

360° endoscopy using panomorph lens technology

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ABSTRACT

Minimally invasive surgical procedures or examinations require increasingly sophisticated devices to explore the interior of the patient's body. The new generation of medical scopes takes advantage of the recent progresses in optic miniaturization and high resolution imaging sensors (1.3MP). Even with such high resolution, the endoscopic vision remains quite different than human vision, especially regarding the field of view. Several optical systems have been developed to meet large field of view requirements. However most of these optical systems suffer from low resolution or poor quality.

This paper presents the results of our investigation of a new innovative approach based on a wide angle panomorph lens designed for endoscopes and its dedicated visualisation software. This lens is based on human vision which increases the resolution in the field of view of interest to meet the image quality requirement specific to endoscopic applications.

We show how the wide angle field of view, augmented resolution, close focus and distortion-free multi-visualisation software can improve laparoscopic and other endoscopic procedures.

Keywords: Panomorph, videoscopes, wide field of view, endoscopes, endoscopy, laparoscopy, thoracoscopy, single-incision laparoscopic surgery (SILS), video-assisted thoracoscopy (VATS), natural orifice transluminal endoscopic surgery (NOTES).

1. INTRODUCTION

Researchers and physicians are always looking for the most effective and least invasive techniques to benefit the patient. For example, single-incision laparoscopic surgery - which is a critical advancement in minimally-invasive surgery, may soon become a preferred method. Minimally invasive surgical procedures or examinations require increasingly sophisticated devices to explore the interior of the patient's body while limiting the impact on the human body.

Recently, optic miniaturization and sensor improvements in size and resolution have led to the development of new smaller and improved videoscopes for medical imaging in various procedures. These modern visual instruments benefit from sensor miniaturization to increase their resolution up to 1.3Megapixel (HD).

Even with such high resolution, the endoscopic vision remains quite different than human vision, especially regarding the field of view and the type of viewing projection. The limited field of view produces poor visualization for the clinician and increases the scope manipulations and procedure time. These drawbacks have driven industry to design endoscopes with a larger field of view. Several optical systems have been developed featuring convex mirrors, prisms or wide angle lenses to meet large field of view requirements. However most of these optical systems suffer from low resolution or poor quality. A particular concern in the optical design of these types of wide angle imager is the uniformity of the image quality and the fact that the more the field of view is enlarged, the more distortion is created on the viewing display.

In this paper, we propose a new approach that can play a significant role in improving endoscopic procedures based on the use of the Panomorph technology.

This paper presents a solution to the existing problematic: the panomorph optical concepts that use innovative wide angle panomorph lenses designed for laparoscopes and endoscopes combined with dedicated visualization software. This lens is based on human vision which increases the resolution in the field of view of interest to meet the image quality requirements specific to laparoscopic applications. A case study is presented to demonstrate the values and benefits for surgeons: We demonstrate how the wide angle field of view, augmented angular resolution, close focus and distortion-free multi-visualization software can improve endoscopic procedures.

2. ENDOSCOPIC DEVICES OVERVIEW AND PROBLEMATICS

During minimally invasive surgery (MIS), the surgeon uses an endoscope to explore the body cavity and tools to perform the surgery. These instruments are inserted using small incisions. There are different types of endoscopes used in MIS: the most popular are the telescopic rod lens system that is usually connected to a video camera outside the body and the digital laparoscope where the lens and the CCD are placed at the extremity of the device.

The most important limitations of the endoscope are the restricted range of motion, the loss of depth perception and the poor field of view. Indeed, the goal of MIS is to minimise the number and size of incisions. The endoscope and surgical tools need to pass through these entry points and pivot about them. This causes counter-intuitive camera motions. A fully-trained assistant is required to provide the best point of view to the surgeon. An assistant's uncontrolled movements can cause surgeon sickness, reduce the surgeon's accuracy and increase procedure time. Furthermore, the narrow angle camera of the endoscope cannot replace the human panoramic stereoscopic system "eye-brain" in open surgery. These limitations drive the industry to provide a new generation of endoscope.

Stereoscopic endoscope[1] is a way to enhance the surgeon's depth perception. By simulating human vision, these cameras recreate left and right eye viewpoints. Unfortunately, these devices do not address the field of view issue of laparoscopes (<70° FoV) and require quite the same counter-intuitive camera movements as a standard endoscope to perform the procedure. Other systems were developed to increase the field of view while decreasing an assistant's manipulation: manufacturer-designed pan, tilt and zoom endoscopes [2]. These devices can be manual or motorised. Using this type of device the surgeon is able to explore the whole scene without moving the endoscope. The endoscope is still a narrow angle camera but by moving the extremity, it provides different points of view of the operating area. These systems increase the range of camera motion but require space to move their extremities inside the body cavity. Furthermore, the practitioner needs to pay attention at the extremity position when he removes the device from the patient's body to avoid damage.

In recent years, robots have been developed to help the surgeon by controlling the endoscope [3] or by controlling endoscope plus all the instruments [4]. Even if these systems improve the image stability and provide a more or less user-friendly control interface, they do not address the limited field of view and will require camera motions.

Increasing the field of view of the endoscope appears a good solution to provide the full scene view, minimise camera motion and the associated disadvantages, and enhance depth perception [5]. Different systems such as mirror attachments [6] or catadioptric imaging systems were designed to increase the field of view of endoscopes. The main limitation of these systems is the blind zone produced by this type of device. A fisheye has no blind zone but the distortion is very important and requires a high resolution sensor to offer sufficient quality picture.

