controlled than in high-resource contexts. Instruments are frequently handled with less delicacy, and protocol-driven handling between consecutive operations is not always guaranteed.

Reprocessing is important because the product needs to accommodate highly variable hospital infrastructures. While some facilities have access to autoclaves, others rely entirely on chemical sterilization. Compatibility with multiple sterilization methods directly correlates with a higher global adoption potential.

Repairability addressing the reality that low-resource clinics often lack stable supply lines or the capital to maintain a large back-up inventory of surgical instruments. If a minor component malfunctions, local technicians must be able to troubleshoot and repair the device on-site using basic, universally available hand tools.

In contrast, unit fabrication cost was considered a secondary priority, provided it remains below a specific threshold. While the device must not cost thousands of dollars (which would negate its benefit over commercial alternatives), the general clinical consensus was that a minor price difference between €100 and €200 would not influence procurement decisions.

Finally, versatility in surgery was deemed the least critical criterion. The surgeons emphasized that if a low-cost laparoscope can reliably facilitate basic, routine procedures, it would already address the vast majority of patient needs. High-volume routine procedures represent a far more pressing healthcare burden in these regions than complex, specialized surgeries. These complex cases can still be performed using open surgery.

Following the collaborative determination of these criterion weighting coefficients, each concept was systematically evaluated. Ultimately, Concept 1 (In-shaft) achieved the highest cumulative evaluation profile, securing a score of 84 out of 100 possible points. The comprehensive quantitative scoring breakdown and comparative matrix metrics are documented in Table 4.2.

Criterion	Weight	1. In-shaft		2. Twister		3. Tendon		4. Passive	
		Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Robustness	6	4	24	3	18	2	12	3	18
Reprocessing	6	4	24	2	12	2	12	4	24
Repairability	6	3	18	2	12	2	12	3	18
Cost	4	3	12	3	12	3	12	3	12
Versatility	3	2	6	4	12	4	12	2	6
Total Score			84		66		60		78

Table 4.2: Multicriteria analysis (MCA) scoring matrix for the four laparoscope design concepts.

4.5 Final Design

Concept 1 was selected for the final design. It offered the best robustness, reprocessing and repairability prospects. The following section describes the journey from this concept to final iteration for the tip of the laparoscope. Additionally, a handle was designed to make a fully functional prototype. Figure 4.5 shows an assembled and exploded view of the final complete prototype.

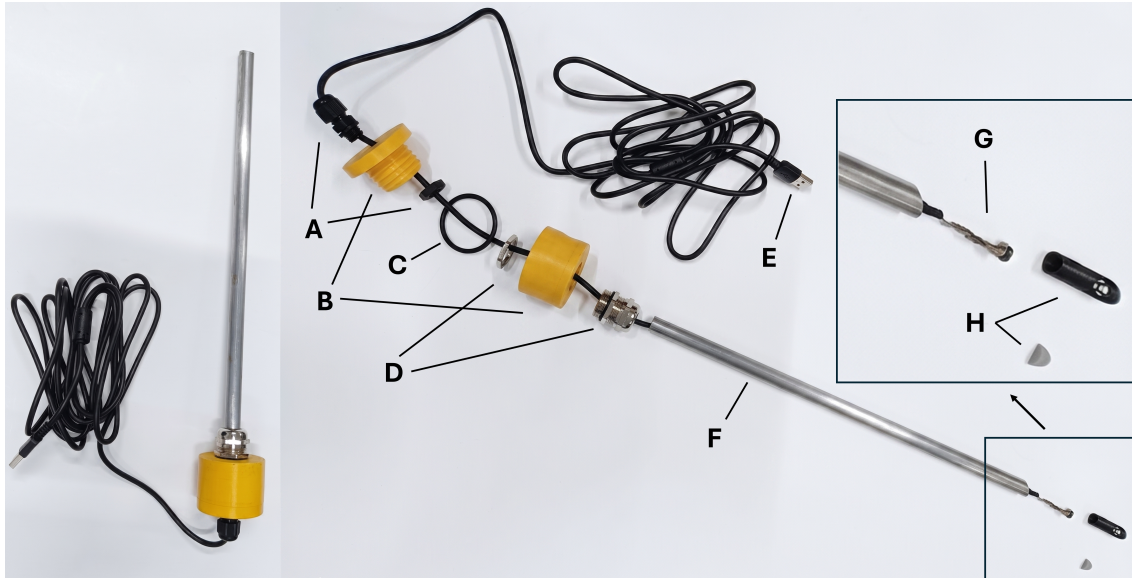


Figure 4.5: Final design of the low-cost laparoscope assembled (left) and disassembled (right)

The components are:

- **A:** Polymer cable gland
- **B:** PETG Handle
- **C:** Rubber O-ring
- **D:** Brass cable gland
- **E:** USB-cable
- **F:** Stainless steel shaft
- **G:** GC2755 camera module
- **H:** PLA tip and locking mechanism

A more complete list of materials, manufacturers and corresponding prices can be found in Appendix B. A step by step assembly explanation can be found in Section 4.6.

4.5.1 Tip

Fine-tuning the initial design of the distal tip, illustrated on the left in Figure 4.6, presented significant engineering challenges. The primary issues identified during initial evaluations were severe light bleeding (where illumination from the LEDs directly saturated the camera sensor) and instability in maintaining the camera's position.

To address these challenges, a wheel-shaped internal structure featuring dedicated cavities for individual LEDs and a slot for an assembly wedge was integrated into the housing. This wheel architecture successfully isolated the LEDs to mitigate direct light bleeding and the wedge firmly secured the camera head upon insertion into the stainless steel shaft. This second iteration is shown in the middle of Figure 4.6. However, the narrow shape of the positioning wedge left little clearance for fine adjustments during assembly. Furthermore, this iteration still lacked an optical window to protect the sensitive camera module from external fluids.

A third iteration introduced a recessed seat for a protective optical window, as shown on the right of Figure 4.6. This picture also demonstrates the operational mechanism of the positioning wedge. Unfortunately, experimental validation revealed that internal reflections within the shared optical window caused the light bleeding issue to re-emerge, severely degrading image quality.



Figure 4.6: Evolution of the distal tip design: initial concept (left), second iteration with wheel structure (middle), and third iteration featuring an optical window recess (right).

By synthesizing the insights gained from these iterations, a finalized tip architecture was developed. As illustrated in Figure 4.7, the light bleeding issue was definitively resolved by implementing a central tubular barrier within the wheel structure. This allowed the camera head to utilize its own independent acrylic optical window, completely isolated from the surrounding LEDs. The LEDs are sealed and protected from environmental exposure using a biocompatible, transparent UV-resin.

Additionally, the geometry of the positioning wedge was optimized to provide a larger clearance gap during initial component insertion without compromising the rigidity of the final fit. Finally, the internal housing section was elongated to entirely enclose the image processing chip connected to the camera head. This modification restricts any lateral movement of the electronics, preventing direct contact with the inner wall of the metal shaft and eliminating the risk of electrical short-circuiting.

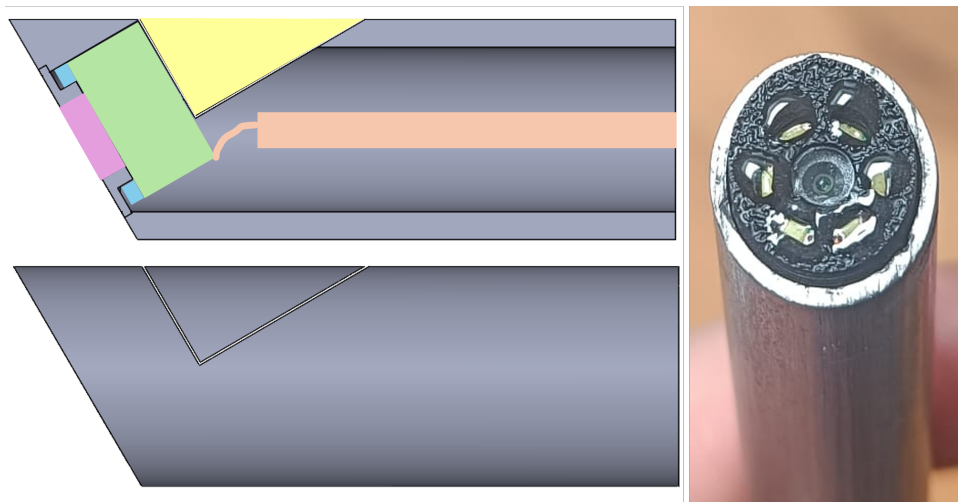


Figure 4.7: Final tip design. Left top: Schematic cross-section showcasing the internal components: acrylic optical window (purple), camera head (green), positioning wedge (yellow), and image processing chip (orange). Left bottom: External side profile. Right: Physical photograph of the completed, resin-sealed prototype tip.

