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Thomas Stehle and Alexander Behrens and Til Aach
Institute of Imaging and Computer Vision
RWTH Aachen University, 52056 Aachen, Germany
tel: +49 241 80 27860, fax: +49 241 80 22200
web: www.lfb.rwth-aachen.de

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Visual Enhancement of Fascial Tissue in Endoscopy

Thomas Stehle\textsuperscript{a}, Alexander Behrens\textsuperscript{a}, Matthias Bolz\textsuperscript{b}, and Til Aach\textsuperscript{a}

\textsuperscript{a}Institute of Imaging and Computer Vision, RWTH Aachen University, D-52056 Aachen, Germany

\textsuperscript{b}Olympus Winter & Ibe GmbH, Kuehnstr. 61, D-22045 Hamburg, Germany

ABSTRACT

A colon resection, necessary in case of colon cancer, can be performed minimally invasively by laparoscopy. Before the affected part of the colon can be removed, however, the colon must be mobilized. A good technique for mobilizing the colon is to use Gerota's fascia as a guiding structure, i.e. to dissect along this fascia, without harming it. The challenge of this technique is that Gerota's fascia is usually difficult to distinguish from other tissue.

In this paper, we present an approach to enhance the visual contrast between fatty tissue covered by Gerota's fascia and uncovered fatty tissue, and the contrast of both structures to the remaining soft tissue in real time (50 fields per second). As fasciae are whitish transparent tissues, they cannot be identified by means of their color itself. Instead, we found that their most prominent feature to distinguish is the color saturation. To enhance their visible contrast, we applied a non-linear transformation to the saturation.

An off-line evaluation was carried out consulting two specialists in laparoscopic colon resection. We presented them four scenes from two different interventions in which our enhancement was applied together with the original scenes. These scenes did not only contain situations where Gerota's fascia had to be found, but also situations where aerosol from ultrasonically activated scissors inhibited the clear vision, or situations where critical structures such as the ureter or nerves had to be identified under fascial tissue. The surgeons stated that our algorithm clearly offered an information gain in all of the presented scenes, and that it did not impair the clear vision in case of aerosol or the visibility of critical structures. So the colon mobilization could be carried out easier, faster, and safer.

In the subsequent clinical on-line evaluation, the specialists confirmed the positive effect of the proposed algorithm on the visibility of Gerota's fascia.

Keywords: Endoscopic Procedures, Image-Guided Therapy, Intraoperative Imaging, Visualization

1. INTRODUCTION

Cancer of the colon is the fourth most common type of cancer and the second leading cause of cancer death in the USA. The greatest risk factors are age, and personal and familiar history of cancer.\textsuperscript{1} But also other factors like a chronic inflammatory bowel disease,\textsuperscript{2} smoking, physical inactivity, alcohol, and diabetes\textsuperscript{3} increase the risk of developing colorectal cancer. More than 135,000 new cases are diagnosed and over 56,000 people die from colorectal cancer each year in the United States.

Endoscopy of the colon (colonoscopy) is a widely used technique in preventive medical check-up and therapy of colorectal cancer. Often, suspect polyps can be visually classified as being benign or malignant using features like texture with chromo endoscopy\textsuperscript{4} or vascularization with narrow band imaging (NBI).\textsuperscript{5} Benign polyps can be removed directly during the colonoscopy with endoscopic means (polypectomy).\textsuperscript{6} This is not possible in case of malignant tumors because the risk of spreading tumor cells is too high. Therefore, in case of cancer, a part of the colon must be removed.

Further author information: (Send correspondence to Thomas Stehle)

Thomas Stehle: E-mail: thomas.stehle@lfb.rwth-aachen.de, Telephone: +49 (0)241 8027862
Alexander Behrens: E-mail: alexander.behrens@lfb.rwth-aachen.de, Telephone: +49 (0)241 8027862
Matthias Bolz: E-mail: matthias.bolz@olympus-owi.com, Telephone: +49 (0)40 669662212
Til Aach: E-mail: til.aach@lfb.rwth-aachen.de, Telephone: +49 (0)241 8027860
This operation can be performed minimally invasively by laparoscopy. Before the affected part of the colon can be removed, however, the colon must be mobilized, i.e. it must be detached from its natural position on the retroperitoneum. A good technique for mobilizing the colon is to use Gerota's fascia as a guiding structure, i.e. to dissect along this fascia, without harming it. In the neighborhood of Gerota's fascia are no nerves, blood vessels or other structures that could be damaged inadvertently. Therefore, dissecting along this structure is possible in a quick and safe way.