In the following section, we will describe how the panomorph technology approach combining unique lens design and image processing algorithms outperform current wide angle endoscopic devices.

3. PANOMORPH TECHNOLOGY

3.1 Panomorph lens concept

The human eye could be the most common panomorph device. Indeed, with its field of view close to 180° , we can classify the human eye as a very wide angle imager. Furthermore, the visual acuity is not linear across the field of view.

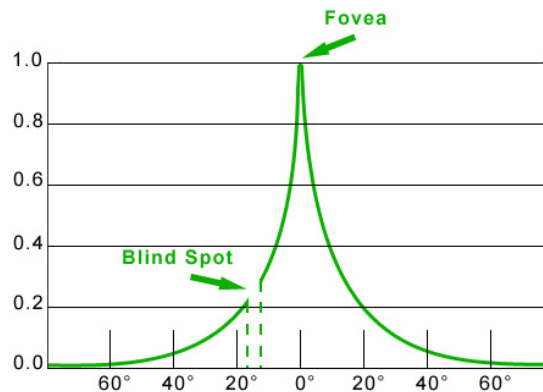


Figure 1 : the relative acuity of the right human eye (horizontal section) in degrees from the fovea

Natural evolution shaped the human eye to provide a higher visual acuity where needed. The fovea located in the center of the macula region of the retina sees only the central two degrees of the visual field but takes up over 50% of the visual cortex. The fovea is an augmented resolution [7] area in the middle of the field of view.

The only thing that prevents the human eye from being qualified as panomorph is the blind spot produced by the optical nerve. Indeed, in contrast to other types of panoramic imagers such as mirror or catadioptric cameras, panomorph lenses have no blind zone.

The panomorph lens is the only wide angle lense (Field of view $> 140^\circ$) with no blind spot which considered resolution curves as design parameters. The resolution curves constrain the lens distortion to provide high resolution coverage where it is required [8].

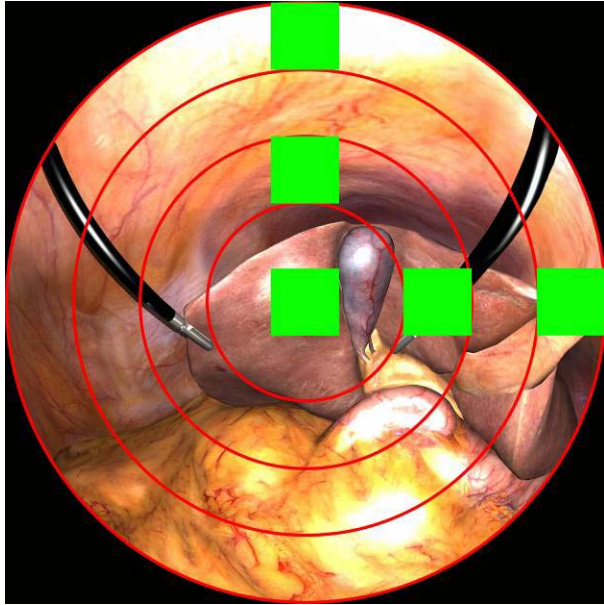


Figure 2 : Simulated linear resolution wide angle lens*

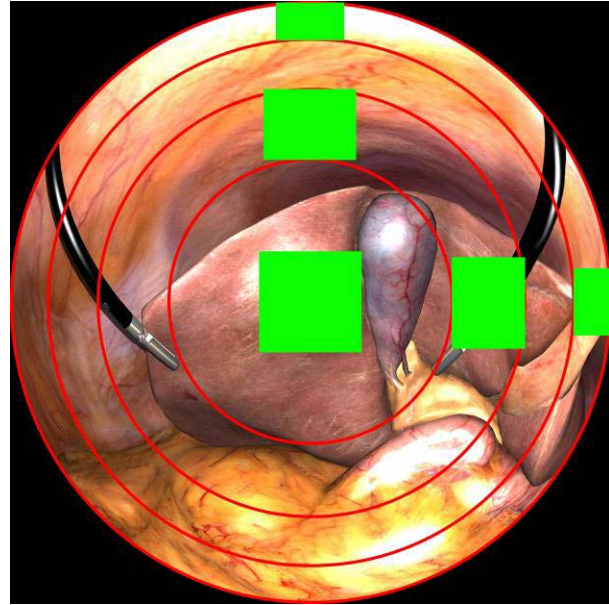


Figure 3 : Simulated panomorph lens with an augmented resolution in the center

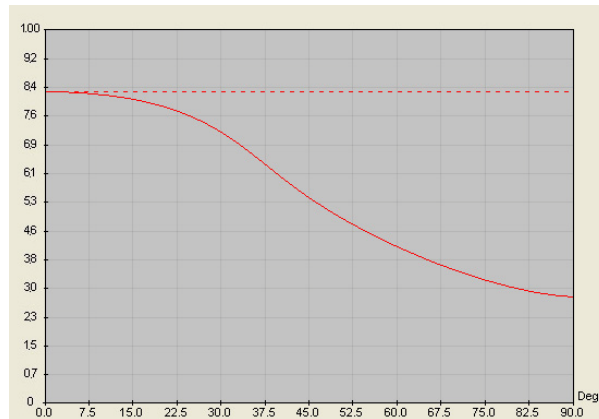


Figure 4 : Normalized resolution across the field of view of the panomorph lens (figure3)

Figure 2 shows a simulated 180° FOV lens with equidistant projection (linear resolution [f-theta] mapping) and the same image produced by a distortion-controlled panomorph lens (figure 3). The green boxes show the relative dimension of objects in the field. Figure 4 shows the resolution ratio of the lens (pixels/degrees) across the field of view. The resolution along the center is 3 times higher than in the border. Where the resolution is higher, the endoscope is able to see for a longer distance or identify smaller objects.