4.5.2 Handle

The handle assembly serves several integrated functions: anchoring the stainless steel shaft, facilitating ergonomic surgical manoeuvrability, incorporating a tactile 12 o'clock orientation index, and providing strain relief for the USB data cord. To satisfy clinical requirements for high-level

disinfection or sterilization, the enclosure must guarantee absolute fluid isolation while remaining fully mock-disassembled for repairability.

The initial handle prototype comprised two longitudinal halves 3D-printed from PLA, clamped together via a series of bolts. Both the shaft and the USB cable interfaces were sealed using standard polymer cable glands. Figure 4.8 illustrates the integration mechanism of the gland alongside the fully assembled baseline construct. Although functionally viable, this architecture suffered from a high component count, and ensuring reliable, long-term waterproofing along the longitudinal seam proved technically unfeasible.



Figure 4.8: Initial longitudinal handle prototype: polymer cable gland interface (left) and bolted PLA assembly (right).

To minimize sub-components and achieve a hermetic seal, the handle was redesigned into a modular transverse configuration consisting of three main elements: a shaft-connecting top part, a cable-terminating bottom part, and an intermediate O-ring. The material was upgraded to PETG to provide higher structural strength and stiffness.

The two main cylindrical halves interface via a screw thread. A dedicated rubber O-ring is seated peripherally to the thread track, compressing upon closure to prevent fluid ingress during operation and reprocessing. Additionally, based on intraoperative feedback from consulting surgeons, a small geometric cut-out was integrated into the upper surface of the top part handle. This recess acts as both a visual and tactile 12 o'clock indicator, allowing the operator to instinctively determine the angular orientation scope viewpoint without breaking line-of-sight from the monitor.

The mechanical connection to the shaft was reinforced by replacing the original polymer gland with a heavy-duty brass cable gland, secured internally by a hex nut. To eliminate angular deflection or wiggling under operational loads, a custom internal spacer sleeve was designed and inserted between the outer the shaft and the clamping collar of the gland.

At the rear entry point, a polymer cable gland seals the enclosure around the USB line while acting as an effective strain relief. Any accidental tensile force exerted on the external cabling is absorbed directly by the rigid gland housing rather than being transmitted to the sensitive internal electronic terminations. The dismantled CAD components and the finalized physical prototype are displayed in Figure 4.9.

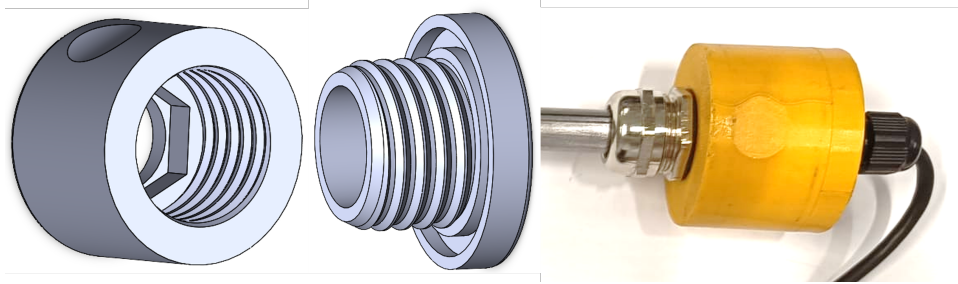


Figure 4.9: Finalized transverse handle configuration: CAD model of the internal mating threads and hex-nut recess (left) and the physical, PETG-printed assembly (right).

4.6 Assembly Instruction

This section provides a step-by-step procedure for assembling the low-cost laparoscope prototype.

4.6.1 Required Materials

- GC2755 Endoscope Module
- Polymer Cable Gland
- 3D-printed PETG Handle (Bottom Part)
- Elastomeric O-ring
- 3D-printed PETG Handle (Top Part)
- Brass Cable Gland
- 3D-printed PLA Spacer
- Stainless Steel Shaft (12 mm)
- 3D-printed PLA Camera Housing (with fitted acrylic window and sealed with UV-resin)
- 3D-printed PLA Positioning Wedge
- Hand tools: spanners and a small screwdriver

4.6.2 Step-by-Step Assembly Procedure

1. Cable Gland Installation

Connect the polymer cable gland to the bottom part of the handle by placing its nut into the corresponding hexagonal recess and screwing the main gland body in from the outside. Repeat this procedure for the brass cable gland and the top part of the handle. Figure 4.10 illustrates this assembly step.



Figure 4.10: Visual representation of assembly step 1 with brass cable gland (A), top part of handle (B), bottom part of handle (C), and polymer cable gland (D).

2. Shaft and Spacer Insertion

Insert the 3D-printed PLA spacer into the brass cable gland. Next, slide the stainless steel shaft into the gland containing the spacer. Align the shaft orientation with the 12 o'clock indicator mark on the handle part, and tighten the brass gland securely using spanners to ensure a rigid, leak-proof mechanical fit. Figure 4.11 illustrates this assembly step.



Figure 4.11: Visual representation of assembly step 2 with 3D-printed PLA spacer (A), top part of handle with brass cable gland (B), and stainless steel shaft (C).

3. O-ring Fitting

Fit the elastomeric O-ring into its dedicated seating recess located inside the bottom part of the handle. Figure 4.12 illustrates this assembly step.

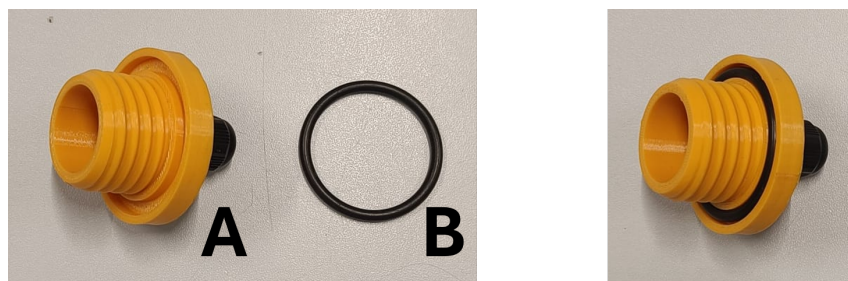


Figure 4.12: Visual representation of assembly step 3 with bottom part of the handle with polymer cable gland (A) and elastomeric O-ring (B).

4. Cable Routing

Feed the camera module and USB cable sequentially through the handle and shaft components in the following order:

- From the outside through the polymer cable gland and the bottom handle part.
- From the inside through the top handle part, the brass cable gland, and down the full length of the stainless steel shaft.

Let the camera module stick out of the shaft and screw the top and bottom handle halves together until fully seated against the O-ring seal. Do not tighten the polymer cable gland yet. Figure 4.13 illustrates this assembly step.

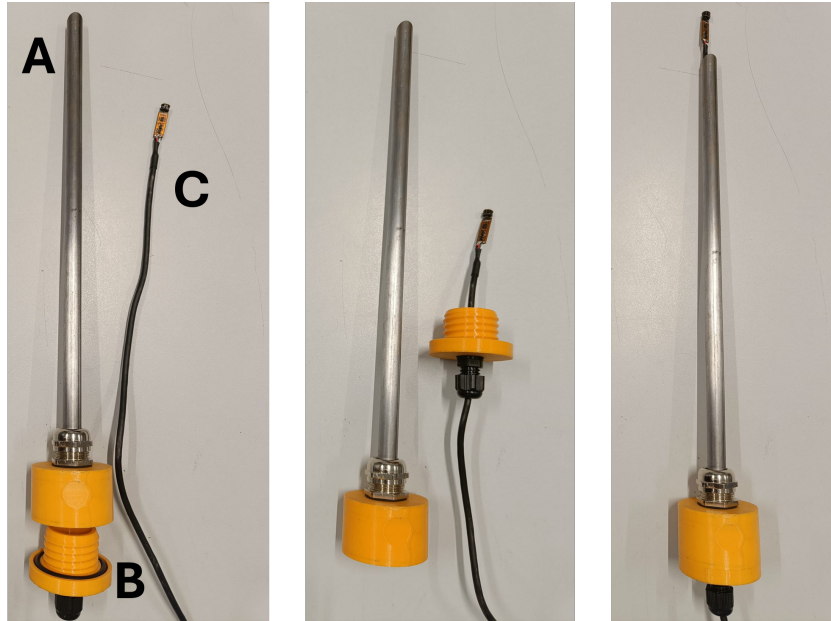


Figure 4.13: Visual representation of assembly step 4 with shaft in top part of handle with brass cable gland (A), bottom part of handle with polymer cable gland and O-ring (B), and camera module with USB-cable (C).

