Enhancing Laparoscopic Surgery Through Advanced Image Processing: A Focus on Reducing Visibility Obstructions

Alicia Ulierte, Álvaro Herrador, Gabriela Díaz, Laura Xifra.

January 14, 2025

1 Abstract

This study addresses visibility obstructions in laparoscopic surgery due to smoke and fog, which complicate surgical procedures and increase the risk of errors. Our primary objective was to develop an algorithm to enhance the visual clarity of images during laparoscopic surgeries, thereby reducing procedural risks and improving patient outcomes. We reviewed existing anti-fog techniques and image enhancement technologies, identifying gaps particularly in the context of laparoscopic applications. Our approach integrates proven image processing techniques, such as Dark Channel Prior and Guided Image Filtering, with contrast enhancement methodologies to selectively improve visibility in surgical videos. Results from testing on low-resolution videos demonstrate notable improvements in image quality, although the effectiveness varies with smoke density and lighting conditions. The study concludes with considerations for further refinement of the algorithm to ensure consistent performance in diverse surgical settings and real-time applications.

2 Keywords

Laparoscopic surgery; Image enhancement; Visibility obstructions; Reduction of smoke and fog; Surgical Imaging; Algorithm Development; Dark channel prior; Guided Image Filtering; Contrast Enhancement; Minimally Invasive Techniques

3 Introduction and Objectives

The evolution of surgical practices from traditional invasive techniques to minimally invasive methods marks a significant advancement in medicine. Minimally invasive techniques, such as laparoscopy, offer considerable benefits over traditional surgery, including reduced recovery times, fewer complications, and better patient outcomes. Laparoscopy involves performing surgical procedures through small incisions using specialized instruments, which minimize tissue damage and accelerate patient recovery. A laparoscope, equipped with an optical lens, facilitates visualization of the pelvic-abdominal cavity by creating a pneumoperitoneum, which is a free air space in the peritoneal cavity achieved by insufflation with gas. [1]
Despite its advantages, laparoscopic surgery faces challenges such as obstruction of the laparoscope view due to cauterization smoke and fogging caused by the temperature difference between the cold laparoscope lens and the warm abdominal environment. These issues, which occur when the dew point is reached, significantly impair visibility and can disrupt the procedural flow, increasing the risk of surgical errors. This study focuses on addressing these visibility obstructions to enhance the efficacy and safety of laparoscopic procedures.
The primary objective of this project is to develop an algorithm that improves the visual clarity of images during laparoscopic surgery, thus supporting surgeons to make better informed decisions, minimize procedural risks, and improve patient outcomes. This work studies the technical nuances of laparoscopic surgery, emphasizing the critical role of clear visibility in successful surgical interventions. Given the challenges posed by surgical smoke, reflections, and inconsistent lighting, the necessity for advanced image processing technologies becomes evident. We conduct a comprehensive review of current advancements in image processing algorithms, underscoring their potential to revolutionize laparoscopic practices. By integrating these technological innovations with robust surgical techniques, this research aims to pave the way for safer, more efficient, and effective laparoscopic procedures, significantly enhancing patient care.

4 State of the Art

We found several types of current techniques that try to deal with this problem:

- **Anti-fog coatings**: Used in personal protective equipment eyewear to reduce fog. Several studies have demonstrated the great efficacy of the sulfonated BiaXam polymer in clinical settings. This polymer has great hydrophilic properties that get rid of moisture over the lenses, therefore enhancing visibility for healthcare professionals wearing surgical masks.

- **Surfactant applications**: Application of detergent-based surfactants to eyewear lenses. The effect produced is a reduction in the surface tension on the lens, allowing moisture to spread evenly and reducing fog. Nevertheless, this is a temporary solution with the tedious need of frequent re-application, leading to a not so good practical application.

- **Mechanical solutions**: Addition of filtered vents on top of the protective eyewear to manage the airflow, reduce the humidity factor and decreasing the likelihood of fog appearing. In some controlled environments, these application have shown good results. [2]

- **Heated endoscopes**: In the digestive system environment, heated endoscopes have been used which aim is to maintain the lens at a temperature near the human body one, to minimize the difference and therefore reducing the likelihood of fog being present.

