Computer Assisted Minimally Invasive Surgery:
Is Medical Computer Vision the Answer to Improving Laparosurgery?

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Abstract

Minimally Invasive Surgery (MIS) is one of the most effective methods of modern surgical intervention that has considerable advantages compared with open surgery, including reduced trauma, pain, and post-operative recovery time. MIS has improved substantially over the years, chiefly due to new hardware innovations, including HD cameras and flexible head endoscopes. However, MIS continues to be hindered by several problems. In addition to hardware innovation, Computer Vision (CV) has been proposed as a way to overcome some of its current limitations. However, the research literature lacks a coherent picture of how the limitations can be best overcome by hardware, CV or a combination of the two. In this paper we focus on laparoscopic MIS, and list these limitations into 5 clear categories. We detail the effectiveness of hardware and CV solutions with respect to each limitation, from which we base the following hypothesis: CV is both complementary and necessary to hardware development, to overcome all 5 limitations in laparoscopy. Our paper is of value to laparoscopy surgeons, by conveying what is expected to be achieved in computer-aided laparoscopy over the next decade. It is also of value to medical CV researchers, by clarifying which problems are best solved with CV, in light of the hardware developments likely to occur over the next decade.

1. Introduction

Minimally Invasive Surgery (MIS) is a highly successful modern method for surgical intervention, based on inserting surgical instruments and an endoscope camera into the patient's body through small incisions or natural orifices. Laparoscopy is the form of MIS that is performed in the abdominal cavity. Since its inception, MIS is considered a true revolution in surgery [1,2,3,33]. From the patient's perspective, there are major advantages compared to open surgery. It decreases trauma, the associated pain, and greatly reduces the post-operative recovery time [32]. Nowadays almost all abdominal surgical procedures, including pelvic exenteration and abdominal aortic aneurysm repair, can be successfully achieved with laparoscopy [4,5]. More than 95% of cholecystectomies are performed by laparoscopy. In our department, a technique for laparoscopic hysterectomy was developed which allows more than 90% of laparotomies to be avoided [6]. This technique has been successfully practiced and taught to residents and fellows since 1996 [12]. Patients now can be discharged in as little as 24 hours after a laparoscopic hysterectomy [7].

Technological progresses have made the development of MIS feasible and successful. The earliest forms of MIS included simple specific procedures such as the treatment of filmy adhesion and the treatment of small ectopic pregnancy. This was started in the early 80s using a cold light laparoscope (with no camera) held with the right hand of the surgeon and two instruments inserted into two suprapubic trocars. One of the instruments was manipulated by the left hand of the surgeon, and the other by an assistant. Even though the assistant was blind to the procedure, since only the surgeon was able to look inside the abdomen, satisfactory results were obtained by the method [8,9]. In the late 80s the problem of visualizing the procedure to multiple persons was solved by using a video camera mounted inside the laparoscope [10]. Now the assistants were no longer blind, and it was discovered just how much they can help the surgeon in laparoscopy. Also in the late 80s, laparoscopic intraperitoneal ovarian cystectomy became possible when the first effective grasping forceps were invented [11]. This technique for laparoscopic hysterectomy became simple when an effective canulation device became available [12]. It is clear that new technological progresses will again change and improve laparoscopy into the future. These improvements will help in various ways, including making laparoscopy easier to perform, learn and teach. As progress is made, it is also essential to keep the costs of adopting the new technology low. This means that patients can benefit from the improvements as early as possible, and that the technology can be widely distributed to hospitals over the world.

The main technological progress made over the last 30 years in laparoscopy has been the improvement in the quality of the image; both in terms of the camera's optics, CCD resolution and image display resolution. Currently in laparoscopy, the surgeon observes the procedure on a High Definition (HD) flat-screen display. This displays the live raw laparoscopic video stream. However, because the video is a 2D projection of the internal 3D operating scene, much of the important visual information is lost to the surgeon. This puts very real performance limitations on current video-based laparoscopy. It seems a natural direction to use computerized image processing to improve laparoscopy by enhancing the laparoscopic video stream before it is displayed. Enhancing does not only mean basic cosmetic operations such color correction. It also means applying advanced algorithms to understand the video content, and possibly combining it with preoperative data [17]. This would allow one to display, for instance, the position of benign or malignant tumors even though they may be hidden from the current laparoscope's viewpoint. The algorithms to reliably achieve this do not yet exist, but scientific grounds exist and are studied in a very well established research field called Computer Vision (CV).