5. Camera Module Positioning

Carefully seat the GC2755 endoscope module into the 3D-printed camera housing, orienting it into its fixed 30° viewing position. A small screwdriver may be used gently to guide the camera head into place. Figure 4.14 illustrates this assembly step.

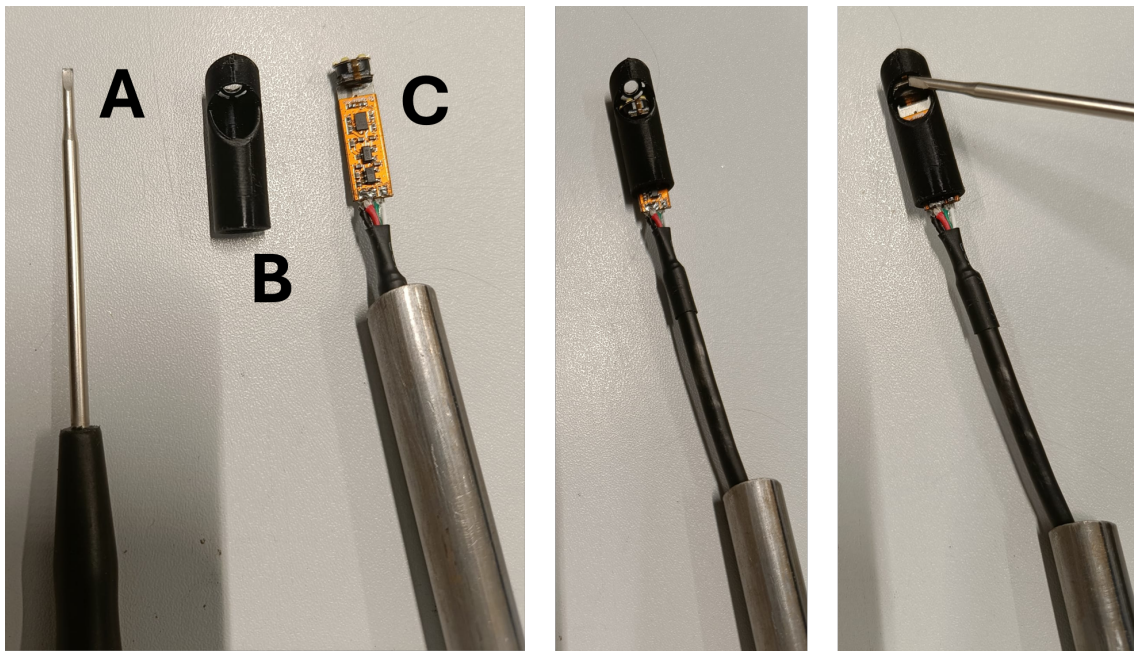


Figure 4.14: Visual representation of assembly step 5 with small screwdriver (A), camera housing (B), and camera module sticking out of the shaft (C).

6. Distal Tip Insertion

Place the 3D-printed positioning wedge into its corresponding alignment slot. Shove the complete sub-assembly -comprising the camera housing, endoscope module, and positioning wedge— back into the distal end of the stainless steel shaft until flush. Figure 4.15 illustrates this assembly step.

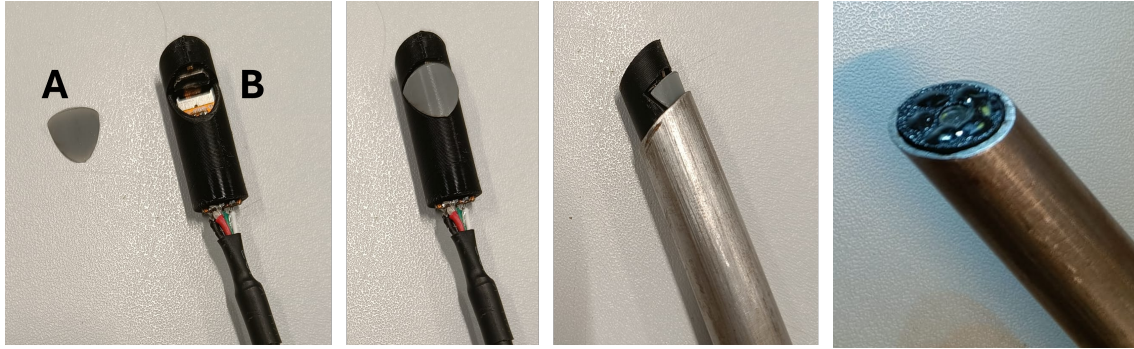


Figure 4.15: Visual representation of assembly step 6 with positioning wedge (A) and camera inside housing (B).

7. Strain Relief and Cable Locking

Verify that the internal USB cable is loose and not exerting tension on the endoscope module at the tip. Finally, tighten the polymer cable gland on the rear of the handle to provide waterproof strain relief for the cable. Figure 4.16 illustrates this assembly step.

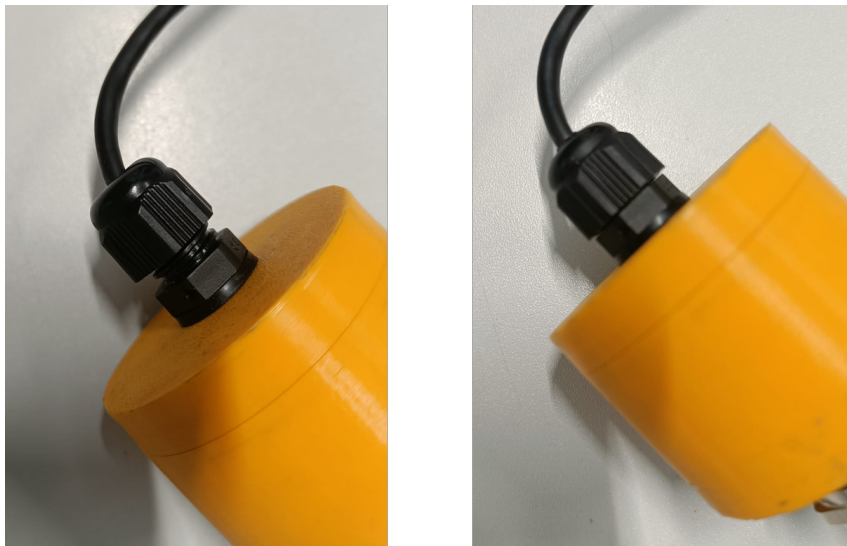


Figure 4.16: Visual representation of assembly step 7.

Chapter 5

Validation

This chapter describes the validation of the prototype. The first section presents a series of mechanical and thermal tests conducted to determine whether the functional requirements were met. The second section describes a usability test carried out with practising surgeons to evaluate the usability of the device in a clinical simulation. The chapter concludes with a summary and an overview table showing which functional requirements have been fulfilled and which have not.

5.1 Mechanical Tests

To establish whether the prototype meets the functional requirements formulated in Chapter 4 and can resist the forces on a laparoscope during surgery, a series of mechanical tests was done. The prototype is weighed, forces are exerted on it in several directions and the temperature of the tip during operation is determined.

5.1.1 Weight

In the functional requirements outlined in Chapter 4, it is stated that the weight of the low-cost laparoscope should not exceed that of commercial alternatives. The total weight of the fabricated prototype is 239.28 grams, which is well under the maximum required threshold of 1 kg.

