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A System for Real-Time Endoscopic Image Enhancement *

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Abstract During endoscopic operations the surgeon works without direct visual contact to the operation area. The image of the operation situs is displayed on a monitor. Currently, only hardware based image enhancement methods are used (e. g., white balance) and often only once at the beginning of an operation. In this contribution we describe a system for real-time endoscopic image enhancement: a typical video-endoscopic system was extended by a computer and a second monitor. Thus the enhanced and the original image can be displayed at the same time. The implemented image enhancement methods (temporal filtering, undistortion and color normalization) were evaluated by 14 surgeons and the results showed that the enhanced images were preferred. The system was already used during a real operation.

1 Introduction

Minimal-invasive endoscopic surgery is carried out by the surgeons without direct visual contact to the operation situs inside the abdomen or chest. Instead, the video of the operation area is displayed on a monitor for visual feedback (see Figure 1). During the course of an operation, image quality may be low due to degradations of the endoscopic images. The cutting techniques using high frequency diatherma lead to smoke and small flying particles which disturb the image. If blood covers large areas of the visible field, the image gets reddish (color error) and the ability to discriminate different tissue types is reduced. Optical lenses with small focal lengths are used to enlarge the visible area and gain clarity. The small focal length leads to a distorted image (e. g., straight lines get twisted). The distortion increases towards the borders of the image. Inexactnesses during the manufacturing process of the optics are another reason for image distortion. Highlights occur on surfaces perpendicular to the viewing direction since the light source is located directly beneath the lens of the endoscope. Additionally, wet tissue surfaces amplify the effect.

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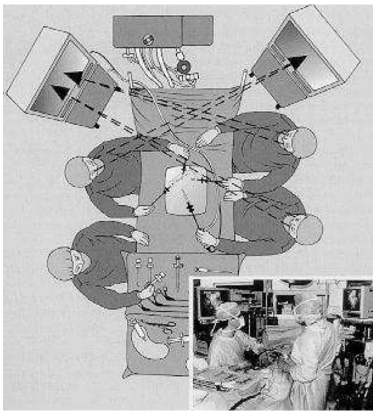

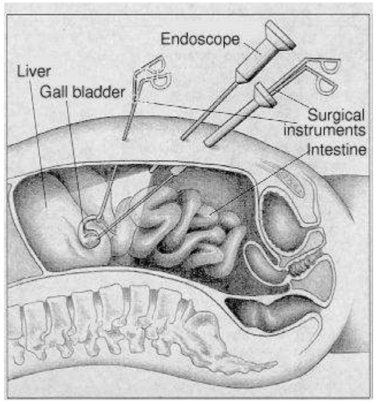

Figure 1. Setup of surgeons during a minimal-invasive operation (left image) and the situation during a laparoscopic cholecystectomy (right image): two surgical instruments and the endoscope are introduced into the abdomen. A camera at the end of the endoscope provides the image of the operation area.

The goal of our research is to reduce the mentioned image degradations in real-time during a minimal-invasive operation. The methods used for image enhancement are temporal color median filtering [1] (reduction of small flying particles), undistortion [2] (reduction of the distortion of the image) and color normalization [3] (reduction of color errors). The first two methods can be applied in real-time, color normalization misses the goal of real-time processing by a factor of four. Currently, no usable method for real-time highlight substitution is available. In [4] we presented a very time-consuming method to substitute highlight pixels by real color values using light fields. In this contribution we focus on methods that are applicable in real-time.

Several papers address the topics highlight detection and substitution of missing image data, e. g., [5–7], but we do not know of any research group working on general endoscopic image enhancement. Currently used commercial video-endoscopic systems do not provide computer-assisted image enhancement methods. Usually, they only provide white balance and in some cases a refinement of the sharpness of edges.

In this article we describe a system for real-time endoscopic image enhancement (see Figure 2). The system allows to display the processed image on a second monitor. The surgeon then has the choice between the original and the processed image.

Cholecystectomy is one example for the effective application of endoscopy. Laparoscopic cholecystectomy has already replaced operations with a large incision and is state of the art. The setup of the surgeons during a minimal-invasive operation and a sketch of the situation during a laparoscopic cholecystectomy are shown in Figure 1. Cholecystectomy is one of the most frequent applications of minimal-invasive surgery. The image sequences we used for evaluating the image enhancement methods were recorded during cholecystectomies at the Department of Surgery, University of Erlangen. A first extensive evaluation of endoscopic image enhancement was presented in [8]. In this article we show the results of an evaluation by 14 surgeons. Altogether, the processed images were evaluated to be better in comparison to the original images.