Input image Shape-from-Motion Shape-from-Shading

Figure 1: Example of 3D shapes (middle, right) obtained using Computer Vision from a single laparoscopic image (left) with no hardware modification. The middle shape was obtained using the technique known as Shape-from-Motion [23] and the right shape was obtained from Shape-from-Shading [39].

Preliminary results of applying CV in the context of laparoscopy were obtained (see figure 1). However, understanding exactly how CV can help improve laparoscopy, how it complements hardware improvements, and knowing what its intrinsic limitations are, are critical questions which have not yet been addressed in the research literature, and are the subject of this paper. This article has two main purposes. The first purpose is to enlighten clinicians on what they can expect to be achieved in computer-aided laparoscopy over the next decade by progress in medical image research. The second purpose is to help CV researchers understand and focus on goals whose solution will help laparoscopy. We achieve this by identifying the critical problems and limitations in laparoscopy for which software solutions are essential, in light of the fact that laparoscopic hardware might change over the forthcoming decade. Importantly, although the focus of this article is on laparoscopy, much of the analysis and conclusions can be transferred to other types of MIS.

2. Laparoscopy’s current limitations

Laparoscopy has intrinsic limitations related to the shortcomings of current technology. As of today, there are five main limitations of monocular laparoscopes, which are as follows:

1. **Weak depth perception.** Most current laparoscopes use a HD camera with a sophisticated optical transmission system. This means that they capture a 2D image of the operating environment, and deliver this to the surgeon's eyes via the HD monitor. The display system therefore cannot convey the 3D structure of the environment, but only flat 2D projections. That is, depth information is lost by the display system. As a consequence, In order for a surgeon to manipulate their instruments to perform a desired task, they have to infer themselves the scene's 3D structure from the flat image. This however is a difficult task, and takes years of training to be able to reconcile the image display with the true 3D scene and the position and movement of the instruments. These difficulties are obvious for laparoscopic suturing which is mastered only by so-called skilled or expert surgeons. Recent developments of robotics surgery which included a stereoscopic sensor image illustrated the importance of these limitations [40,41]. Indeed using this very expensive technology, it was demonstrated that the learning curve is much shorter. Moreover it was demonstrated [42] that even experts benefit from an improved depth perception through a significant decrease in the number of movements.

2. **Constrained vantage point.** The laparoscope enters the patient’s body through a trocar centred at a small incision which is usually made only once throughout the procedure. This constrains what can be observed by the laparoscope, since it must pass through this entry point. This has two consequences. Firstly, the patient’s anatomy may be viewed from an undesirable vantage point. This for example can make associating the movement of the instruments with the 2D image hard. Secondly, it may be impossible to observe some important parts of the patient's anatomy. This may make further dissection harder.

3. **Limited field-of-view.** At any given instance, the laparoscope's camera captures only a small 2D window of the internal environment. Furthermore, in laparoscopy the focal length is usually very low, and is hardly ever changed during a procedure, which means that the surgeon's field-of-view is limited. In order to successfully navigate, the surgeon must construct in their mind a visual representation of the environment, which is a difficult task.

4. **Weak haptics.** Haptic (or kinesthetic) feedback is the tactile sense, which is almost completely lost in current laparosurgery. Haptic feedback can be extremely important for the surgeon to evaluate the nature of tissue. For example, to find a tumor and its boundaries

prior to excision. The biomechanical properties of the tumor are usually significantly different to the surrounding healthy tissue. In open surgery, the boundary can be estimated by probing the tissue with the hand. By contrast, in laparoscopy this approach is not feasible using the kinesthetic feedback of current laparoscopy instruments [15].

5. **Occluded anatomy**. Some anatomical structures are hidden from the surgeon because they are behind visible tissue. Locating these however is often critical. For example, it is difficult to locate occluded structures that should not be harmed during surgery, such as major vessels, the ureter, or structures which should be resected such as myoma or endometriosis nodules. This limitation does not only apply to laparoscopy and MIS, but to open surgery.