5.1.2 Forces

To determine how the prototype reacts to forces that are exerted on it during surgery, three distinct experimental tests were performed, with visual results documented in Figure 5.1:

1. **Pull test:** This test determines whether the mechanical connection between the shaft and the handle is strong enough under tension. This longitudinal force is present in laparoscopy primarily due to friction between the scope and the trocar, typically reaching a magnitude of approximately 2 N [47]. During testing, the handle was securely clamped and the shaft was pulled in the longitudinal direction through a force gauge. The configuration passed successfully, demonstrating no movement or displacement in the shaft when pulled with a force of 25 N.
2. **Torque test:** The second force evaluation comprised a torque test, which simulates the force present when a surgeon rotates the scope within the trocar. These rotational forces are expected to lie within a similar operational range. A torque on the shaft was facilitated by inserting a 10 cm beam into the shaft to create a leverage arm, after which the inserted beam was pulled at the tip. No rotational movement was observed up to a force of 17 N, which translates to a torque of 1.7 Nm. Above this threshold, the shaft began to twist with respect to the rubber interface holding it in place, while the rigid screw connections of the gland remained static.

3. **Bending test:** This procedure simulates the distal tip getting caught behind an organ, resulting in a force on the tip perpendicular to its longitudinal axis. While this force typically lies within the same range as the pull test, it creates a substantial bending moment on the connection between the shaft and the handle due to the leverage arm of the shaft. The force was measured utilizing the same force gauge. Up until a load of 15 N, no deformation was observed. When the applied force was increased to 25 N, the shaft exhibited sideways bending. This deformation was entirely elastic, and because a force of this magnitude does not realistically occur in laparoscopic surgery, the structural integrity was verified as sufficient.



Figure 5.1: Visual Results of the Pull test (left), Torque Test (middle) and Bending test (right)

5.1.3 Heat

Another functional requirement stated that the operating temperature should stay below 48°C at all times to prevent burns when touching human tissue [46]. To test the prototype's compliance with this requirement, a test was conducted where the temperature of the prototype is measured in two places during a period of 60 minutes. The measurement locations were the LED's on the tip and the part of the shaft where the chip is located, as these locations are the only heat-producing elements in the prototype.

The temperature of the tip plateaus around 38°C after 45 minutes. The shaft does not exceed a temperature of 26°C . Therefore, the operating temperature of the prototype remains well below the maximum value of 48°C . The exact results of this test are displayed in Figure 5.2.

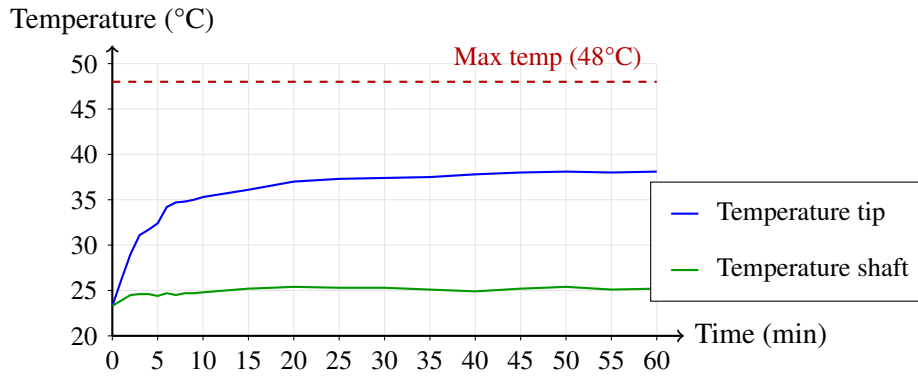


Figure 5.2: Operating Temperature of Tip and Shaft over 60 minutes.

5.2 Test with surgeons

While quantitative functional requirements form a rigid framework for technical verification, they do not guarantee clinical adoption. If the user experience fails to align with the intuitive workflows of medical professionals, the device will not be integrated into practice. For this reason, an evaluative usability test was conducted with surgeons. This section delineates the evaluation methodology and the subsequent findings. The test was conducted in accordance with the guidelines of and with approval by the Human Research Ethics Committee (HREC) of TU Delft.

5.2.1 Methodology and Experimental Setup

Participants were tasked with utilizing the low-cost laparoscope prototype to successively locate and identify the gallbladder and the appendix within a high-fidelity surgical simulation mannequin. This workflow replicated standard diagnostic and basic intervention paths. A representative photograph of a participant executing the usability test is displayed in Figure 5.3.

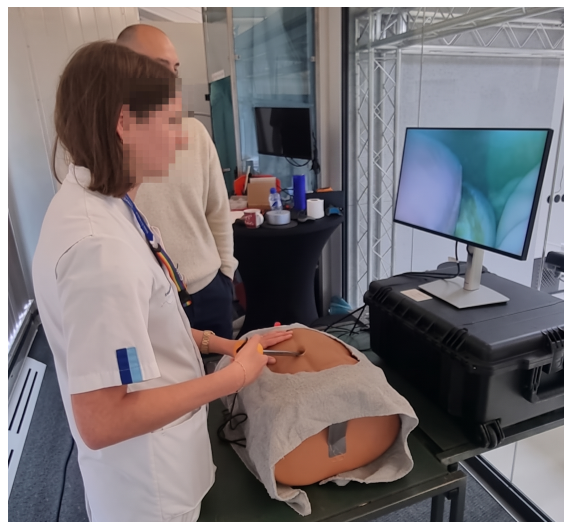


Figure 5.3: Surgical professional performing anatomical identification tasks within the simulation mannequin setup.

Immediately after the simulation task, each participant completed a standardized 20-item Likert-scale questionnaire assessing usability, optical fidelity, and ergonomics. The comprehensive questionnaire from the experiment can be found in Appendix C.

The initial ten items were directly extracted from the validated System Usability Scale (SUS) framework [48]. The SUS provides a globally recognized benchmark for product usability, generating a cumulative score ranging from 0 to 100. Within this framework, a score of 68 serves as the baseline threshold indicating a commercially viable, usable system [48]. The quantitative data derived from these SUS evaluations are summarized in Table 5.1.

Statistical Metric	Value
Sample Size (N)	6
Median Score	83.75
Range	72.5 – 95.0

Table 5.1: Summary of calculated System Usability Scale (SUS) scores from the surgeon cohort.

5.2.2 Questionnaire and Qualitative Results

Beyond the baseline usability metrics, specific questionnaire items (Q11–Q19) targeted clinical requirements, including image sharpness, depth perception, color rendering, illumination adequacy, and physical handling. The distribution of participant responses for these evaluation parameters is visualized in Figure 5.4.