The challenge of this technique is that Gerota's fascia is usually difficult to distinguish visually from other tissue. In open surgery, the surgeon can identify Gerota's fascia with his fingers palpating the tissue. During laparoscopic surgery, the surgeon does not have this possibility of tactile feedback, therefore a better visual distinction of fascial tissue is desirable.

In section 2, we present our approach to enhance the visual contrast between fatty tissue covered by Gerota's fascia, uncovered fatty tissue, and the remaining soft tissue. In section 3, we demonstrate the effect of our algorithm using sample endoscopic images. Furthermore, we will give a qualitative evaluation of the algorithm based on the statements of two experts in colon resection. In section 4, we will give a summary and draw conclusions.

2. ENHANCEMENT OF FASCIAL TISSUE

Fascial tissues can be characterized by their whitish transparent appearance. Because of their transparency, the color of the underlying tissue can be observed. The whitish layer does not change the color itself but it reduces color saturation of the underlying tissue. To reduce the color saturation means to reduce the color's purity or, equivalently, to increase the color's white fraction. The basic idea to enhance the visibility of these structures is to apply a non-linear saturation-dependent transformation to the color saturation.

For this purpose, the image is first transformed into a color space which allows manipulation of color saturation without changing the color itself. Then, the non-linear transformation is applied to the saturation. Finally, for display, the manipulated image is transformed back to RGB color space. Fig. 2 gives an overview of the algorithm.

![Enhancement of fascial tissue overview.](image)

2.1 Color Space Transformation

A suitable color space is the LUV color space as it separates the luminance information from the chrominance information. With an additional computation of the saturation, it allows a manipulation of color saturation without changing the color itself. The derivation of this color space is described in the following.

One feature of the LUV color space is that it is a decorrelated color space, i.e. a color space in which the covariance matrix

\[
C = \begin{pmatrix}
\sigma_{RR} & \sigma_{RG} & \sigma_{RB} \\
\sigma_{GR} & \sigma_{GG} & \sigma_{GB} \\
\sigma_{BR} & \sigma_{BG} & \sigma_{BB}
\end{pmatrix}
\]

\[1\]

*We implemented the algorithm using both the HSV and LUV color spaces. Because of the surgeon’s feedback, we chose the LUV color space for further usage.
becomes a diagonal matrix under the condition that all variances are equal. In Eq. (1) \( \sigma_{jk}, j, k \in \{ R, G, B \} \) is the covariance in case of \( j \neq k \) and the variance if \( j = k \). With the assumption that all color channels have equal variances, Eq. (1) simplifies to:

\[
C = \sigma^2 \begin{pmatrix}
1 & \text{cov} & \text{cov} \\
\text{cov} & 1 & \text{cov} \\
\text{cov} & \text{cov} & 1
\end{pmatrix}
\]  

(2)

where \( \sigma^2 \) is the common variance and \( \text{cov} \) is the common covariance. The zero crossings of the characteristic polynomial give the eigenvalues \( \lambda_1 = 1 + 2 \cdot \text{cov} \) \( \lambda_{2,3} = 1 - \text{cov} \).

The eigenvectors corresponding to \( \lambda_2 \) and \( \lambda_3 \) are not unique. A possible normalized choice is:

\[
\vec{m}_1 = \begin{pmatrix} \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \end{pmatrix}, \quad \vec{m}_2 = \begin{pmatrix} \frac{2}{\sqrt{6}} \\ -\frac{1}{\sqrt{6}} \\ -\frac{1}{\sqrt{6}} \end{pmatrix}, \quad \vec{m}_3 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{pmatrix}
\]

(4)

which are the base vectors of the LUV color space. Now, \( (R, G, B)^T \) vectors can be projected onto these base vectors with:

\[
\begin{pmatrix} L \\ U \\ V \end{pmatrix} = \begin{pmatrix} R \\ G \\ B \end{pmatrix} \begin{pmatrix} \vec{m}_1 & \vec{m}_2 & \vec{m}_3 \end{pmatrix}
\]

(5)

where \( L \) provides the luminance information, and \( U \) and \( V \) provide chrominance information. To enable a faster computation of the saturation, we choose a different scaling for \( \vec{m}_1 \):

\[
\vec{m}_1 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}
\]

(6)

such that \( L \) becomes the sum of \( R, G, \) and \( B \). Note that the new base vector \( \vec{m}_1 \) has not length 1, i.e. the base vectors are not orthonormal but only orthogonal.