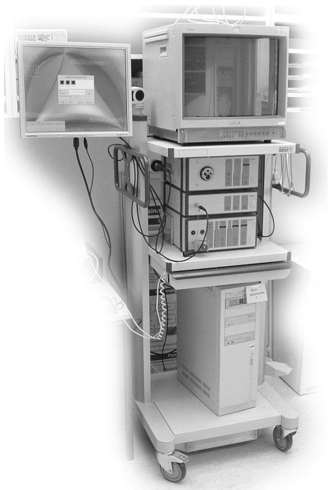

Figure 2. The real-time endoscopic image enhancement system: a typical video-endoscopy system on a rack extended by a computer and a second monitor (on the left-hand side fixed with a positioning arm) to display the original and the processed image at the same time.

The system, the image enhancement methods and the evaluation procedure are described in Section 2. The processing time for each method and results of the evaluation can be found in Section 3.

2 Methods

2.1 Real-Time Endoscopic Image Enhancement System

The basis of our system is a typical video-endoscopic system (Richard Wolf GmbH, Knittlingen, Germany) including a rack, a camera, a light source, a carbon dioxide insufflator and a video monitor for displaying the image of the endoscope. To provide real-time computer-assisted image enhancement methods, a computer with frame grabber card and a second monitor was added (see Figure 2). This setup allows grabbing the image from the endoscopic camera, processing it in the computer and displaying it on the second monitor at the same time with the original image.

2.2 Temporal Filtering

If degradations like small flying particles or fast moving smoke are defined as temporal noise, i. e. if we assume that the degradations are only visible at a certain pixel position for a short time, a temporal color median filter is a very good method to reduce this temporal noise in the image sequence. This assumption can be made because flying particles move very fast and the camera stands still for the surgeon needs a steady image the whole period while performing the operation. Especially during the cutting of tissue the mentioned degradations appear.

Color median filtering can either be done by filtering each color channel separately by a grey value median filter, or by using the median value of the sorted color pixel values as the result, where the values are sorted according to an ordering criterion (e. g., the Euclidean norm). The disadvantage of the second method is the processing time due to the sorting process. The disadvantage of the first method is that the resulting image can (and usually does) contain new color values. As the difference between the two methods on real images is small (in our experiments the mean value of the pixel difference was ≈ 2 pixels), we decided to use the first method which also enables the usage of optimized image processing libraries.

Although currently available optimized image processing libraries (like the Intel Image Processing Library IPL) only provide spatial filters, these filters can be used to implement and accelerate temporal filtering. We described two possible implementation methods in [1], therefore we only sketch the method we used here. The technique merges single lines of temporal images into several spatial images. These images are filtered with the spatial color median filter of the IPL (color channels are filtered separately). The time filtered image is generated by extracting the corresponding lines from the spatial filtered images. Because only lines are copied and additionally the optimal filter of the IPL is used, the technique is very fast (cf. Section 3 and [1]) and is therefore qualified for usage in the operating room.

2.3 Color Normalization

Bleeding (due to tissue cuts) during minimal-invasive operations with imbibition of the tissue with hemoglobin leads to an immoderate reddish coloring of the image. Color normalization provides the possibility to transform each color pixel so that different tissue types can be separated more clearly. The correction by normalization should lead to as lifelike an image as possible. The normalization is realized by an affine transformation of the color space [3]. The color covariance matrix $\boldsymbol{C}$ of the original image $[\boldsymbol{f_{ij}}]_{1\le i\le N, 1\le j\le M}$ is calculated first:

$$\boldsymbol{C} = E\left[(\boldsymbol{f_{ij}} - \boldsymbol{m}) \cdot (\boldsymbol{f_{ij}} - \boldsymbol{m})^T\right]$$

where $E[\cdot]$ is the expectation value and $\boldsymbol{m} = E[\boldsymbol{f_{ij}}]$. Then the eigenvalues and eigenvectors of the 3×3 matrix $\boldsymbol{C}$ are determined. The direction of the main color axis is the eigenvector corresponding to the largest eigenvalue. A rotation of the color space, i. e. a multiplication of each pixel by a 3×3 rotation matrix, is performed so that the main color axis is projected onto the main diagonal of the *RGB* color space. The rotation of the other two axis should be as small as possible. For further details see [3].

2.4 Undistortion

We use the camera model proposed by Tsai [9]. Additionally, we assume a rectangular camera sensor coordinate system. The correction terms of the undistortion process are composed additively from a radial and a tangential component [2]. With these preconditions the intrinsic camera parameters and the correction terms can be determined by calibrating the endoscope using a calibration pattern.