These five limitations explain why laparoscopic surgery and particularly laparoscopic suturing is often considered as difficult and reserved to expert, skilled or even highly skilled surgeons. These limitations were partly resolved with current robotics-based approaches. This explains why the learning curve of endoscopic procedures is shorter when using a telemanipulator featuring stereovision.

3. Overcoming the current limitations of laparoscopy: hardware and Computer Vision solutions

3.1 Hypothesis

The major technological breakthroughs in laparoscopy have so far been obtained only by improving the hardware. We can identify three main landmarks, which are the introduction of (1) HD video cameras, (2) flexible laparoscope's head and (3) stereo-laparoscopes. By contrast, the image processing techniques used in current laparoscopy are very primitive. These mainly involve trivial tasks such as contrast correction and white balancing, which do nothing to address the above-mentioned current limitations. An open question is whether significant progresses could be made to overcoming these limitations by modifying the laparoscope's software by using and developing powerful, state-of-the-art CV methods. 3D CV offers cutting edge techniques for 3D sensing from a single optical camera, and might be one way to open new major steps in laparoscopy. 3D CV could be deployed in two settings (1) as a complete alternative to hardware modification or (2) by achieving enhancements which cannot be achieved by hardware modification alone. An example of the second case is for stereo-laparoscopes. Here, even though depth can be perceived by the surgeon, limitation 2 (constrained vantage point) is not solved. By contrast 3D CV can use the additional information provided by the second camera to provide even better enhancements.

Solutions with hardware modification. One possible route for improving laparoscopy is to modify the hardware of the laparoscope. That is, to go beyond using a single monocular camera and to use sensing technologies which provide more information with which to assist laparoscopy. There already exist some examples of this [13,31].

Solutions with Computer Vision. A second possible route to overcome the limitations is by using a computer program to enhance the laparoscopic video stream and enrich it with extra information before being displaying to the surgeons. To achieve this means applying advanced algorithms to understand the video content, and also exploit additional information such as preoperative data acquired by a different modality, to present and visualize new, useful data to the surgeons to help them perform their tasks. For example, if a malignant tumor has been detected in a pre-operative

MRI scan, by automatically registering (or aligning) this scan to the laparoscopic image, it would be possible to display its position, even if it were hidden from the laparoscope's camera.

The overarching goal of CV is to infer information about the environment from images. This ranges from semantic information obtained by detecting and recognizing object and people to geometric information such as lengths, areas, surface shapes and volumes. The latter is the topic of 3D CV, which seeks to find a 3D model of the environment from 2D images. This is particularly relevant in the context of laparoscopy where the absence of true 3D sensing is one of the major limitations. 3D CV has been actively researched for over 30 years. Now, successful, real-world 3D CV applications have started to emerge, particularly in the video game and cinematographic post-production industries [28,29].

Our Hypothesis: Computer Vision software is necessary, and complementary to hardware modification for overcoming the current limitations of laparoscopy.

3.2 Evidence

In developing and producing an enhanced laparoscopic system using hardware modification and/or CV, at the fore-front there are three main considerations: (1) the effectiveness of the solution, (2) the technical difficulty of achieving the solution and (3) the cost of adopting the new technology.

Overcoming the current limitations with hardware modification. We now review the technologies for overcoming the current limitations of monocular laparoscopy by modifying the laparoscopy hardware. A summary of this is presented in Table 1.

Limitation	Hardware solution	Effectiveness	Technical difficulty
1. Weak depth perception	Stereo-laparoscope	Medium/High	Achieved/Low
2. Constrained vantage point	Flexible head	Medium	Achieved
3. Limited field-of-view	Wide-angle lens	Low	Low
4. Weak haptics	Haptic sensor instruments	High	High
5. Occluded anatomy	Laparoscopic US	Medium	Achieved

Table 1: Overcoming the current limitations of laparoscopy with hardware modification.