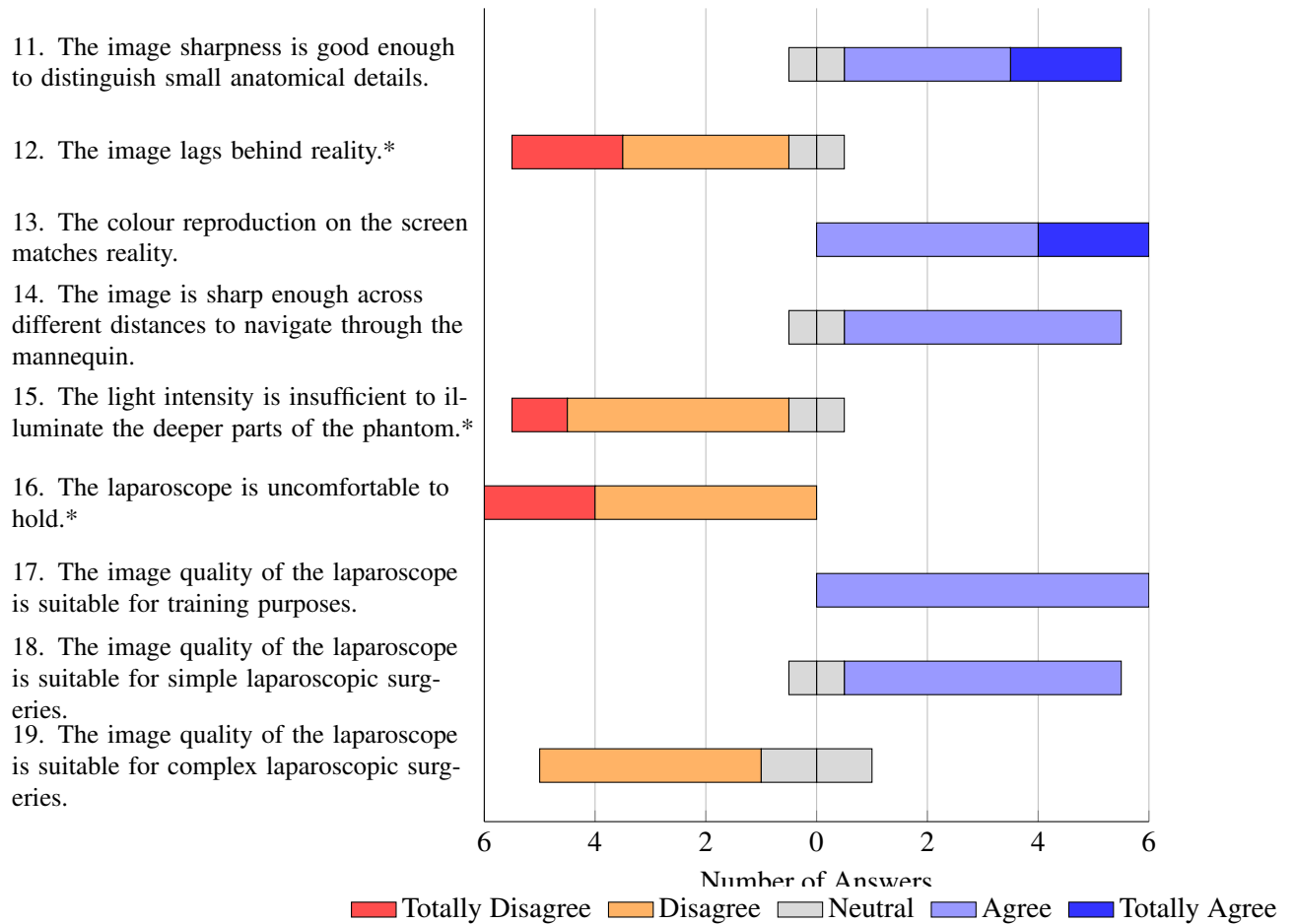


Figure 5.4: Diverging bar chart of participant responses for non-SUS questions (Q11–Q19). Negative expressions (marked with *) indicate a positive system outcome when scored with disagreement.

The final question allowed participants to provide qualitative open feedback. This commentary highlighted several critical focus areas regarding the device’s operational behavior and potential field application:

- **Ergonomics:**

“No heavy wires is a big advantage. The ergonomics of the handle can be improved.”

- **Illumination Performance:**

“Light dimmer would be useful.”

“Light adjustment would be appreciated.”

- **Clinical Deployment Potential:**

”Very suitable for main need in LMIC: diagnostic laparoscopy, less for complex procedures.”

“Perfect for military surgery, also as a disposable scope. No laparoscopy is available yet in military surgery.”

5.3 Summary of Validation

Table 5.2 provides a comprehensive overview of the prototype’s compliance with the functional requirements established in Chapter 4. The majority of the criteria were successfully fulfilled, with exceptions regarding the illumination dynamics and chemical disinfection.

The total material cost of the fabricated laparoscope is €45.53, well below the predefined design threshold of €200. A detailed breakdown of the component costs and procurement sources is provided in Appendix B.

Illumination is signed with a check and a cross. While the forward-facing LEDs provided sufficient illumination during static phantom evaluations, feedback from the surgical cohort highlighted that dynamic, in-vivo procedures necessitate adjustable dimming control to prevent localized glare and tissue overexposure.

Finally, the disinfection requirement is marked as unfulfilled. The mechanical interface between the camera housing and the stainless steel shaft is not yet fluid-tight, and a reversible sealing mechanism that preserves modularity was not realized in this design iteration. The engineering trade-offs and prospective design solutions for this interface are further elaborated in Chapter 6.

Requirement	Unit	Description	Status
Cost	< €200	The laparoscope’s purchasing price must not exceed € 200 to ensure affordability.	✓
Consumables	0	The design must eliminate the need for consumables such as drapes.	✓
Imaging System	-	The imaging system must deliver comparable performance as the state-of-the-art laparoscope.	✓
Shaft Length	300 mm	The distance from the tip to the handle must be enough to reach the entire abdominal region.	✓
Shaft diameter*	< 12 mm	The shaft must fit through commercially available trocars for gas laparoscopy.	✓
Illumination	-	Illumination must provide sufficient light to distinguish anatomical differences in training phantom.	✓/✗
Weight Specification	1 kg	Total mass must not exceed state-of-the-art values.	✓
Disinfection	-	All materials must withstand High-Level Disinfection (HLD) agents such as Cidex OPA and Glutaraldehyde. The scope should also be cleanable with an autoclave.	✗
Viewing offset	30°	A 30° viewing angle offset relative to the shaft is required for optimal viewing and direct transfer of laparoscopic skills.	✓
Temperature	48°C	All parts of the device temperature must stay below temperatures where sustained contact can cause burns [46].	✓
Power Supply	USB	The device should be powered by USB to eliminate the dependency on constant electricity.	✓

Table 5.2: Overview of the functional requirements and their fulfilment

Chapter 6

Discussion

This chapter provides an interpretation of the empirical and qualitative findings presented in this thesis. The optical benchmarking results, the engineering trade-offs made during the design phase, and the outcomes of the clinical usability validation are contextualized within the broader framework of laparoscopy in low-resource settings. Furthermore, the methodological and technical limitations of the study are evaluated, concluding with actionable recommendations for future research.

The research yielded two main results. First, a quantitative image quality evaluation showed that off-the-shelf camera modules can deliver competitive optical performance, low geometric distortion, and accurate colour reproduction compared to state-of-the-art commercial laparoscopes costing up to €100,000. Second, a functional, modular 30° low-cost laparoscope prototype was successfully developed, built, and validated through mechanical, thermal, and usability tests with actual surgeons. The prototype operates without external light cables, runs directly via USB, demonstrated high usability during surgical tasks in a training mannequin, and costs only €45.53.

6.1 Image Quality Testing and Camera Selection

The quantitative image quality evaluation presented in Chapter 3 revealed counter-intuitive insights regarding low-cost CMOS camera modules versus commercial clinical standards. While commercial setups (Stryker 1688 and Olympus OTV S7) demonstrated superior diagonal field-of-view ($\approx 91^\circ$ vs. 74° – 83°) and low-light signal robustness ($SNR > 1$ down to -9.75 stops), the off-the-shelf camera modules outperformed the reference systems in color reproduction accuracy (ΔE and ΔC) and geometric distortion. Commercial systems exhibited significant barrel distortion (up to -4.9%), whereas the OV5693 and GC5035 camera modules remained under -1.8% .

Although the 2-megapixel GC2755 camera module scored lowest in MTF50 sharpness at a 100 mm working distance, it was ultimately selected for the final prototype. This design decision is justified by two primary factors. First, clinical laparoscopy typically operates at much closer focal distances (20–50 mm) [43]. At a 50 mm working distance, the GC2755 yielded the highest MTF50 score across all evaluated candidates. Second, interviews with surgeons revealed that the maximum allowable shaft diameter in LMICs is 12 mm to ensure compatibility with standard 12 mm trocars for gas laparoscopy. The GC2755 was the only camera module compact enough to be placed at a 30° angle within a necessary 10 mm inner shaft diameter to not exceed the 12 mm outer diameter requirement.

6.2 Design Choices, Mechanical Behavior, and Usability Validation

One of the big barriers to the uptake of laparoscopy in LMICs, besides costs, is the lack of trained personnel. Therefore, it was decided that the low-cost laparoscope should resemble a commercial laparoscope as much as possible. This eliminates the need for additional training for surgeons who are already able to perform laparoscopic surgery. This is where other efforts, like the previously mentioned ReadyView laparoscope, came short and were not widely adopted. The functional

requirements were formulated specifically so that the low-cost laparoscope would resemble commercial alternatives in dimensions, operation and viewing orientation.

The interviewed surgeons heavily prioritized robustness, reprocessing ease, and repairability over surgical versatility and minor cost differences. They emphasized that basic routine procedures constitute the vast majority of minimally invasive surgical demand in LMICs. Providing a reliable instrument for basic laparoscopic interventions frees up critical hospital infrastructure and reduces bed occupancy far more effectively than designing a complex, articulating scope for rare, specialized surgeries. Consequently, it would bring down the costs for patients, making surgery more accessible for people with little resources. These findings were translated into the weights of the multi-criteria analysis. Consequently, the rigid "In-shaft" architecture (Concept 1) was chosen, eliminating internal mechanical linkages, pull-wires, or other moving parts.