The distortion control [9] approach is one of the two main features powered by panomorph lenses. This allows objects to be magnified in an area of interest and target definition to be increased (amount of pixels that image the object). The second feature is the anamorphic image mapping [10]. This anamorphosis allows customization of the image footprint's aspect ratio to maximize sensor coverage. For example, considering that common CCD or CMOS

* All simulated lens images in this publication were processed by ImmerVision Panomorph Geometrical Model Simulator using raw data from Immersion's LapVR Surgical Simulator

imagers have a standard 4:3 ratio, this feature provides at least an immediate 30% gain in pixel coverage on the sensor i.e. an elliptical image covers more pixels than a circle on a rectangular sensor.

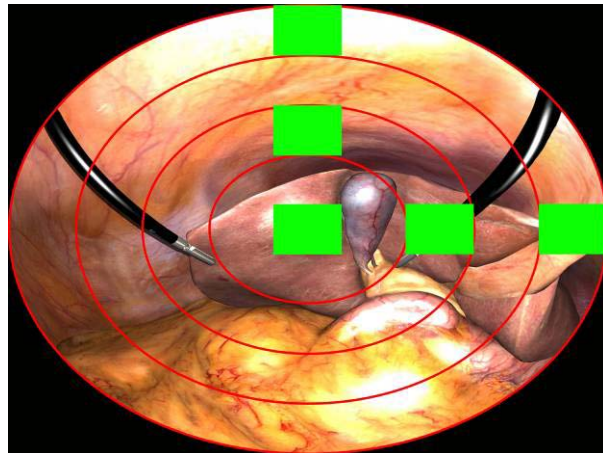


Figure 5 : Simulated panomorph lens with 4:3 anamorphic ratio.

Figure 5 shows a simulated 180° FoV from a panomorph lens with a 4:3 anamorphic ratio fitting. The green boxes show the relative dimension of an object in the field. The elliptical footprint produces an increased resolution. By combining the distortion-control and anamorphic ratio feature, the proposed panomorph technology allows customised resolution (pixel/° or rad/pixel) across the field of view. This combination provides a unique advantage over all other types of panoramic imagers.

Figure 7 shows the same simulated panomorph lens image with increased resolution in the center. This augmentation is close to human eye behaviour. Figure 8 shows the normalised resolution ratio of the lens (pixels ratio/degrees) across the field of view. The resolution along the center is 3 times higher than in the periphery. Consequently the object's magnification in the center is larger and more details can be analysed in this part of the image.

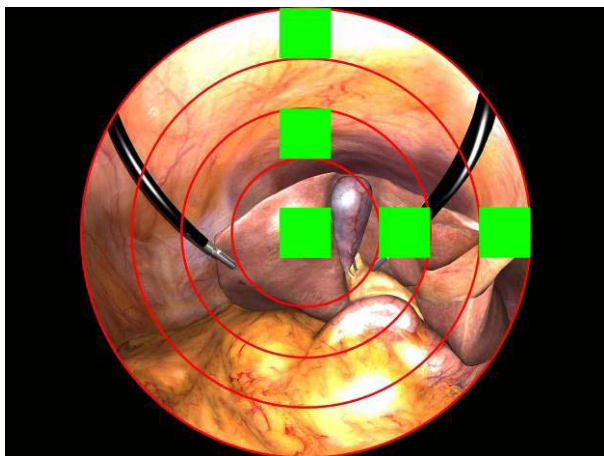


Figure 6 : Linear resolution wide angle lens

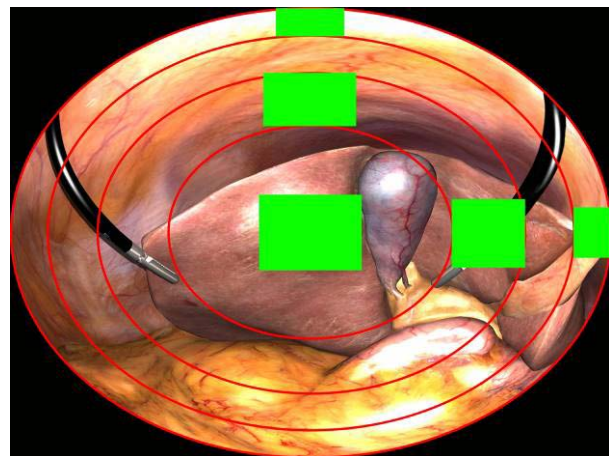


Figure 7: Panomorph lens with an augmented resolution in the center and 4:3 anamorphic ratio