The undistorted image point $(X_\mathrm{u}\ Y_\mathrm{u})^T$ is obtained by first calculating the distorted sensor coordinates $(X_\mathrm{s}\ Y_\mathrm{s})^T$ from the distorted image point $(X_\mathrm{d}\ Y_\mathrm{d})^T$, undistorting $(X_\mathrm{s}\ Y_\mathrm{s})^T$ and then transforming the result $(X_\mathrm{us}\ Y_\mathrm{us})^T$ to the corresponding image point $(X_\mathrm{u}\ Y_\mathrm{u})^T$:

$$(X_\mathrm{d}\ Y_\mathrm{d})^T \overset{(1)}{\Longrightarrow} (X_\mathrm{ds}\ Y_\mathrm{ds})^T \overset{(2)}{\Longrightarrow} (X_\mathrm{us}\ Y_\mathrm{us})^T \overset{(3)}{\Longrightarrow} (X_\mathrm{u}\ Y_\mathrm{u})^T$$

Initially we assumed that one radial correction term would be sufficient [2] but it showed that the second one is also large enough to influence the undistortion process. Using the optimized image processing library OpenCV (based on IPL), color images (PAL resolution, i. e. size 768×576) can be undistorted in real-time.

2.5 Evaluation

For the evaluation of the methods we use a program which allows to define a set of criteria (with range $-c$ to $+c$). The physician evaluates a number of image pairs (original and processed image). The pairs are arranged in a double blind setup so that neither the physician nor the tutor knows which is the original image. Experienced as well as unexperienced physicians (concerning minimal-invasive operations) do the evaluation.

The criteria we used were: better/worse, sharpness, distortion and color impression. The ranges were -2 to 2 except for better/worse with a range of -1 to 1. Negative values mean the original image is better, positive values mean the processed image is better, the value 0 means no observable difference. For each criterion the mean value $\overline{x}$ and standard deviation σ over all evaluated image pairs are calculated. To prove that the applied method leads to an enhancement of the image, the mean values should be larger than zero (the larger the better).

3 Experiments and Results

Several endoscopic image sequences were recorded during laparoscopic cholecystectomies. They were used as testing material for the image enhancement methods. The images of 8 prominent sequences were used for the evaluation. Altogether 120 image pairs were evaluated by 14 physicians. For each of the evaluated methods (temporal color median filtering with sizes 3 and 5, color normalization and undistortion) 30 images were evaluated. Example image pairs are shown in Figure 3. Table 1 summarizes the results of the evaluation (positive mean values indicate that the processed images were the better ones with respect to the criteria). The large standard deviations (compared to the difference of the mean values from zero) show that the evaluations of the surgeons were not uniform.

For color normalization all mean values were positive but interestingly the value for color impression was the smallest one (we expected this value to be larger than the other image quality criteria). The results for undistortion were as expected: the mean values for better/worse and distortion were 0.43 and 0.52, the other two values were close to zero.

For temporal filtering with size 3, the mean values of all criteria were close to zero which means the physicians did not see any difference between the original and the

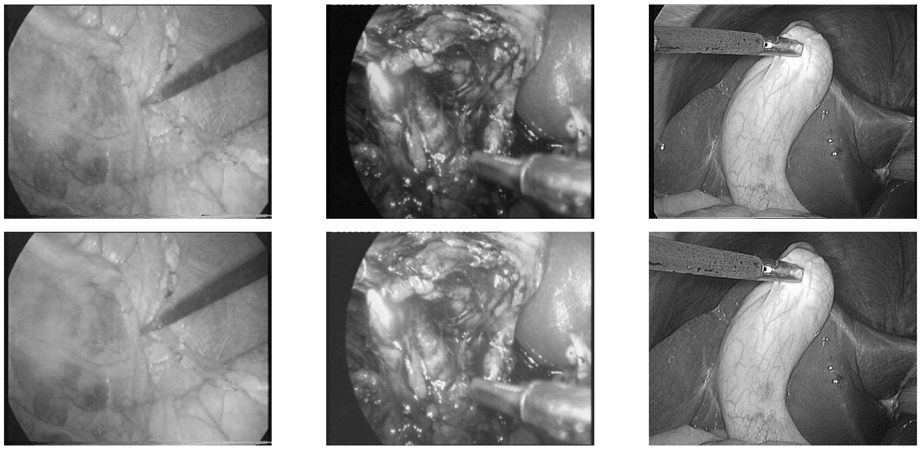

Figure 3. Example images showing the applied image enhancement methods. The original images are located in the top row, the processed ones in the bottom row. The methods are from left to right: temporal filtering (size 3), color normalization and undistortion.