The mechanical tests demonstrated that the prototype can resist the forces on a laparoscope during surgery. Longitudinal friction between the scope and the trocar typically reaches approximately 2 N [47]. During the pull test, the prototype showed no movement or displacement up to 25 N. In the torque test, no rotational movement was observed up to 1.7 Nm (17 N at a 10 cm leverage arm), after which the shaft began to twist with respect to the internal rubber interface while the screw connections of the gland remained static. In the bending test, no deformation was observed up to 15 N, and only elastic bending occurred at 25 N, confirming that the structural integrity is sufficient for surgery.

A notable physical finding during validation was the steady-state operating temperature profile. Driven by the tip LEDs and internal chip, the temperature plateaued around 38°C after 45 minutes, remaining well below the required safety threshold of 48°C to prevent tissue burns [46]. In clinical practice, commercial laparoscopes frequently suffer from lens fogging when inserted cold into the warm, humid abdominal cavity. The steady tip temperature of approximately 38°C closely matches human body temperature (37°C), providing an intrinsic anti-fogging effect that can eliminate the need for external scope warmers or anti-fogging liquids.

The evaluative test with actual surgeons yielded a median System Usability Scale (SUS) score of 83.75 (mean: 83.75 ± 9.05 , range: 72.5–95.0), which is well above the clinical acceptability threshold of 68 [48]. Surgeons confirmed that the scope could be operated intuitively without retraining, validating the core requirement of serving as a direct replacement. Furthermore, unprompted qualitative feedback highlighted an unforeseen strategic deployment domain in military and disaster medicine. Because the device is powered via a unified 5 V USB connection, it eliminates dependency on high-voltage power grids. When paired with the RAIS device to raise the abdominal wall, laparoscopic procedures could be performed using just a laptop or ruggedized tablet, making it suitable for field hospitals and military surgery where no laparoscopy is currently available.

Overall, the validation established that nine of the eleven functional requirements were completely met: Cost (<€200 achieved at €45.53), Consumables (0 drapes), Imaging System (comparable for basic laparoscopy), Shaft Length (300 mm), Shaft Diameter (< 12 mm), Total Mass (239.28 g vs. 1 kg threshold), Viewing Offset (30°), Temperature (< 48°C achieved at 38°C), and Power Supply (USB). However, the requirement for Illumination was only partially fulfilled (✓/✗) due to the lack of light dimming, while Disinfection was not met (✗) due to the distal connection not being waterproof.

6.3 Limitations

To ensure academic rigour, several methodological and technical limitations must be acknowledged across the three phases of this project.

Regarding image quality testing, images from the low-cost USB camera modules were captured using Resolume Avenue 6, whereas commercial laparoscopes recorded via native medical video processors. Although both exported uncompressed frames for Imatest analysis, variations in driver-level colour management and hardware gamma curves could not be completely isolated. Furthermore, camera benchmarking was conducted exclusively under static, planar chart conditions. Real laparoscopic environments are dynamic, characterized by fluid movement, specular highlights from wet tissue, tissue smoke, and blood contamination.

Regarding the hardware and design process, the 7mm version of the GC5035 camera module exhibited severe overheating shutdowns during preliminary evaluation, forcing its exclusion despite promising dimensions and image specifications. In addition, manufacturing constraints played a significant role. The prototype used 3D-printed PLA and PETG parts. 3D-printed material is inherently porous, meaning that the parts are not waterproof and not suitable for hospital sterilization methods like autoclaving or chemical soaking agents.

At the assembly level, assembling the camera housing requires very steady hands. Gluing the small optical window into place and sealing the holes for the LEDs with epoxy is a very precise job, which could be a problem if the low-cost laparoscope were to be assembled locally in LMICs.

Furthermore, the connection between the camera housing and the shaft is not sealed waterproof. This prevents the low-cost laparoscope from being sterilized. Sealing the distal tip permanently with epoxy or UV resin would ensure waterproofing for high-level disinfection, but it eliminates the repairability of the scope because the camera module and wiring cannot be disassembled without breaking them. Because this trade-off was avoided to preserve the prototype for surgeon testing, a waterproofness test was not conducted.

Regarding clinical validation, the usability test was conducted with a small cohort of $N = 6$ surgical professionals. While sufficient for identifying major usability and ergonomic issues [48], statistically robust sub-analyses across surgical specialties require a larger sample size. Furthermore, testing was conducted using a synthetic simulation mannequin, which does not fully replicate real tissue optical properties, bleeding, or organ deformation.

Finally, the force tests validated the prototype only for mechanical forces occurring during surgery; forces that can occur outside surgery, such as drops on the floor, transport, or handling during reprocessing, were not tested.

6.4 Recommendations

Based on the insights and limitations identified in this study, future development should focus on several key recommendations.

First, future iterations should incorporate dynamic dimming controls for the illumination. Feedback from the surgeons showed that while static light is sufficient for training phantoms, light adjustment or a dimmer switch is necessary in a dynamic surgical environment to avoid overexposure and glare on tissue. This could be implemented with hardware pulse-width modulation (PWM) or a dial on the handle.

Second, research must be done into production methods for the parts that are now 3D printed. If the scope reaches production, the parts should be manufactured using injection moulding. Injection moulding eliminates the inherent porosity of 3D printing, making the handle and camera housing waterproof and suitable for chemical disinfection and autoclaving.

Third, a reversible waterproofing method must be developed for the connection between the camera housing and the shaft. Research should investigate whether micro O-rings or precise shape-fitting can create a waterproof seal that withstands sterilization while still allowing technicians to disassemble and repair the camera module. If achieving a reversible waterproof seal is

not feasible, future research should evaluate whether it is economically viable to glue the tip shut with epoxy and use the low-cost laparoscope as a semi-disposable unit.

Fourth, in vitro studies using heated, humidified chambers should be carried out to validate the anti-fogging behaviour of the prototype. This will confirm whether the measured tip heat of 38°C prevents condensation on the optical window during actual surgery, eliminating the need for external scope warmers.

Fifth, additional mechanical and environmental durability tests should be conducted. These tests should simulate handling outside surgery, including drop tests, fatigue testing of the cable connection, and repeated heat and disinfection cycles, to verify the long-term robustness of the low-cost laparoscope.

Finally, clinical trials should be expanded. Testing should progress from training mannequins to dynamic settings, such as ex-vivo and in-vivo models, and eventually trials in partner hospitals in low-resource environments and mobile military surgical units.

Chapter 7

Conclusion

Based on the empirical findings regarding the clinical viability of off-the-shelf camera modules in low-resource environments, a low-cost laparoscope prototype with a total component cost of €45.53 was successfully developed. The resulting instrument features a 12 mm outer diameter shaft and a fixed 30° viewing angle integrated via a localized chip-on-the-tip configuration. By utilizing a direct USB connection to a standard laptop, the system successfully eliminates the infrastructural and financial dependencies associated with a commercial laparoscopic setup [22].

Mechanical characterization trials demonstrated that the prototype possesses the structural resilience required to withstand the physical boundary forces expected during laparoscopic interventions [47]. Furthermore, thermal dissipation profiling verified that the steady-state operating temperature of the distal tip plateaus at 38°C, remaining well below the critical 48°C safety threshold established to prevent thermal tissue damage or burns [46].

Finally, a qualitative human-factors usability evaluation conducted with active healthcare professionals validated the operational efficacy of the device. The laparoscope achieved a mean System Usability Scale score of 83.75, placing the prototype significantly above the standardized acceptability threshold of 68. While the participating surgeons unanimously agreed that the native image quality is sufficient to perform basic interventions and diagnostic laparoscopy, they also concluded that the current prototype configuration is not yet suitable for highly complex surgical procedures.