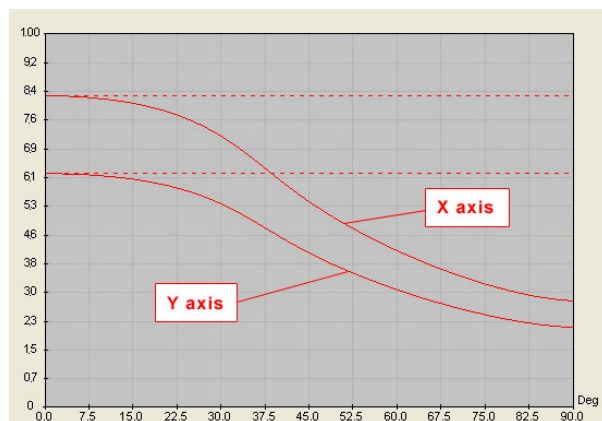


Figure 8: Normalized resolution across the field of view

The panomorph resolution is fully customisable depending on the application. In the opposite the following figures show a panomorph image with 4:3 anamorphic ratio and an augmentation of resolution on the periphery Figure 9). The associated resolution curve is shown at the figure 10. The resolution along the periphery is now 3 times larger than the one in the center.

Section 4 will describe in more details how these images can be used and visualized in various ways. The viewing algorithm must embed the proper resolution curve to provide an undistorted image. As another reference, we suggest a published case study for a panoramic imaging security scenario [11] and a panoramic imaging scenario for the automotive industry [12].

Finally, the main benefit of panomorph optics is its custom-design approach, meaning that the panoramic lens and the image projection software can be customized to meet real and very specific needs in endoscopy such as gastroscopy, laparoscopy, thoracoscopy, arthroscopy, etc.

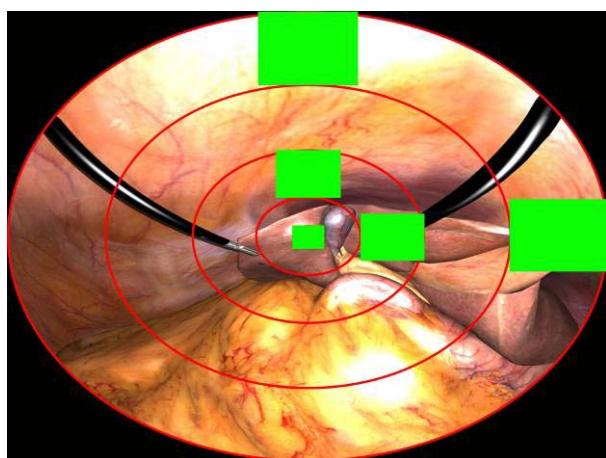


Figure 9 : Panomorph lens with an augmented resolution in the border and 4:3 anamorphosys

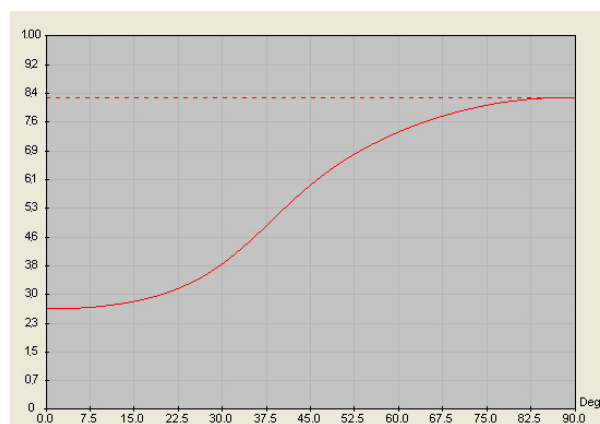


Figure 10 : normalized resolution across the field of view

3.2 Panomorph Optics for Miniature Endoscope Camera Module

Currently, wide angle endoscopes exist on the market. It was demonstrated during the last few years that a panomorph lens while more challenging can be built to replace a regular wide angle lens in various applications. This is again the case here. So the goal of this section is not to describe a detailed panomorph lens design but to discuss the principal issues that we have to deal with when you design such lenses for this particular application.

From an optical design point of view, we can consider some aspects which are unique to biomedical applications. The scale of an endoscope or a laparoscope camera system creates particular challenges for the lens designers that are unique. When designing such a wide angle lens, it is not always helpful to use as a starting point a traditional larger scale lens. Scaling down the lens will result in elements that are unmanufacturable. For example, the element thickness can become too thin to be fabricated. The particular environment of the human body is also of consideration. The optics will be submitted to blood and various types of fluids. The lens material must be selected to withstand this environment and the lens must be sealed. The strict hygiene conditions required in a surgical theatre or treatment room necessitate the highest possible sterility of all instruments used. Any optical lens developed must hold up to the high temperature sterilisation process. The challenge is to maintain a high precision, compact lens design using glass and plastic elements, well aligned after many cleaning and sterilisation cycles.

The development of sensors has been moving towards smaller pixels and higher density formats. Like the cell phone camera industry, the small biomedical vision system will face the same challenges. The higher resolution formats have made the lens designer's job extremely challenging because the reduction of the pixel size has required an increase in lens performance. The lens performance requirements are closer to the diffraction limits and the lens tends to be more sensitive to misalignment. Another problem with small pixels is the limited light collection ability. The sensor surface is not uniformly sensitive. Circuitry integrated with the sensor reduces the active area significantly. To improve sensitivity, an array of microlenses located above the active area of the sensor is applied but this will also impose a chief ray angle (CRA) specification on the lens design. The CRA is the angle of incidence of the chief ray at the image plane for any field point. The microlens acts as a condenser, relaying the sensor image to the exit pupil of the microlens. This increases the apparent pixel size.