filtered images. When the size of the temporal filter was increased to 5, the original images were evaluated as the better ones (mean values of better/worse and sharpness < -0.2). The reduction of the sharpness of the image is due to the fact that a hand-held endoscope will usually not remain exactly steady during the number of frames contributing to the temporal filtering (especially edges are blurred in this case). We found out that it is very hard to observe the reduction of small flying particles by comparing image pairs whereas the reduction can be seen easily by comparing image sequences. Therefore an evaluation of temporal filtered sequences was done by the 14 surgeons. Each physician had to compare time filtered sequences with the original sequence and decide which sequence was the better one. Only in 4 of 28 cases the original sequence was chosen as the better one, 8 times the processed sequence with time filter size 3 and 16 times the processed sequences with time filter with filter size 5 was evaluated to be the better one (nobody decided that two sequence pairs looked the same). These results lead to the assumption that regarding image sequences the reduction of small flying particles is more important to the surgeon than maintaining the sharpness.

We also separated the evaluation results into two groups: experienced and unexperienced physicians (in the field of minimal-invasive endoscopic operations). Undistortion and temporal filtering results are the same in both groups. The only difference occurred at color normalization. The results are shown in Table 2. The unexperienced group prefers the color normalized images much more than the experienced group. This may be due to the fact that they were not already used to (or confident with) the colors of a ’normal’ endoscopic image.

Table 3 summarizes the processing time for each image enhancement method. As can be seen, temporal filtering and undistortion can be applied in real-time while the usage of color rotation currently results in a lower frame rate.

Method	Criterion x	$\overline{x}$	σ	# positive	# negative	# zero
Color normalization	Better/worse	0,28	0,87	235	118	67
	Sharpness	0,17	0,85	154	98	189
	Distortion	0,08	0,60	76	45	299
	Color impression	0,02	1,01	182	192	46
Undistortion	Better/worse	0,43	0,71	234	53	133
	Sharpness	-0,06	0,52	42	69	309
	Distortion	0,52	0,82	223	46	151
	Color impression	0,02	0,25	8	15	397
Temp. filtering size 3	Better/worse	-0,07	0,65	75	104	241
	Sharpness	-0,08	0,68	63	94	263
	Distortion	-0,04	0,39	22	39	359
	Color impression	-0,03	0,32	14	28	378
Temp. filtering size 5	Better/worse	-0,21	0,71	72	158	190
	Sharpness	-0,25	0,78	63	152	205
	Distortion	-0,06	0,44	28	50	342
	Color impression	-0,04	0,29	8	25	387

Table 1. Evaluation of image pairs: mean values $\overline{x}$, standard deviations σ and absolute numbers of 14 physicians and 30 images for each method, i. e. 420 evaluations per method, are shown. The last three rows contain the number of positive values (processed image better), the number of negative values (original image better) and the number of zero values (images equal).

Color normalization	Better/worse	Sharpness	Distortion	Color impression
Experienced	$0,16 \pm 0.87$	0.06 ± 0.74	0.01 ± 0.39	-0.24 ± 0.97
Unexperienced	0.40 ± 0.87	0.28 ± 0.93	0.15 ± 0.75	0.28 ± 1.13

Table 2. Evaluation of color normalization, split into two groups: experienced and unexperienced physicians. Mean values $\overline{x} \pm$ standard deviations σ are shown. Each group contains 7 physicians, 30 images were evaluated for each criterion. Positive values mean the color normalized image was better, negative values mean the original image was better.

The whole system was used during a laparoscopic cholecystectomy (in accordance with the patient). The operator told his assistant which image enhancement method (or a combination of several) should be used. A detailed evaluation of the system during real operations is part of future work.

4 Conclusion

With the described system for endoscopic image enhancement it is possible to reduce image distortions by computer vision methods: temporal color median filtering is used to eliminate small flying particles, color normalization corrects color errors and after calibrating the camera undistortion eliminates lense distortion effects. Undistortion and temporal filtering are already provided in real-time. The implementation of the color normalization algorithm should be optimized by a factor of 4. Discussions with the

Method	Time filter size 3	Time filter size 5	Color normalization	Undistortion
Time (msec)	15	23	165	19

Table 3. Processing times for the image enhancement methods. A computer with Pentium IV processor with 1.9 GHz was used. All time values are given in milliseconds for images with PAL resolution (i. e. size 768×576).

participating surgeons show that it is probably better to use color normalization only in parts of the image (e. g., the periphery) which will also decrease the required processing time.

The evaluation of the three image enhancement methods showed that the enhanced images (or image sequences in the case of temporal filtering) were preferred by the surgeons. The next step will be an extensive evaluation of the system during real operations.

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