Bibliography

- [1] A. Buia, F. Stockhausen, and E. Hanisch, "Laparoscopic surgery: a qualified systematic review," *World Journal of Methodology*, vol. 5, no. 4, pp. 238–254, 2015.
- [2] R. Garry, "Laparoscopic surgery," *Best Practice & Research Clinical Obstetrics & Gynaecology*, vol. 20, no. 1, pp. 89–104, 2006.
- [3] C. Huang, J.-C. Shen, J. Zhang, T. Jiang, W.-D. Wu, J. Cao, K.-J. Huang, and Z.-J. Qiu, "Clinical comparison of laparoscopy vs open surgery in a radical operation for rectal cancer: A retrospective case-control study," *World Journal of Gastroenterology*, vol. 21, no. 48, pp. 13532–13541, 2015.
- [4] G. A. Vilos, A. Ternamian, J. Dempster, and P. Y. Laberge, "Laparoscopic entry: A review of techniques, technologies, and complications," *Journal of Obstetrics and Gynaecology Canada*, vol. 29, no. 5, pp. 433–447, 2007.
- [5] S. Krishnakumar and P. Tambe, "Entry complications in laparoscopic surgery," *Journal of Gynecological Endoscopy and Surgery*, vol. 1, no. 1, pp. 4–11, 2009.
- [6] N. T. Nguyen, B. Nguyen, A. Shih, B. Smith, and S. Hohmann, "Use of laparoscopy in general surgical operations at academic centers," *Surgery for Obesity and Related Diseases*, vol. 9, no. 1, pp. 15–20, 2013.
- [7] E. Sebban, "Les examens du diagnostic du cancer de l'ovaire," 10 2018. Accessed November 18, 2025.
- [8] G. Ahmad, D. Gent, D. Henderson, H. O'Flynn, K. Phillips, and A. Watson, "Laparoscopic entry techniques," *Cochrane Database of Systematic Reviews*, no. 8, p. CD006583, 2015.
- [9] J. Raiga, J. M. Kasia, and M. A. Bruhat, "Laparoscopic surgery in the cameroon," *International Journal of Gynecology & Obstetrics*, vol. 65, no. 1, pp. 65–66, 1999.
- [10] Y. Teerawattananon and M. Mugford, "Is it worth offering a routine laparoscopic cholecystectomy in developing countries? a thailand case study," *Cost Effectiveness and Resource Allocation*, vol. 3, p. 10, 2005.
- [11] C. Ramsay, R. Pickard, C. Robertson, A. Close, L. Vale, N. Armstrong, D. A. Barocas, C. G. Eden, C. Fraser, T. Gurung, D. Jenkinson, X. Jia, T. B. Lam, G. Mowatt, D. E. Neal, M. C. Robinson, J. Royle, S. P. Rushton, P. Sharma, M. D. F. Shirley, and N. Soomro, "Systematic review and economic modelling of the relative clinical benefit and cost-effectiveness of laparoscopic surgery and robotic surgery for removal of the prostate in men with localised prostate cancer," *Health Technology Assessment*, vol. 16, no. 41, pp. 1–313, 2012.
- [12] R. M. Oosting, L. S. G. L. Wauben, J. K. Madete, R. S. Groen, and J. Dankelman, "Availability, procurement, training, usage, maintenance and complications of electrosurgical units and laparoscopic equipment in 12 african countries," *BJS Open*, vol. 4, no. 2, pp. 326–331, 2020.

-
- [13] R. K. Mishra, *Textbook of Practical Laparoscopic Surgery*. New Delhi: Jaypee Brothers Medical Publishers, 3 ed., 2013.
- [14] R. Sinha, M. Sundaram, S. Raje, G. Rao, M. Sinha, and R. Sinha, “3d laparoscopy: technique and initial experience in 451 cases,” *Gynecological Surgery*, vol. 10, pp. 123–128, Jan. 2013. Published 22 January 2013.
- [15] Z. A. Bhutta, R. A. Salam, J. K. Das, and Z. S. Lassi, “Tackling the existing burden of infectious diseases in the developing world: existing gaps and the way forward,” *Infectious Diseases of Poverty*, vol. 3, p. 28, 2014.
- [16] A. Hussain, H. K. Mahmood, and K. Dulku, “Laparoscopic cholecystectomy can be safely performed in a resource-limited setting: the first 49 laparoscopic cholecystectomies in yemen,” *JSLs*, vol. 12, no. 1, pp. 71–76, 2008.
- [17] R. Troller, J. Bawa, O. Baker, and J. Ashcroft, “First experience in laparoscopic surgery in low and middle income countries: A systematic review,” *World Journal of Gastrointestinal Surgery*, vol. 16, no. 2, pp. 546–553, 2024.
- [18] J. G. Meara, S. L. M. Greenberg, *et al.*, “Global surgery 2030: Evidence and solutions for achieving health, welfare and economic development,” *Surgery*, vol. 157, no. 5, pp. 834–835, 2015.
- [19] A. G. Bedada, M. Hsiao, B. Bakanisi, M. Motsumi, and G. Azzie, “Establishing a contextually appropriate laparoscopic program in resource-restricted environments: Experience in botswana,” *Annals of Surgery*, vol. 261, no. 4, pp. 807–811, 2015.
- [20] M. Alfa-Wali and S. Osaghae, “Practice, training and safety of laparoscopic surgery in low and middle-income countries,” *World Journal of Gastrointestinal Surgery*, vol. 9, no. 1, pp. 13–18, 2017.
- [21] T. E. Chao, M. Mandigo, J. Opoku-Anane, and R. Maine, “Systematic review of laparoscopic surgery in low- and middle-income countries: benefits, challenges, and strategies,” *Surgical Endoscopy*, vol. 29, no. 2, pp. 334–344, 2015.
- [22] E. Wilkinson, N. Aruparayil, J. Gnanaraj, J. Brown, and D. Jayne, “Barriers to training in laparoscopic surgery in low- and middle-income countries: A systematic review,” *Tropical Doctor*, vol. 51, no. 3, pp. 408–414, 2021.
- [23] M. M. Webb, P. Bridges, N. Aruparayil, C. Chugh, T. Beacon, T. Singh, S. S. Sawhney, L. Bains, R. Hall, D. Jayne, J. Gnanaraj, A. Mishra, and P. R. Culmer, “The rais device for global surgery: Using a participatory design approach to navigate the translational pathway to clinical use,” *IEEE Journal of Translational Engineering in Health and Medicine*, vol. 10, p. 3700212, 2022.
- [24] J. L. Mueller, N. Rozman, E. D. Sunassee, A. Gupta, C. Schuval, A. Biswas, B. Knight, S. Kulkarni, M. Brown, N. Ramanujam, and T. N. Fitzgerald, “An accessible laparoscope for surgery in low- and middle-income countries,” *Annals of Biomedical Engineering*, vol. 49, no. 7, pp. 1657–1669, 2021.
- [25] R. van Loon, “Design and validation of a modular laparoscope for low-income countries,” Master’s thesis, Delft University of Technology, Delft, The Netherlands, Feb. 2024. Master Thesis.

-
- [26] Resolume B.V., *Resolume Avenue (Version 6)*. Resolume B.V., The Hague, The Netherlands, 2017.
- [27] Imatest LLC, *Imatest Image Quality Testing Software*. Imatest LLC, Boulder, CO, USA, 2023.
- [28] Microsoft Corporation, *Microsoft Excel*. Microsoft Corporation, Redmond, WA, USA, 2024.
- [29] International Organization for Standardization, “ISO 8600-3:2019 Endoscopes — Medical endoscopes and endotherapy devices — Part 3: Determination of field of view and direction of view of endoscopes with optics.” International Standard, Edition 2, Aug. 2019. Published 2019-08, 8 pages.
- [30] International Organization for Standardization, “ISO 12233:2024 Digital cameras — Resolution and spatial frequency responses,” Sept. 2024. Edition 5, 73 pages.
- [31] M. Kaur and S. Kaur, “Image sharpening using basic enhancement techniques,” *International Journal of Research in Engineering, Science and Management*, vol. 1, no. 12, pp. 122–127, 2018.
- [32] H. H. Nasse, “How to read MTF curves,” 2008.
- [33] N. Koren, “Sharpness: What is it and how it is measured.”
- [34] N. Koren, “MTF curves and image appearance.”
- [35] N. Koren, “Comparing sharpness in cameras with different pixel count,” 2021. Posted June 12, 2021 (Imatest RSS mirror page).
- [36] N. Koren, “Sharpness comparisons for several digital cameras.”
- [37] Imatest LLC, “Composite test chart generated in Imatest Master.” Software-generated figure (composite target assembled from Imatest chart elements), 2026.
- [38] N. Koren, “Color/tone interactive analysis.”
- [39] N. Koren, “Using stepchart.”
- [40] N. Koren, “Gamma, tonal response curve, and related concepts.”
- [41] N. Koren, “Tone, color and spatial modules,” 2019. Imatest Documentation.
- [42] N. Koren, “Distortion: methods and modules.”
- [43] G. El Shallaly and A. Cuschieri, “Optimum view distance for laparoscopic surgery,” *Surgical Endoscopy*, vol. 20, no. 12, pp. 1879–1882, 2006.
- [44] R. Vroom and B. van Vliet, “Reader Ontwerpmethoden – WB164X werktuigkundig Ontwerpproject.” https://wop.me.tudelft.nl/WOP1/reader_ontwerpmethoden.html, 2026. Delft University of Technology.
- [45] R. M. Oosting, J. Dankelman, L. S. G. L. Wauben, J. Madete, and R. S. Groen, “Roadmap for design of surgical equipment for safe surgery worldwide,” in *Proceedings IEEE Global Humanitarian Technology Conference (GHTC 2018)* (E. Perkins and S. Figueira, eds.), (Piscataway, NJ, USA), IEEE, 2018.