The total track length (TTL) of the lens (from first optical surface to sensor) is also an important factor for miniature optics. The TTL of cell phone cameras can be as small as 2 mm on the market. Panomorph lens TTL can be smaller than 5.5 mm. In general the panomorph lens is about two times longer than a 30 degree lens. Consequently, the panomorph lens can meet the size requirements of biomedical endoscopes.

As part of the design process, the material selection is critical. Plastic injection molded optics can be a good choice. Keeping in mind the manufacturing limits, plastic has the big advantage that the flanges can be molded to eliminate the need for spacers and allow for mechanically driven centering of one element to another. One disadvantage is that there are very few plastic materials (low and limited index of refraction), so the choices are limited. The temperature requirement can also discard some types of regular plastic as the one used in the cell phone camera. Another option which is available is molded glasses, allowing the advantages of both high index and aspheric correction. The manufacturing process is more complicated and less flexible than plastic, nevertheless molded glass can be the material of choice when the goal is stability, color correction and extreme temperature conditions.

Lens performance for digital vision systems is commonly expressed in terms of MTF at spatial frequencies between Nyquist/2 ($Ny/2$) and Nyquist/4 ($Ny/4$). The Nyquist frequency is $(2 \times \text{pixel size})^{-1}$. So for a 5.6 μm pixel, $Ny/2$ is 45 lp/mm; for a 2.2 μm , $Ny/2$ is 113.6 lp/mm; and for a 1.75 μm , $Ny/2$ is 142.9 lp/mm. The size of the sensor is not as critical as the pixel pitch for the design of a panomorph lens.

4. CASE STUDY: PANOMORPH TECHNOLOGY IN MINIMALLY INVASIVE SURGERY (MIS)

In this section we will consider the situation where an endoscope using a panomorph lens is used to capture the full body cavity. We present new innovative points of view to the surgeon which help to execute MIS procedure based on dedicated projection (unwarping) algorithms

4.1 Wide field-of-view (FoV)

During an open surgery, the surgeon uses the wide field of view of his eyes to analyse the situation. He has a bird's eye view of the surgery and he always has his tool in his field of view. However in MIS, using a standard endoscope causes a narrow viewing angle. With its wide field of view, the panomorph lens increases the coverage of the operating area. Then, the surgeon observes a hemispheric field of view in the front of the endoscope.

By increasing the coverage, this device decreases the number of manipulations and repositioning of tools and endoscope. For example, by placing the endoscope near the insertion point, the surgeon has an overview of the whole body cavity. He can well appreciate each tool position in the operating area.

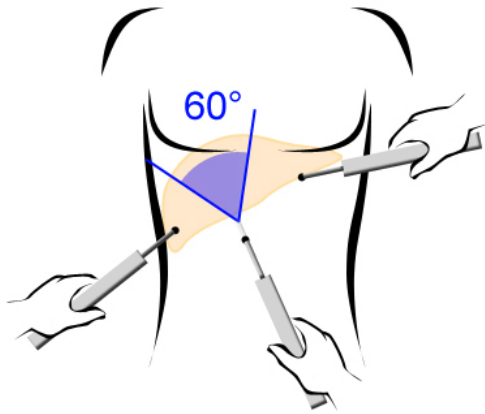


Figure 11 : Cholecystectomy procedure field of view with a classic laparoscope

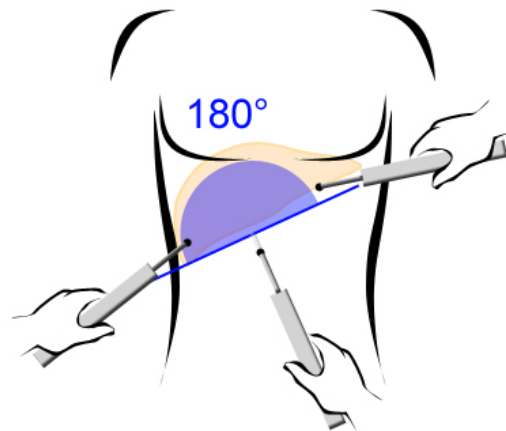


Figure 12 : Cholecystectomy procedure field of view with a panomorph laparoscope

Furthermore, the panomorph endoscope displays more anatomical landmarks which help to localise the dissection plan and increases the perception of depth. Being able to keep an eye on his/her tools all along the procedure is a major improvement for the surgeon, to avoid manipulation mistakes.

4.2 Resolution, Anamorphosis and Lens distortion

By introducing at the optical design stage a proper angular to pixel function (distortion control), the panomorph lens can increase the resolution in a defined zone of interest. Depending on the procedure or the examination, an appropriate distortion curve can be designed.

For MIS, we could design a laparoscope panomorph lens with augmented resolution in the center. This resolution distribution enhances the operating area (center area) while keeping the large field to survey the whole scene. Panomorph optics could also be designed with a small high depth of field. This close focus capability allows the endoscope to move forward close to the interesting targets and in a certain way increases the magnification capabilities while maintaining a large field of view.

4.3 Software projection types and virtual camera manipulations

The image display on the screen for the surgeon is an improved representation of the image captured by the panomorph lens and the sensor. The associated video-viewing algorithms will correct the image distortion to provide a rectilinear view (or a more natural view). These unwarping algorithms project pixels from the endoscope sensor to the display and produce one or more standard virtual views in real time. The viewing algorithms allow simultaneous display of as many views as desired from one endoscope as shown in figure 13.