The saturation \( S \) is defined as the normalized Euclidean distance of a point in the color space to the luminance axis. As \( \vec{m}_2 \) and \( \vec{m}_3 \) are orthogonal to the luminance axis \( \vec{m}_1 \), the saturation can be expressed as the relative length of the vector spanned by \( U \cdot \vec{m}_2 \) and \( V \cdot \vec{m}_3 \):

\[
S = \frac{||U \cdot \vec{m}_2 + V \cdot \vec{m}_3||}{||U_{\text{max}} \cdot \vec{m}_2 + V_{\text{max}} \cdot \vec{m}_3||}
\]

(7)

where \( U_{\text{max}} \) and \( V_{\text{max}} \) are the maximal coefficients for which the vector

\[
\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M^{-1} \begin{pmatrix} L \\ U_{\text{max}} \\ V_{\text{max}} \end{pmatrix}
\]

(8)

does not leave the RGB cube \( (R, G, B \in [0, 1]) \) which was normalized according \( L \). This can be written compactly as:

\[
S = 1 - 3 \text{min}\{r, g, b\}
\]

with

\[
r = \frac{R}{R+G+B} = \frac{R}{L}
\]

\[
g = \frac{G}{R+G+B} = \frac{G}{L}
\]

\[
b = \frac{B}{R+G+B} = \frac{B}{L}
\]

(10)

so the \( L \) component could be efficiently reused for the computation of the saturation.
2.2 Non-Linear Transformation of Saturation

An example of a non-linear saturation transformation is depicted in Fig. 2(a). This transformation is designed to reduce the dynamic range of pixels in a saturation interval where fasciae are not expected (the part where its slope is lower than 1). This is called saturation compression. The dynamic range of pixels is increased in saturation intervals which are expected to contain information about fasciae (the part where its slope is greater than 1). This leads to a better distinguishability between different types or layers of fasciae. Additionally, the overall contrast to the remaining soft tissue is enhanced as the saturation of the fasciae is reduced whereas uncovered soft tissue remains saturated (upper part where the slope of the transformation function is equal to 1).

The proposed function is composed of a linear function and an exponential function. The composed function is implemented as a look up table (LUT)

\[
LUT(S) = \min\left( S, S_0 + w \cdot \left( \frac{S - S_0}{w} \right)^d \right)
\]  

(11)

where \( S_0, w, \) and \( d \) define the position, the width, and the depth of the non-linear part of the function, respectively.

At this point, we can apply the non-linear transformation to the saturation channel. As the chrominance components \( U \) and \( V \) must be rescaled, we define another LUT which relates the input saturation with the multiplicative factor which rescales \( U \) and \( V \) accordingly. The resulting LUT is

\[
LUT_{\text{conversion}}(S) = \frac{LUT(S)}{S}
\]

(12)

which is depicted in Fig. 2(b). The chrominance components \( U \) and \( V \) are multiplied with the output of this look up table

\[
U' = LUT_{\text{conversion}}(S) \cdot U
\]

\[
V' = LUT_{\text{conversion}}(S) \cdot V
\]

(13)

yielding the chrominance values with reduced saturation \( U' \) and \( V' \).

Subsequently, the image is transformed back to the RGB color space. This transformation is simply the multiplication with the inverse base matrix \( M^{-1} \).

\[
\begin{pmatrix}
R' \\
G' \\
B'
\end{pmatrix} = M^{-1} \begin{pmatrix}
L \\
U' \\
V'
\end{pmatrix}
\]

(14)
2.3 Real-Time Implementation

For clinical evaluation, we developed RealTimeFrame, a CPU efficient framework which allows to process video streams in real-time. RealTimeFrame consists of three independent threads. Fig. 2.3 shows the design of RealTimeFrame.

![Figure 3. Design of RealTimeFrame.]

Thread 1 is responsible for the image acquisition. Possible image sources are frame grabber cards, video files, or sequences of single images. The support of a frame grabber card is mandatory for clinical evaluation. Video files or image sequences are beneficial for algorithm development on systems without frame grabber card. The system can be extended flexibly to support new video sources as the video sources are realized as dynamic linked libraries (DLLs) which can easily be implemented and deployed. Therefore, it is not necessary to recompile the whole framework if another video source is added.

The acquired image is subsequently passed to thread 2 which performs the actual image processing. The image runs through a pipeline which may consist of an arbitrary number of single processes. This allows the flexible combination of different image processing algorithms and the reuse of available algorithms. Again, all processes are implemented as DLLs, which enables a fast and convenient implementation of image processing algorithms. In case of the enhancement of fascial tissue, we implemented the complete algorithm in one single DLL.