- **Algorithms**: we did not find any algorithm applied to laparoscopic surgeries. However, we found other scenarios where algorithms are applied to reduce fogginess:
  - **Smoke detection algorithm based on wavelet transformation and energy analysis**: we have a shortage when using color-based RGB algorithms due to the difficulty of being able to distinguish fog from surrounding, leading to false alarms. This method applies a wavelet that divides the original image into 4 sub-images and, using the wavelength coefficients of each, computes the energy. By comparing the ratios of HF energy to the whole energy in the picture, we could distinguish smoke. [3]
  - **Integrated fog removal algorithm IDCP with airlight**: Integrate a dark channel prior with CLAHE and adaptive gamma correction in order to get rid of fog in digital images. This algorithm is implemented in MATLAB using the image processing toolbox. [4]
  - **Design a hardware applying fog removal algorithm using median dark channel prior for autonomous driving car**: Usage of the dark channel prior methodology, which has the disadvantage of causing a blocking phenomenon. To overcome this problem, they have modified it to the Median Dark channel method. This method is designed in Verilog HDL. [5]
  - **A novel smoke detection algorithm based on improved mixed Gaussian and YOLOv5 for textile workshop environments**: This algorithm is capable of detecting suspected smoke areas in video by using the dynamics of smoke and its characteristics. Afterwards, an adaptive attention module is added to the feature pyramid infrastructure of the YOLOv5 target detection network to improve the multiscale target recognition ability. [6]

5 Materials and methods

The medical videos used in this project have been extracted via internet. The sources are: MEDtube and Youtube. However, the project was also performed in real-time videos, obtained with the camera of our personal computer. The coding was implemented in Python, and the libraries used are from OpenCV and NumPy.

5.1 Algorithm

In our preliminary research, we explored the existing state of the art, identifying algorithms originally designed to mitigate fogginess in various contexts, such as traffic conditions. Building on this foundation, we developed a specialized code focused in enhancing image quality in laparoscopic surgery settings. This code leverages proven image processing techniques detailed in our state of the art review and is specif-

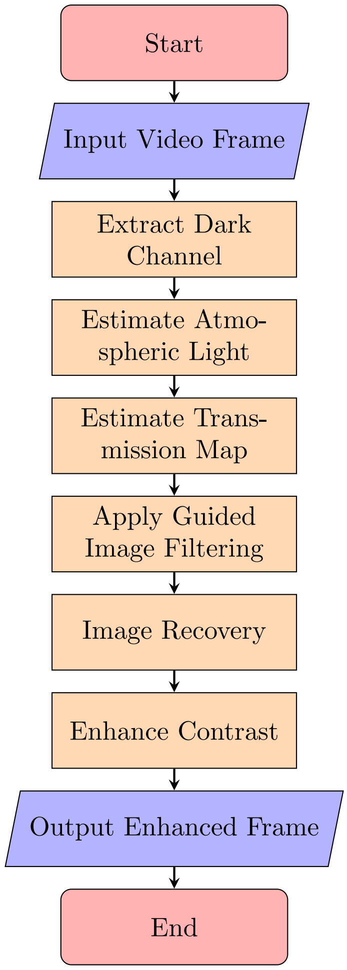


Figure 1: Flowchart of the Image Processing Algorithm for Laparoscopic Surgery Enhancement

ically engineered to improve visibility in surgical videos by addressing common obstructions like smoke and fog.

The algorithm operates by processing live video feeds from a camera used during laparoscopic procedures. It systematically enhances image clarity by identifying frames with diminished visibility and selectively enhancing the contrast in these areas. The process involves several key steps, starting with the real-time capture of video frames, followed by their subsequent analysis and enhancement:

1. **Dark Channel Prior Extraction**: The `dark_channel()` function computes the dark channel of the image, which is a concept used primarily in image processing, particularly in algorithms designed to remove haze from images. It is based on the observation that in most non-sky patches of haze-free outdoor images, at least one color channel (red, green, or blue) has some pixels which will have very low intensities in at least one of the channels. Essentially, the dark channel is a way to estimate the thickness of the haze or fog present in an image.

   For an image, it is defined as the minimum intensity value among the three color channels at each pixel, calculated over a local patch around the pixel.

   The dark channel will be close to zero in haze-free areas because at least one of the color channels will have a low value in the absence of haze. In contrast, in hazy areas, all color channels are more uniformly lit due to the scattering of light by particles in the air, thus raising the minimum value observed in the dark channel.

2. **Atmospheric Light Estimation**: Using the dark channel, the `atmospheric_light()` function estimates the atmospheric light, which is the light that is scattered by the atmosphere (or smoke), assumed to be caused by scattering due to the smoke. This step involves finding the brightest pixels in the dark channel, which represent areas with the highest concentration of smoke, and averaging them to estimate the light intensity of the atmosphere.

3. **Transmission Map Estimation**: The `transmission_estimate()` function calculates how much of the light is not scattered and reaches the camera. It assumes that the smoke causes a decrease in this transmission. The function adjusts the transmission based on the dark channel, helping to identify areas in the image where smoke is present. A darker channel indicates lower transmission (more haze/smoke), while a lighter channel indicates higher transmission (less haze/smoke).