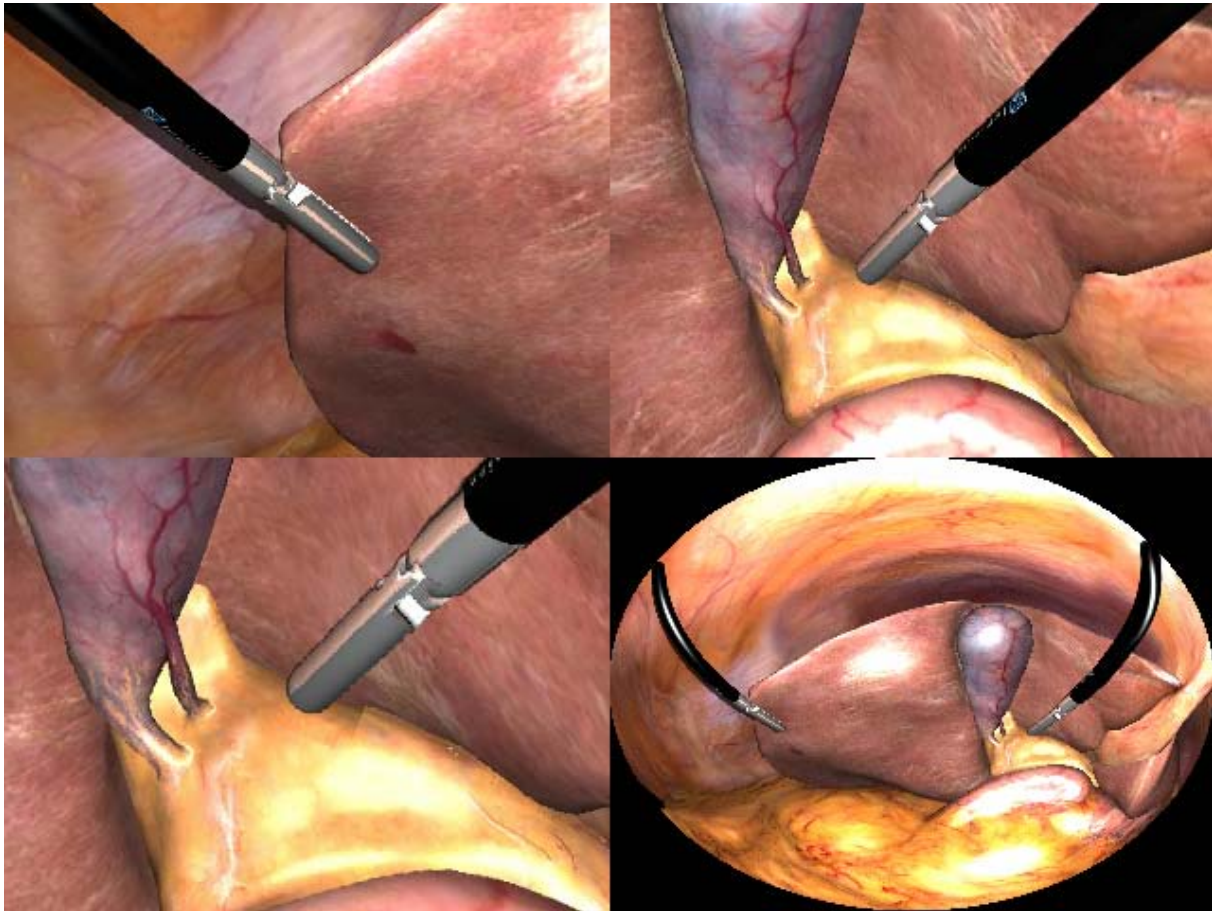


Figure 13 : Different views processed from the same endoscope

Consequently, the viewing process unwarps the image in real time in order to provide views that reproduce real world proportions and geometrical information. These projection algorithms can be adapted for each specific surgical procedure, which is then related to human vision (display) or artificial vision (analytic function).

It is possible for the surgeon to easily choose the best view (projection algorithm configuration) which best fit his/her psycho-motor skills, his/her position and the intervention conditions without having to manipulate the laparoscope. For example, trocar positioning could be achieved by moving the view (virtual camera) without moving the panomorph laparoscope.

Surgeons and assistants have to deal with counter-intuitive endoscope manipulations. For example, in the case of a laparoscope with a 30 degree view, by rotating the laparoscope the assistant changes the viewing angle of the scene. With panomorph technology, views are based on image processing, and virtual camera movements can be performed without any endoscope movement.

Moreover, the surgeon could arrange each view on several screens to have a global overview of the surgery. For example, the following screen configuration well known in flight simulation software respects the aspect ratio, proportion and orientation of each object and would increase the surgeon's perception of depth and surrounding positions. Previous work demonstrates that panoramic visualisation increases the surgeon's accuracy [13]. In this case the panoramic view consists in different videos calculated from only one laparoscope which provides a surrounding view of the working area in real time. This concept is presented in figure 14.

