HIGH PRECISION OPERATOR FOR SURGERY VISION SYSTEMS

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ABSTRACT

In laparoscopic surgery systems, the camera has to center the exact region of interest in which the operation is being carried out. Since the objective is in constant movement there is the need of a vision system that implements a tracking of this objective by the camera. In order to achieve a reliable tracking, targets must be tracked by the vision system using as input some singular points which determine the region of interest. Due to the nature of the laparoscopic imaging environment, singular points will be obtained from the intrusive surgery tools which present a more structured aspect than the organic environment.
In this paper we present a new method to determine with high precision the orientation and position of the surgical tools. A new operator used in this method estimates the orientation of an object in a scene with a higher precision than the existing ones. This permits to have a more accurate tracking system which makes the laparoscopic system robust and reliable.

1. INTRODUCTION

Laparoscopic surgery requires the introduction into the patient abdomen of several instruments, the surgical tools, as well as the TV camera microoptics, the laparoscope, to provide the surgeon with the visualization of the intraabdominal working space (Ornstein, 1994). A good centering of the camera field of view onto the interest zone is essential to operate efficiently. In order to adequately track the interest zone, the movement of the camera probe can be done by the surgeon himself or by an assistant. In the latter case, a certain experience and a surgeon-assistant mutual understanding is necessary, but usually difficult to obtain. In the former case, the difficulty arises from the surgeon's need to move the camera support while working. Consequently, some efforts have been done towards the automation of these movements under the surgeon supervision. In (Casals, 1995) is described a robotic system that automatically guides, by means of computer vision, the laparoscope during a surgical procedure.

In this paper we describe a new operator that determines the orientation of an edge with a higher precision than existing ones. This operator is used in a vision system, to locate the surgical tools, and to center the field of view onto the interest area.

2. PRELIMINARIES

Edge detection is an important first stage in the determination of the orientation of objects in images. Much progress has been made in developing techniques for edge detection (Davis, 1975), (Levialdi, 1981), (Kunt, 1982). Some sophisticated operators have been developed in this way, like the one developed by Canny (Canny, 1986) based on the first derivative of the image function, the one developed by Marr and Hildreth (Marr, 1980) based on the second derivative, or the one initially developed by Hueckel (Hueckel, 1973) based on sets of Fourier-like orthonormal basis functions. Though theoretical understanding of edge detection has advanced considerably by these sophisticated operators, practical operators based on them will inevitably be slow and hardware-intensive. In surgical applications and other practical systems, there is a need for fast edge detection operators that are capable of running rapidly on inexpensive hardware.

This paper is particularly concerned with 'fast' edge detection operators. Available edge detection schemes include the well-known template matching approach (Robinson, 1977) and the differential gradient approach (Duda, 1973). Each of these can be used to estimate the magnitude and orientation of edges of particular types. It is the purpose of this paper to develop a new fast edge detection operator that can be optimized and adapted to laparoscopic surgery applications. Emphasis will be placed on improving the accuracy with which this fast detector operator, estimates edge orientation. This emphasis is important, since local edge orientation data is being used to determine the orientation of the surgical tools.

Further discussion of the edge detection problem involves consideration of the accuracy with which edge orientation can be estimated when the local intensity pattern cannot be assumed to be planar. For this purpose, various edge models have been suggested (Davis, 1975). The main relevant edge models include the so-called 'step', 'planar', 'roof' and 'line' edges. In this paper discussion will be restricted only to 'step' edges, since they constitute a 'worst case' situation, as distinct as possible from the planar edge approximation.

3. FAST OPERATORS FOR DETERMINING EDGE ORIENTATION

As remarked in last section, fast edge detection operators fall into two classes: differential operators and template matching operators.

Differential operators include the Roberts 2x2 pixel operator (Roberts, 1965), and the Sobel (Duda, 1973) and Prewitt (Prewitt, 1970) 3x3 pixel operators. These operators have been analyzed in (Davies, 1984) and will not be discussed in detail here. Many image processing applications require a knowledge only of the orientation of an edge, and dispense with magnitude orientation. This orientation is determined using the formula:

$$\alpha = arctan\frac{g_y}{g_x}$$

where g_y and g_x are the y and x components of slope estimated using a suitable pair of gradient masks.

There have been a number of analyses of the angular dependencies of edge detection operators for a step edge approximation (O'Gorman, 1978), (Abdou, 1979). In these papers, it is found a variation of angular error varying from an edge orientation of 0° to 45°. Prewitt leads to a maximum angular error of 7.38° and a mean angular error of 5.18°. Using Sobel, the maximum angular error is 1.36°, and the mean angular error is 0.73°. In (Davies, 1984), it is considered the angular variation resulting from a step edge observed within a circular neighbourhood instead of a square neighbourhood. Using Davies circular operator, the mean angular error is 0.53°. All these mentioned errors are dependent of the edge orientation, so, we can conclude that gradient operators have a lack of isotropy.