1. **Weak depth perception.** Laparoscope manufacturers have proposed stereo-laparoscopes that embed a second camera. Each of the two images is then displayed to each eye of the surgeon, whose brain can naturally perceive depth. For instance, Intuitive Surgical's Da Vinci system integrates a stereo-laparoscope [13]. The surgeon positions their head in front of two small screens, displaying the corresponding stereo images to the two eyes. In this setup, the system does not recover any 3D information; it is the surgeon's brain which achieves this. The effectiveness of this solution is medium when using a fixed convergence angle stereo setup (such as the Da Vinci system). It will be high when variable convergence angle systems have been developed.

2. **Constrained vantage point.** Two hardware solutions have been proposed for this. The first is to use a second trocar to introduce the laparoscope from a different vantage point. However this can introduce difficulties for the surgeon, who has to find new landmarks to orient themselves, and has to become familiar with viewing their instruments from the different view. The second, more recent hardware solution is the flexible-head laparoscope. Here, the

camera can change orientation, and lets the surgeon observe some of the structures which would be hidden with fixed-head hardware. Flexible head laparoscopes allow for orientation change along one degree of freedom. For instance, Karl Storz' Endocameleon [14] and Olympus' Endoeye Flex 5 [38] are laparoscopes that feature a flexible head. The clinical use of this prototype is still preliminary. The effectiveness of this solution is medium, and is limited by the flexible head's single degree of freedom. A real or virtual mirror could also be used to aid visualization, but the effectiveness of this solution is currently minor [34].

3. **Limited field-of-view.** Current laparoscopes allows one to adjust the laparoscope's level of zoom, and hence the field-of-view. However, this is not a practical solution, as it is inconvenient to switch between wide-angle and narrow-angle focal lengths during surgery. Surgeons thus generally retract the laparoscope. Wide angle lenses also exist but they typically distort the image.

4. **Weak haptics.** No existing solution.

5. **Occluded anatomy.** Laparoscopic Ultrasound (LUS) requires that the port sites are placed to allow the laparoscopic ultrasound probe to be inserted for biplanar examination. It has not been widely used in gynecologic procedures, though it may be useful in the identification of the location of a cyst within an ovary [35] and of the myoma of the uterus [36]. There exist other techniques such as fluorescence imaging [37] but their use in gynecologic procedures is currently marginal.

The likelihood that a manufacturer proposes a product which implements any of the hardware solution is a combination of two factors: this solution's effectiveness at solving a limitation and the technical difficulty of its development. We can see from table 1 that it is thus unlikely that limitations 3 and 4 be overcome by hardware modification in a near future.

> **Proposition 1.** Of the limitations which have been overcome by hardware, the cost of these systems when compared with standard monocular endoscopes currently prohibits their wide-spread use.

We already have evidence for this proposition. For instance, the Da Vinci system, which seems to have the potential to substantially improve training in laparoscopy (but which lacks clinical benefits for expert surgeons [13]), has not been widely adopted. Because of its costs this technology is reserved to complex, selective surgical procedures and will probably never be used in small hospitals and in developing countries. Even in university hospitals of affluent countries, it is highly unlikely that they would invest in a robot for each operating theater whereas this investment would be necessary if this technology was mostly used for simple routine procedures such as cholecystectomy and hysterectomy.

> **Proposition 2.** Breakthroughs in hardware will be extremely difficult to integrate in a single system.

For example, consider the case of resolving limitations 1 and 2 with a single hardware solution. This would require integrating stereo and a flexible head. This is technically far from being trivial.

> **Proposition 3.** There are some enhancements which overcome current limitations that can never be achieved with hardware modification alone.

One very important example of this is limitation 4 (weak haptics). A second example is when considering the recent trend of using a single entry port [24], or the NOTES approach [25], which require all devices to be miniaturized even more. This requirement puts hard, physical limits on the hardware solution. In the case of limitation 1 (weak depth perception), for a NOTES approach, this may mean that the stereo baseline is too small to acquire the proper sensation of depth.

Overcoming the current limitations with Computer Vision. We now turn to CV-based solutions to the same set of limitations, and provide a similar level of analysis in terms of the effectiveness of the solution and its technical difficulty.