- [46] N. B. D. Doa, E. Andreassen, S. Edwardsen, A. Lifjeld, K. E. Aasmundtveit, H.-V. Nguyen, and K. Imenes, “Thermal management of an interventional medical device with double layer encapsulation,” *Experimental Heat Transfer*, vol. 35, no. 5, pp. 708–725, 2022.
- [47] H. Yamanaka, K. Makiyama, K. Osaka, M. Nagasaka, M. Ogata, T. Yamada, and Y. Kubota, “Measurement of the physical properties during laparoscopic surgery performed on pigs by using forceps with pressure sensors,” *Advances in Urology*, vol. 2015, pp. 1–10, 2015.
- [48] J. Brooke, “Sus: A “quick and dirty” usability scale,” in *Usability Evaluation in Industry* (P. W. Jordan, B. Thomas, B. A. Weerdmeester, and I. L. McClelland, eds.), pp. 189–194, London: Taylor & Francis, 1996.

Appendix A

Interviews with surgeons notes

Meeting 1 - Surgeon 1 – 24-10-2025

Persoonlijke informatie:

Ervaring met laparoscopische chirurgie in meerdere landen in Centraal Afrika

Main takeaways

- Sierra Leone goede target situatie. Nog geen laparoscopische afdeling, maar wel ambitie. Surgeon 1 is hier bij het Masanga Hospital geweest. Hier is ook een autoclaaf en 3d printer aanwezig.
- Grote barriers voor het opzetten van deze en soortgelijke afdelingen zijn:
 - Continue stroomvoorziening. Stroom kan overdag vaak uitvallen.
 - Getraind personeel. In heel Sierra Leone maar 1 vaste getrainde chirurg.
 - Geen gezondheidsverzekering. Patiënten moeten behandeling volledig uit eigen zak betalen en daardoor zijn operaties vaak te duur en te laat.
 - Materiaal. Zoals het er nu voor staat zou het materiaal voor laparoscopische chirurgie aanwezig moeten komen op basis van donatie.

Meeting 2 – Surgeon 1 – 8-1-2026

Functional requirements & Performance criteria

- 12 mm maximum diameter i.p.v. 15.
- Beeldkwaliteit van 7mm scope al goed genoeg
- Veiligheid belangrijkste performance criterium
- Stel dat de beeldkwaliteit niet fantastisch is kan er eerst gefocust worden op simpele operaties of slechts diagnose om risico te verminderen. Dit zou al waarde toevoegen.
- Rest van de requirements goed

Meeting Surgeon 2 – 5-2-2026

Persoonlijke informatie:

Heeft missies gedaan in Centraal Afrika o.a. Liberia en Sierra Leone

Beeldkwaliteit:

- GC5035_10mm het best, maar in principe allemaal bruikbaar.
- Interessant om te kijken hoe camera's presteren bij bloed, rook en beslaan etc.

Functional requirements & performance criteria:

- 12mm max diameter
- 3R's het belangrijkste:
 - Robustness
 - Repairability
 - Reprocessing (sterilisation)
- Dimmen van de belichting gebeurt bij commerciële laparoscopen, wordt automatisch gedaan door de toren.

Verdere notities

- Interessante invalshoek om eventueel te beginnen met simpele operaties. Chirurg denkt dat dit wel zou kunnen helpen en alsnog toegevoegde waarde zou hebben.
- Is erg enthousiast en is benieuwd wanneer er getest kan worden.

Meeting Surgeon 3 – 12-3-2026

Persoonlijke informatie:

Heeft missies gedaan in Centraal Afrika en gaat daar een laparoscopisch trainingsprogramma opzetten

Beeldkwaliteit:

- Allemaal bruikbaar.
- Deze testomstandigheden niet elke representatief

Functional requirements & performance criteria:

- 12mm max diameter
 - Robustheid en herbruikbaarheid belangrijkste.
- Kosten zolang het onder de €200 blijft niet heel belangrijk

Verdere notities

- Scope zou ook gebruikt kunnen worden als trainingsinstrument als het nog niet voor echte operaties is gevalideerd

Appendix B

Bill of Materials

This appendix provides a complete itemized breakdown of the components, materials, component costs, and suppliers utilized to manufacture the low-cost laparoscope prototype.

Table B.1: Detailed Bill of Materials with supplier procurement links.

Component Description	Supplier Link	Cost (€)
GC2755 Endoscope Module	AliExpress	24.39
Polymer Cable Gland	Allekabels	2.29
3D-printed PETG Handle Bottom Part	RPM3D	0.37
O-ring (36 × 5 mm NBR70)	Lagerkoning	1.25
3D-printed PETG Handle Top Part	RPM3D	0.53
Brass Cable Gland (PG16)	Onlinekabelshop	4.99
3D-printed PLA Spacer	123-3D	0.02
Stainless Steel Shaft (RVS 304, 12 × 10 mm)	MetalNXT	10.71
3D-printed PLA Camera Housing	123-3D	0.03
3D-printed PLA Positioning Wedge	123-3D	0.01
Acrylic Optical Window	LaserSheets	0.01
UV-curable Resin	ItsOkay	0.93
Total Unit Cost		45.53

Appendix C

Questionnaire

Question	Totally disagree	Disagree	Neutral	Agree	Totally agree
1. I think that I would like to use this laparoscope frequently.	☐	☐	☐	☐	☐
2. I found the laparoscope unnecessarily complex to use.	☐	☐	☐	☐	☐
3. I found the laparoscope easy to use.	☐	☐	☐	☐	☐
4. I think that I would need support of a technical person to be able to use this laparoscope.	☐	☐	☐	☐	☐
5. I found the various functions of the laparoscope to be well integrated.	☐	☐	☐	☐	☐
6. I felt that the laparoscope performed inconsistently.	☐	☐	☐	☐	☐
7. I can imagine that surgeons would learn to use this laparoscope very quickly.	☐	☐	☐	☐	☐
8. I found the laparoscope cumbersome to use.	☐	☐	☐	☐	☐
9. I felt confident while using the laparoscope.	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get started with this laparoscope.	☐	☐	☐	☐	☐
11. The image sharpness is good enough to distinguish small anatomical details.	☐	☐	☐	☐	☐
12. The image lags behind reality.	☐	☐	☐	☐	☐
13. The color reproduction on the screen matches reality.	☐	☐	☐	☐	☐
14. The image is sharp enough across different distances to navigate through the mannequin.	☐	☐	☐	☐	☐
15. The light intensity is insufficient to illuminate the deeper parts of the phantom.	☐	☐	☐	☐	☐
16. The laparoscope is uncomfortable to hold.	☐	☐	☐	☐	☐
17. The image quality of the laparoscope is suitable for training purposes.	☐	☐	☐	☐	☐
18. The image quality of the laparoscope is suitable for simple laparoscopic surgeries.	☐	☐	☐	☐	☐
19. The image quality of the laparoscope is suitable for complex laparoscopic surgeries.	☐	☐	☐	☐	☐
20. Do you have any further feedback or comments?					