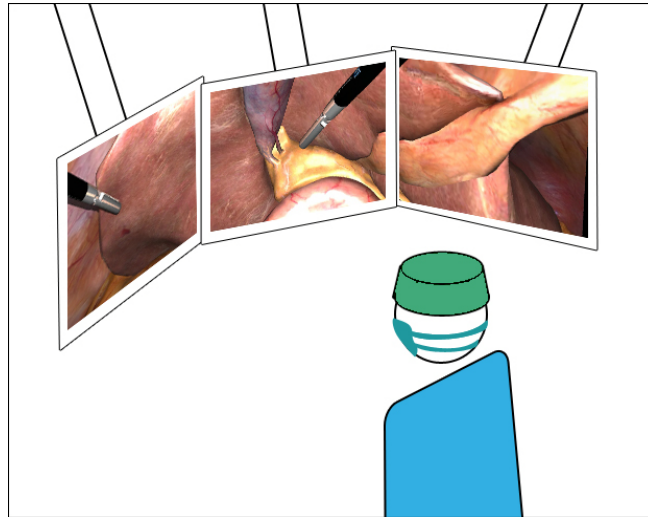


Figure 14 : Immersive screen configuration sample

Lateral color aberrations are a well known issue that optical designers have to deal with when designing wide angle lenses. Their optical design needs to be constrained to reduce them as much as possible. Being able to correct lateral color aberrations using software (or other electronic image management devices) may allow optical designers to relax some design constraints, help to reduce the size and cost of the optics and increase image quality. With panomorph systems, the software is created based on optical design parameters. The software adds special features dedicated to improving the visual perception of the environment. This includes image unwarping, luminance correction or improvement and lateral color correction.

Software lateral color correction consists in repositioning each color component (red, green, blue), spread on several pixels, on a single pixel to recover the original color and image sharpness. To avoid image quality loss due to several image transformations, the projection (unwarping) and the lateral color correction of the picture have to be done at the same time.

To unwarp and correct the color aberration at the same time, it is necessary to unwarp each color component separately, using color dependent resolution curves provided by the optical design itself. Since panomorph lenses are not rotationally symmetric, it can be necessary to use two or more distortion curves per color component or even a complete color distortion map covering the whole image for each component. These curves and maps could be used unchanged directly in the unwarping color correction algorithms or could be used to build color dependent distortion mappings optimized for the unwarping algorithm. Any of these methods recompose each pixel on the destination image using unwarping color components.

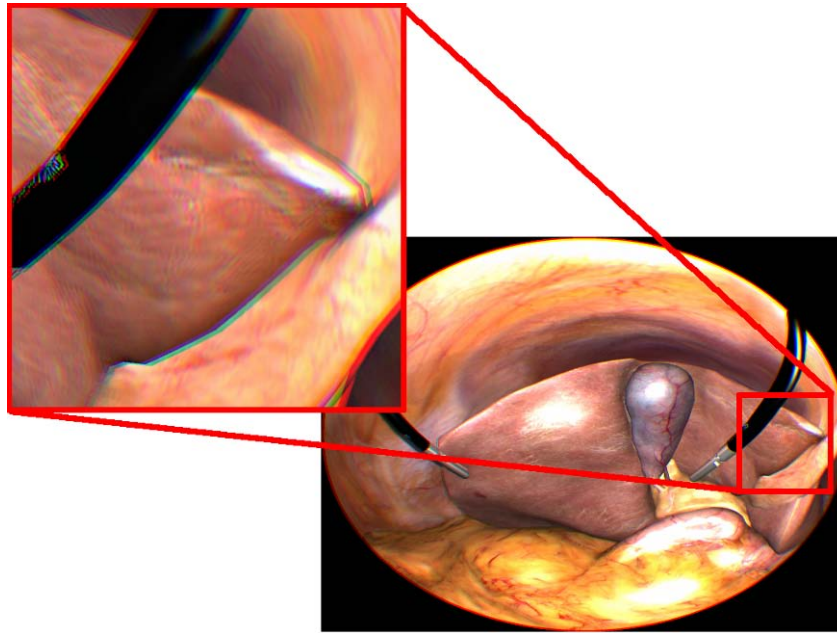


Figure 15 : Simulated panomorph lens with lateral color aberrations

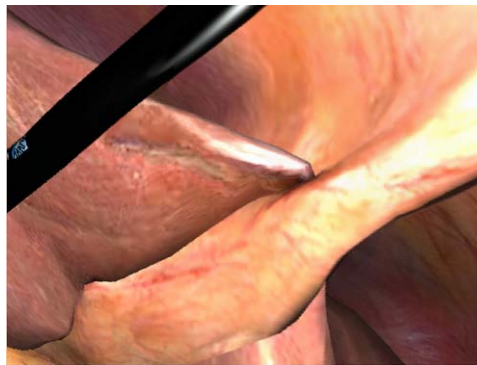


Figure 16 : Simulated panomorph rendering with lateral color aberration correction at the unwarping phase

The projection algorithms include the panomorph lens calibration parameters and they reproduce real world proportions and geometrical information. Using these algorithms, measurement of anatomical parts can be done in real time even in a surgical theater.

4.4 Technology complementarities

Image stabilisation and horizontal orientation can pose challenges to an untrained assistant manipulating a laparoscope. As the panomorph laparoscope provides a wide field of view, we can combine the projection algorithms (virtual camera view calculations) with image stabilisation algorithms. This combination compensates any unintentional laparoscope wavering and rotation. Indeed, as soon as the orientation of the horizon can be acquired using a manual device or an electronic device (gyroscopes, accelerometers or any other system providing orientation information of an object) the orientation of the horizon can be automatically rectified by the projection algorithms.