Existing template mask operators will be reviewed briefly. The most popular of these are the Prewitt (Prewitt, 1970), Kirsch (Kirsch, 1971) and Robinson (Robinson, 1977) 3x3 pixel operators, and the Nevatia-Babu (Nevatia, 1980) 5x5 pixel operators. The template mask methods estimate edge magnitude by determining which of a given set of masks gives the largest response of the convolution product for the neighbourhood:

$$g = max(g_i : i = 1..M);$$

Being M de number of masks in the set and g_i the result of the convolution product using the i-th mask. Edge orientation is estimated as that of the mask giving the largest response.

Clearly, methods based on template masks such as these will give rise to large angular errors. It is due to the fact that a discrete set of template masks is used, and so, all edge orientations present in an image can only be estimated by the orientations represented by a mask.

4. ADAPTIVE TEMPLATE MASKS

High accuracy in the estimation of edge orientation is often vital. Errors derived from having a discrete set of masks are solved in this section by designing an operator with a continuous spectrum of masks.

This operator is modeled like a plane with a given orientation α (being α=0° the north orientation). It is defined in a circular neighbourhood, with a radius R, like the one defined in (Davies, 1984). Figure 1 shows the shape of this plane.

$$Op(x,y) = x\cos\alpha - y\sin\alpha \qquad ; x^2 + y^2 \leq R^2$$

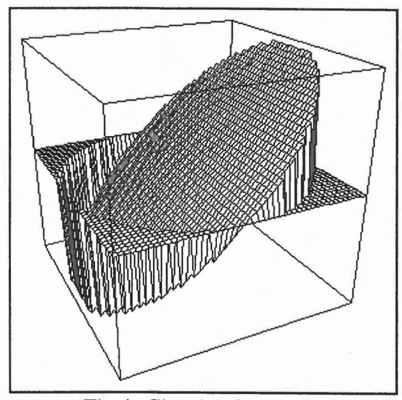

Fig.1. Circular Operator.

Our operator is a continuous set of 6x6 discrete masks. Each value Op[i][j] of the mask is obtained as the volume of the solid delimited by the planes y=i, y=i+1, x=j, x=j+1, and Op(x,y):

$$Op[i][j] = \int_{y=i}^{y=i+1}\int_{x=j}^{x=j+1} Op(x,y)dxdy = \begin{bmatrix}
\begin{matrix}-0.06\cos\alpha\\ -0.06\sin\alpha\end{matrix} & \begin{matrix}-0.82\cos\alpha\\ -1.33\sin\alpha\end{matrix} & \begin{matrix}-0.48\cos\alpha\\ -2.33\sin\alpha\end{matrix} & \begin{matrix}0.48\cos\alpha\\ -2.33\sin\alpha\end{matrix} & \begin{matrix}0.82\cos\alpha\\ -1.33\sin\alpha\end{matrix} & \begin{matrix}0.06\cos\alpha\\ -0.06\sin\alpha\end{matrix} \\
\begin{matrix}-1.33\cos\alpha\\ -0.82\sin\alpha\end{matrix} & \begin{matrix}-1.5\cos\alpha\\ -1.5\sin\alpha\end{matrix} & \begin{matrix}-0.5\cos\alpha\\ -1.5\sin\alpha\end{matrix} & \begin{matrix}0.5\cos\alpha\\ -1.5\sin\alpha\end{matrix} & \begin{matrix}1.5\cos\alpha\\ -1.5\sin\alpha\end{matrix} & \begin{matrix}1.33\cos\alpha\\ -0.82\sin\alpha\end{matrix} \\
\begin{matrix}-2.33\cos\alpha\\ -0.48\sin\alpha\end{matrix} & \begin{matrix}-1.5\cos\alpha\\ -0.5\sin\alpha\end{matrix} & \begin{matrix}-0.5\cos\alpha\\ -0.5\sin\alpha\end{matrix} & \begin{matrix}0.5\cos\alpha\\ -0.5\sin\alpha\end{matrix} & \begin{matrix}1.5\cos\alpha\\ -0.5\sin\alpha\end{matrix} & \begin{matrix}2.33\cos\alpha\\ -0.48\sin\alpha\end{matrix} \\
\begin{matrix}-2.33\cos\alpha\\ +0.48\sin\alpha\end{matrix} & \begin{matrix}-1.5\cos\alpha\\ +0.5\sin\alpha\end{matrix} & \begin{matrix}-0.5\cos\alpha\\ +0.5\sin\alpha\end{matrix} & \begin{matrix}0.5\cos\alpha\\ +0.5\sin\alpha\end{matrix} & \begin{matrix}1.5\cos\alpha\\ +0.5\sin\alpha\end{matrix} & \begin{matrix}2.33\cos\alpha\\ +0.48\sin\alpha\end{matrix} \\
\begin{matrix}-1.33\cos\alpha\\ +0.82\sin\alpha\end{matrix} & \begin{matrix}-1.5\cos\alpha\\ +1.5\sin\alpha\end{matrix} & \begin{matrix}-0.5\cos\alpha\\ +1.5\sin\alpha\end{matrix} & \begin{matrix}0.5\cos\alpha\\ +1.5\sin\alpha\end{matrix} & \begin{matrix}1.5\cos\alpha\\ +1.5\sin\alpha\end{matrix} & \begin{matrix}1.33\cos\alpha\\ +0.82\sin\alpha\end{matrix} \\
\begin{matrix}-0.06\cos\alpha\\ +0.06\sin\alpha\end{matrix} & \begin{matrix}-0.82\cos\alpha\\ +1.33\sin\alpha\end{matrix} & \begin{matrix}-0.48\cos\alpha\\ +2.33\sin\alpha\end{matrix} & \begin{matrix}0.48\cos\alpha\\ +2.33\sin\alpha\end{matrix} & \begin{matrix}0.82\cos\alpha\\ +1.33\sin\alpha\end{matrix} & \begin{matrix}0.06\cos\alpha\\ +0.06\sin\alpha\end{matrix}
\end{bmatrix}$$