4. **Guided Image Filtering**: The guided filter is an image processing technique that serves as an edge-preserving smoothing operator, which means it can smooth the image while maintaining sharp edges, making it particularly useful in various image processing tasks such as detail enhancement, noise reduction, and image matting/segmentation. The key idea is to perform local linear regression on the guidance image to predict the output image. This local linear model depends on the content of the guidance image, allowing the filter to adapt to different structures in the image and preserve edges.

   This linear transformation is applied to all pixels, with the linear coefficients recalculated for each local window, allowing the filter to adapt to changes in the guidance image and preserve edge structures effectively.

5. **Image Recovery**: The `recover()` function reconstructs the clear image from the distorted input using the refined transmission and the estimated atmospheric light. This step aims to remove the effects of smoke by adjusting the intensity of the image based on the transmission map.

6. **Contrast Enhancement**: The `enhance_contrast()` function is specifically targeted at regions with low transmission (i.e., higher smoke density). It applies a contrast-limited adaptive histogram equalization (CLAHE) to these areas to improve visibility where it is most needed. CLAHE operates differently from standard histogram equalization by improving local contrast and enhancing definitions of edges in regions that are darker or lighter than most of the image. [7]

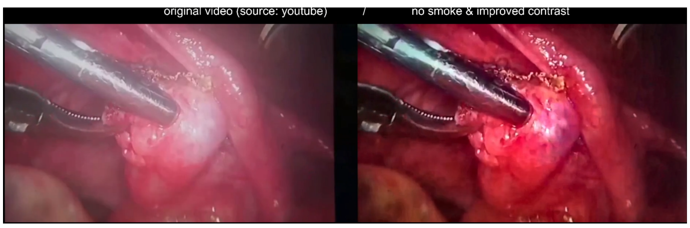
   Initially, the image is divided into small blocks or tiles, such as 8x8 pixels. This segmentation allows for localized contrast enhancement; using larger tiles results in more uniform contrast across broader areas, while smaller tiles sharpen the contrast in finer details. Subsequently, each tile undergoes CLAHE, which applies histogram equalization individually to each tile rather than to the entire image. This method adjusts image luminance based on the specific lighting conditions of each tile. After histogram equalization, any histogram bins that exceed a predetermined contrast limit are clipped to curb noise amplification commonly found in darker image regions. The clipped portions are then uniformly redistributed across other bins to further refine the contrast. Finally, to eliminate any artificial boundaries caused by tile processing, the algorithm interpolates the histograms between adjacent tiles, ensuring a seamless transition and preventing noticeable artifacts at the borders of the tiles.

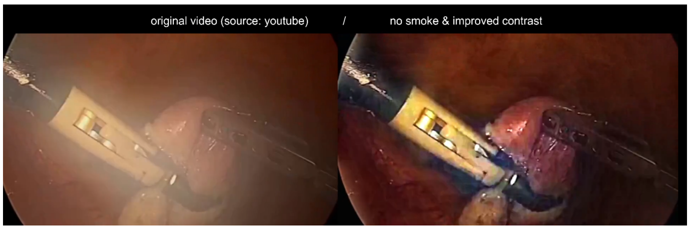
5.2 Limitations

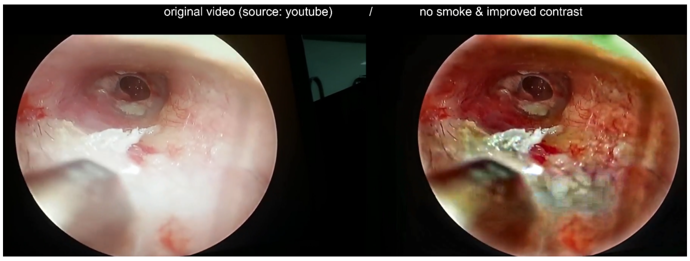
Despite its potential to enhance visual clarity in laparoscopic surgeries, our approach presents several limitations that we have to take into consideration. The computational demands of techniques such as dark channel prior and guided filtering may restrict the real-time application of our algorithm without the aid of specialized hardware. Additionally, there is a risk of over-enhancement, which could introduce artifacts that mislead surgeons. The algorithm's performance also varies with the density and type of smoke encountered, necessitating further adjustments to ensure consistent outcomes across different surgical settings. Moreover, while the algorithm performs well under controlled conditions, its effectiveness may decrease in varied lighting environments or with differing camera qualities typically found in medical contexts. These issues highlight the need for ongoing research and refinement to fully integrate this technology into practical surgical applications and to verify its effectiveness in real-world scenarios.