Some organs such as the liver or spleen absorb light while other tissues reflect light. This variation in organ reflection property could create bright and dark area across the field of view. Depending on the area displayed by the virtual camera, dynamic range expansion or histogram equalization algorithms could be applied to enhance dark area luminance.

It is difficult for an assistant to keep the working area in the middle of the screen all along the procedure. This is the main complaint with surgeons. Panomorph technology combined with object tracking and recognition algorithms can answer this need. Object tracking and recognition algorithms can be used to control virtual camera movements to keep surgeon-marked areas in view while the practitioner simultaneously translates the panomorph endoscope to obtain a drastically different viewing angle.

By mounting a panomorph laparoscope on a robotic device, the real laparoscope movements and virtual camera movements (unwarping) can be combined to provide a full user-friendly interface for endoscope manipulation. This type of device would combine digital and real movements where the digital movements would increase the robotic device range of motion.

All along this case study, we illustrated a panomorph lens with an augmented resolution in the center but the main benefit of panomorph technology is its custom-resolution approach depending on the application, meaning that the panoramic lens and the image projection software can be designed to meet the various needs in endoscopy. For example, we would prefer a smooth augmentation of the resolution on the border where the focus of the examination is on peripheries such as in gastroscopy or colonoscopy as illustrated in figure 17.

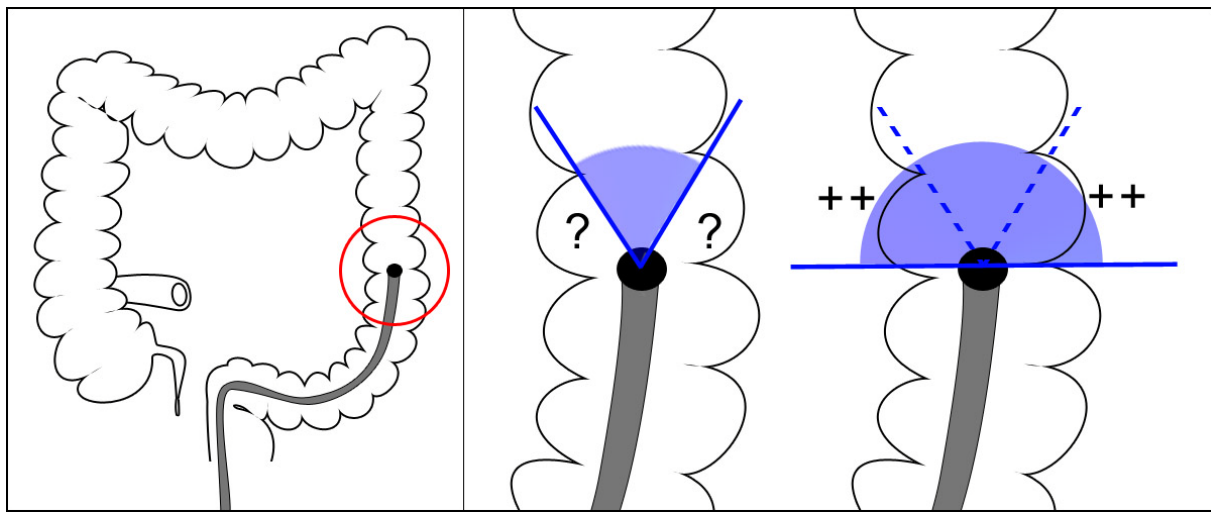


Figure 17: Panomorph augmented resolution in colonoscopy context

5. CONCLUSION AND OPPORTUNITES

There is a worldwide trend to move away from invasive inspection, biopsy and surgical procedures. Panomorph seems a promising technology for the field of minimally invasive surgery. We are only at the beginning of a new minimally invasive revolution and videoscope improvements in the technological aspects of endoscopic procedures will likely yield better outcomes.

This paper presented the problems facing surgeons when using videoscopes in laparoscopic or endoscopic procedures. These are:

- limited range of motion;
- poor field of view;
- loss of depth perception;
- counter-intuitive camera motions;
- uncontrolled movements by the assistant potentially reducing surgeon accuracy and increasing procedure time.

We showed how the panomorph technology combining innovative lens design and image processing algorithms outperform current endoscopic devices.

Panomorph technology addresses the fundamentally limited range of motion of the standard scopes. A panomorph videoscope could be inserted into the cavity and stabilized in the trocar. Once the full field of view ($180^\circ \times 360^\circ$) is obtained, no movement of the videoscope is necessary since the distortion management algorithms will be able to

generate any needed real-time virtual windows using customizable unwarping algorithms. Advanced video processing can also be used to enhance the image quality or locate areas of interest and then track them (i.e. in the center of virtual windows) while other virtual windows follow the instruments.

The new laparo-endoscopic surgical instruments that will be developed using panomorph technology will provide surgeons with a larger field of view, enhanced angular resolution in the areas of interests, more intuitive viewing and user interface. The final benefit: it will help them see everything at the same time and avoid situations where the tips of different instruments collide in smaller spaces during the operation.

Finally, gastro-intestinal patients had only two surgical options: conventional open surgery or laparoscopic with multiple incisions. A new critical advancement in minimally-invasive surgery called single-incision laparoscopic surgery (SILS) - may soon become the preferred method of the future. This new advanced procedure will force the progression of imaging technology thus providing much opportunity for panomorph technology to show its tremendous potential.

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