Finally, the image is passed to thread 3 which shows the processed image on the computer monitor. We use Microsoft’s DirectX to copy the image directly to the graphic card’s back buffer so that we can take advantage of the full hardware acceleration. Optionally, we interpolate the image to double height if the frame grabber acquires fields instead of frames, which is mandatory in low latency real-time applications.

Our real-time capable demonstrator platform consists of high-performance standard PC components: 2× Intel Xeon 5140 dual core processors with 2.33 GHz, a GeForce 7950 GX2 video adapter, and 2 GB RAM. As storage we attached two SATA-2 hard discs with a capacity of 500 GB each. In our development system, we used both discs independently so we could read a video sequence from one disc and write the processing results to the other hard disc. This minimizes performance problems which would occur, if both videos were read and written to the same disc. In our clinical demonstrator, we organized the hard discs as redundant array of independent drives - striped set without parity - (RAID 0) which provides enough space to capture uncompressed video data from clinical interventions. In this case, the setup with one single hard disc does not cause any performance problems as the input images are acquired from a frame grabber and not read from the hard disc.

3. RESULTS AND EVALUATION

Figs. 4 and 5 show scenes from a laparoscopic colon mobilization. On the left hand sides information from the the original images are shown whereas on the right hand sides the same information after application of the proposed algorithm are presented. The first row shows the images themselves, the second row shows the saturation images, and the third row shows the saturation histograms.

The fascial structures are clearly better visible in the processed image due to their reduced saturation. Fatty and other soft tissues, however, remain well saturated, preserving a natural appearance. In the saturation images, it can be seen how saturation of weakly saturated pixels is further reduced. The effect is also illustrated in the saturation histograms where saturation of pixels in the saturation interval between [0.1, 0.45] are shifted to the left (see third row of Figs. 4 and 5).
Figure 4. Laparoscopic colon mobilization.
Figure 5. Laparoscopic colon mobilization.
An off-line evaluation was carried out consulting two specialists in laparoscopic colon resection. We presented them four scenes, each about 10 seconds long, from two different patients in which our enhancement was applied. These scenes contained situations where Gerota's fascia was to be found. The experts stated that our algorithm clearly offered an information gain so that a colon mobilization could be carried out easier, faster, and safer.

We further investigated if problems could arise from our algorithm in other critical scenes. One of the main issues was the application of ultrasonically activated scissors which generate aerosol. This aerosol is also of low color saturation and will therefore be desaturated by the algorithm. The result in this case was that the saturation was indeed reduced. However, as most structure information is carried by the luminance component, image details remained clearly visible. Another question was the visibility of the ureters under a layer of fascia and fatty tissue. As the ureter itself is a weakly saturated structure, its visibility was enhanced by the algorithm.

During this evaluation, the non-linear saturation transformation was parametrized according to the feedback from the surgeons. A third movie sequence from a different patient was used to validate this parametrization and the portability of the non-linear transformation to other sequences. This sequence (about 1.5 h) was completely transformed using our algorithm. Again, the experts stated a clear information gain.

During a clinical on-line demonstration, our system was installed next to the conventional laparoscopy system so that the physician could directly compare the output of both systems. He confirmed the information gain and that Gerota's fascia can be better distinguished from other tissues. The ureter's visibility, however, was first reduced by our processing. This could be explained by the way the non-linear transform was parametrized. We defined the parameters according to the data which was available for the off-line evaluation. As these data came from a different laparoscopy system, the color characteristic of the input data was different from the data we expected. After the parameters were adapted to the new system, the ureter's visibility was satisfying again.

4. SUMMARY AND CONCLUSIONS

To counteract the problem of weakly visible fasciae, we analyzed the appearance of fascial tissues in laparoscopic video sequences. We found their color saturation as most prominent feature. With this insight, we developed an algorithm which is capable of enhancing their visibility. The algorithm consisted of three steps: the transformation to a color space which allows the independent manipulation of the color saturation, the non-linear rescaling of the color saturation, and the transfer back to RGB color space.

For clinical evaluation, we developed RealTimeFrame - a CPU efficient, modular, multi-threaded software framework which allows to rapidly implement and deploy video processing algorithms. The proposed algorithm was implemented as plug-in for this framework.

We carried out a clinical off-line and on-line evaluation. Two experts in laparoscopic colon resection confirmed an information gain for the colon mobilization. Critical structures like the ureters remained clearly visible during the off-line and on-line evaluations.

Therefore, we think that the proposed algorithm has the potential to improve laparoscopic interventions and make them easier, faster, and safer.

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