CV seeks to solve the limitations in current laparoscopy by performing 3D reconstruction of organs and tissue in the abdominal cavity, and performing automatic preoperative to laparoscopic image data registration in realtime. A main advantage of CV-based solutions is that the costs of adopting, improving and distributing CV solutions are negligible when compared with hardware modification.

To achieve CV-based solutions, one is required to use highly advanced CV techniques and to develop efficient implementations to meet the realtime constraints. Currently realtime 3D CV is limited to specific cases [26], and the field is quite far from providing solutions to situations as complex as encountered in laparoscopy. A whole new field is beginning to emerge at the intersection of CV, medical imaging and realtime parallel processing. This field, which has already gained some ground in the last few years [27] may be one day known as Live Medical Computer Vision.

Based on the current state-of-the-art in CV, and current research trends, we can hypothesize about the kinds of CV solutions we can expect to emerge over the next 10 years for enhancing monocular laparoscopy. Table 2 provides a high-level description of the current and future CV solutions that are most suitable for resolving each limitation.

Limitation	Monocular CV solution	Effectiveness	Technical difficulty
1. Weak depth perception	Depth estimation	Low	High
2. Constrained vantage point	Novel view synthesis	Medium/High	Medium
3. Limited field-of-view	SLAM	Medium	Medium
4. Weak haptics	Preoperative registration	High	High
5. Occluded anatomy	Preoperative registration	High	High

Table 2: Overcoming the current limitations of laparoscopy with Computer Vision.

1. **Weak depth perception.** 3D CV can estimate a partial 3D model of the environment from single or multiple images, by using visual cues such as motion and shading. Given such a model, 3D vision immediately facilitates the perception of depth for the surgeon. This is because it allows one to synthetically generate the two images corresponding to viewing the 3D model with two eyes. A stereo-laparoscope does not explicitly reconstruct the 3D structure. The drawback of this is that the stereo images must match the user's convergence angle, which is difficult to achieve perfectly [18]. In contrast, a reconstructed 3D model can be easily rendered so that the images match the user's parameters. Monocular-based 3D

reconstruction is tremendously difficult however, and it is likely that no solution will exist which provides anything comparable in effectiveness to a hardware solution.

2. **Constrained vantage point.** Similarly to the case of weak depth perception, a 3D model can help overcome this limitation. Indeed, such a model can be rendered from virtually any vantage point, which could then be interactively chosen by the surgeon using a device such as a trackball. The effectiveness of this solution may therefore be higher than the flexible head. However, this approach does not allow looking at parts hidden from the real current laparoscope's vantage point. A more advanced CV solution is based on exploiting preoperative data. For example, if an organ be segmented and its 3D shape reconstructed in a preoperative MRI. Finding the spatial transformation from the MRI to the current patient's body pose would here be a solution that would let the computer fill in the missing surface information in the hidden parts, and thus allow the surgeon to enjoy a virtually arbitrary viewpoint in the abdominal cavity in realtime.

3. **Limited field-of-view.** This limitation can be solved by CV by solving the problem known in the community as Simultaneous Localization and Mapping (SLAM). Methods now exist when the 3D environment is approximately rigid. In some settings in MIS, such as brain surgery this can be a valid assumption. However in laparoscopy, the rigid assumption is too constrained. Recent work has been attempted to extend SLAM to deformable settings, with some success when the deformable motion is predictable or periodic. However, in the general case when tissue deforms by instrument manipulation, the problem is challenging and as yet unsolved. The CV solution is more effective than the hardware solution since arbitrary wide angle/narrow angle views can be synthesized, overlaid and presented to the surgeon.

4. **Weak haptics.** We propose that CV can be used to solve this limitation, albeit indirectly. Instead of trying to recreate haptics, which is not possible by software only, we propose that preoperative information can act as a surrogate for the lost haptic information. The primary purpose of haptics is to let the surgeon identify pathological tissues and their boundaries. Such tissues are generally visible in preoperative images, and can be demarked by a surgeon or radiologist in the planning phase. We argue that CV can be used to automatically transfer this information to the live laparoscopic view by a process called registration. This process automatically aligns the preoperative data with the current laparoscopic image. Hence, the haptic information lost in laparoscopy in fact becomes redundant. This is because the information gleaned from haptics (the nature of the tissue) can be visualized via the registered preoperative data. For example, this would let the surgeon see the boundaries of a nodule by highlighting its region in the laparoscopic image with a special color.