6 Results

Our algorithm was evaluated using low-resolution laparoscopic videos (approximately 850x480 pixels). We specifically focused on videos depicting smokey and foggy conditions to test the effectiveness of our filtering approach. To facilitate a direct comparison of the algorithm's impact, we structured the display to show the original input video on the left and the filtered output on the right. Selected images demonstrating the performance are included below to illustrate the improvements.







7 Discussion

We assessed the performance of our algorithm by examining the enhancement of contrast, reduction of fogginess, and improvement in brightness and object distinction in the right frames processed from the left video frames. The evaluation was based on visual inspection, as opposed to employing quantitative methods, and the results indicate a notable enhancement in image quality across the stated parameters. However, it is important to acknowledge that excessively blurry inputs did not show significant improvement, suggesting a potential area for future research.

The computational efficiency of the algorithm was satisfactory, with all processes executed and the results displayed in less than a second. This rapid processing capability is critical in surgical settings, where immediate video feedback is essential. Preliminary tests with a standard camera demonstrated effective smoke and fog reduction in real-time. While these results are promising, the application of the algorithm in actual surgical environments remains to be tested, representing a direction for future work.

8 Conclusions and future directions

Following an initial assessment of the algorithm using publicly available videos from platforms such as YouTube, modifications were implemented to use a real-time camera input, allowing for immediate processing and display of outputs, that we can see in the figure below.

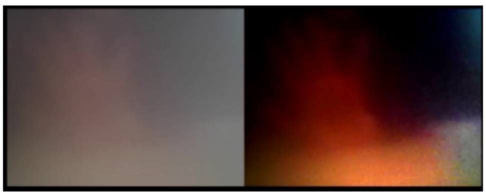


Figure 2: After we created a foggy environment, the original real-time image on the left shows a hand that is difficult to discern. The processed image on the right, however, better delineates the hand's shape.

Looking forward, we aim to deploy this algorithm within actual laparoscopic surgeries to garner feedback from surgical professionals. Additionally, we plan to test its efficacy using statistical validation across a broader range of scenarios. This will not only refine the algorithm but also extend its utility in enhancing medical imaging within the field of surgical laparoscopy.

9 Acknowledgments

We express our gratitude to the professors and experts who we talked to in order to detect the medical need to be solved (Prof. and Surgeon **María Rodríguez Monsalve Herrero** gave us insights about the main issues of laparoscopy), to develop and check the code (Prof. and Programmer **David Roldán Álvarez** guided us in the optimization of the code and the implementation in real time), and to evaluate the project, providing valuable insights into practical and theoretical aspects, to reach the best performance (Professors **Norberto Malpica and Ángel Torrado Carvajal** guided and tutored us, evaluating our performance and provided feedback).

We are also grateful for our classmates, that asked high value questions after the presentation of our project, and the evaluators, which also provided feedback.

References

[1] Caridad de Jesús Pérez Martínez. Historia de la cirugía laparoscópica: particularidades de su introducción y desarrollo en cuba. *Universitas Médica*, 55(2):200–210, abril-junio 2014. Consultado el 2 de enero de 2025.

[2] Arvind Kumar, Owais Ahmed Qureshi, Rajesh Arora, Sandeep Kumar, Javed Jameel, and Rizwan Khan. Comparison of three low-cost techniques to control fogging of sealed eyewear in a simulated operating room environment: A preliminary analysis. *Journal of Clinical Orthopaedics and Trauma*, 11(Suppl 5):S696–S699, 2020.

[3] Yijun Xu and Ning Han. Smoke detection algorithm based on wavelet transformation and energy analysis. In *Proceedings of the 2012 National Conference on Information Technology and Computer Science*, Advances in Intelligent Systems Research, 2012.

[4] Tarun A. Arora, Gurpadam B. Singh, and Mandeep C. Kaur. Evaluation of a new integrated fog removal algorithm idcp with airlight. *I.J. Image, Graphics and Signal Processing*, 2014(8):12–18, 2014.

[5] Chang-Yong Lee, Heon-Bin Jang, Yyong-Seok Kim, and Yong-Hwan Lee. Design a hardware applying fog removal algorithm using median dark channel prior for autonomous driving car. In *2023 International Conference on Computational Science and Computational Intelligence (CSCI)*, page 1298. IEEE, 2023.

[6] Xin Chen, Yipeng Xue, Yaolin Zhu, and Ruiqing Ma. A novel smoke detection algorithm based on improved mixed gaussian and yolov5 for textile workshop environments. *IET Image Processing*, 1(1):First published online, 2023.

[7] Xiwel Liu and Thao Do Chi Nguyen. Medical images enhancement by integrating clahe with wavelet transform and non-local means denoising. *Academic Journal of Computing Information Science*, 7(1):52–58, 2024.