5. **Occluded anatomy**. CV offers a solution to this problem by registering and visualizing pre-operative 3D data to the live laparoscopy image. The solutions to this are very similar to those for overcoming limitation 2.

Combining hardware and CV solutions: a middle ground. It is far more likely that rather than a hardware based or software based solution, a middle ground will be reached combining the best of both. We are already learning that a small amount of hardware modification can make a big effect on the feasibility of CV algorithms. For instance, using two images from a stereo-laparoscope makes 3D reconstruction far easier than with a standard monocular laparoscope, although the problem is still not trivial. CV can also benefit from high frame-rate cameras. Of course, knowing precisely where on the hardware / software divide the solutions to each of the limitations lie, and understanding how best to complement CV with minimal hardware modifications will be a very valuable piece of information.

Limitation	Hardware + Computer Vision	Effectiveness	Technical difficulty
1. Weak depth perception	Variable angle stereo-laparoscope	High	Low
2. Constrained vantage point	Flexible head + novel view synthesis	High	Medium
3. Limited field-of-view	Wide-angle lens + SLAM	High	Medium
4. Weak haptics	Stereo + Preoperative registration	High	High
5. Occluded anatomy	Stereo + Preoperative registration	High	High

Table 3: Plausible combinations of hardware and CV to overcome the current limitations of laparoscopy.

Table 3 suggests what we believe to be the plausible hardware and CV combinations to solve the limitations in laparoscopy over the next decade. Limitation 1 will be solved with a hardware solution using a stereo-laparoscope with variable convergence angle. Here CV plays little to no role in solving this limitation. Limitation 2 will be solved with a flexible head setup. CV will be used to synthesize novel views from arbitrary viewpoints, but will be assisted by the additional data coming from the differing images acquired by changing the physical camera's vantage point. The technical difficulty is limited by solving the CV problem of novel view synthesis. Limitation 3 will be solved partially by hardware using a wide angle lens with a very high definition camera, which facilitates zooming done in software. It will also be solved partially in software using SLAM, in order to acquire a large-scale map of the intraoperative environment. Limitations 4 and 5 involve CV solutions which are technically hard to achieve. However, they are greatly helped by hardware modification, and in particular stereo image data.

We believe that our hypothesis will be proved correct if the technical difficulties of CV-based solutions to limitations 4 and 5 are not too high to realize highly effective solutions.

4. Evaluation

The way to evaluate our hypothesis is in developing and implementing a solution to limitations 4 and 5, and having its effectiveness tested clinically. This is one of our group’s focuses for the upcoming decade. Our group includes medical doctors and non-medical scientists whose field of expertise is CV.

In defense of our hypothesis. CV is a well-established research field with a rigorous theoretical underpinning (see for instance the textbooks [20,21,22]). The general problem of CV in a deformable environment observed with a monocular camera like a laparoscope has been an important focus of research for about a decade. Effective methods now exists which may be successfully applicable to laparoscopy. The constraint of realtime processing may be met by using Graphical Processing Units (GPU) which, thanks to parallel programming, runs computer programs at extremely fast rates. Graphics cards supporting GPU programming are available in most consumer grade computers. We can expect therefore, that in the next coming years many problems in CV will have corresponding realtime GPU implementations. HD laparoscopes provide sharp images of extremely high quality, which is a strong asset for developing CV methods. In our group, we have successfully applied advanced monocular 3D CV techniques to laparoscopy [23].

In contention to our hypothesis. On the other hand, there are arguments to support the fact that the laparoscopic conditions are extremely difficult for applying CV techniques. Firstly, the fact that the environment is moist will make it reflect light unevenly. Common assumptions, such as photoconstancy, which are cornerstones of current successful CV algorithms, do not apply here in general. Secondly, the extreme shape, anatomical and topological changes undergone by the organs through surgery are major hurdles. These are far more challenging than the simplified conditions used for developing most current deformable 3D sensing algorithms [30]. Thirdly, phenomena such as smoke and blood are also extremely challenging to handle.

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