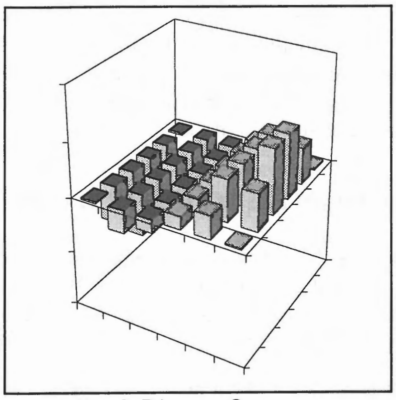

Fig.2. Discrete Operator.

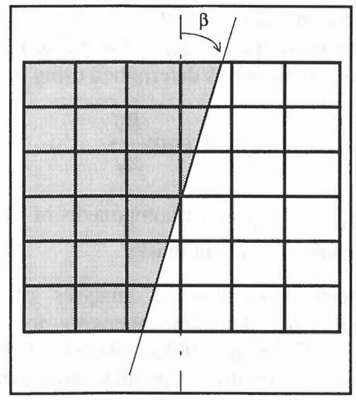

Fig.3. Step Edge.

Figure 2 shows a mask obtained in this way. A 'step' edge in a 6x6 neighbourhood with an orientation β, is presented in figure 3:

Each pixel has an exact value Im[i][j] depending on the orientation β. The values of the pixels in the image are considered within the interval [-1/2,1/2].

When the edge mentioned above is convoluted with our operator, we obtain:

$$Op[i][j] \otimes \mathrm{Im}[i][j] = \sum_{i=-3}^{i=2} \sum_{j=-3}^{j=2} Op[i][j] \cdot \mathrm{Im}[i][j] = \begin{cases} (-4.28764\,\mathrm{tg}\beta + 18)\cos\alpha + \\ +16.666667\,\mathrm{tg}\beta \sin\alpha & \text{if } 0 \le \mathrm{tg}\beta \le \frac{1}{3} \\ (-7.51112\,\mathrm{tg}\beta + 20.149 - \frac{0.358164}{\mathrm{tg}\beta})\cos\alpha + \\ +(7.666667\,\mathrm{tg}\beta + 6 - \frac{1}{\mathrm{tg}\beta})\sin\alpha & \text{if } \frac{1}{3} \le \mathrm{tg}\beta \le \frac{1}{2} \\ (-10.0785\mathrm{tg}\beta + 22.7613 - \frac{1}{\mathrm{tg}\beta})\cos\alpha + \\ +(11.6667\,\mathrm{tg}\beta + 2)\sin\alpha & \text{if } \frac{1}{2} \le \mathrm{tg}\beta \le \frac{2}{3} \\ (-3.27825\mathrm{tg}\beta + 13.6494 + \frac{2.0232}{\mathrm{tg}\beta})\cos\alpha + \\ +(0.207685\,\mathrm{tg}\beta + 17.2786 - \frac{5.09288}{\mathrm{tg}\beta})\sin\alpha & \text{if } \frac{2}{3} \le \mathrm{tg}\beta \le 1 \end{cases}$$

Figure 4 shows a 3D representation of the result of convolution using our operator, where β are the real edge orientations, and α are the orientation of the masks. Template mask operators estimate the orientation of an edge by selecting the mask that maximizes the result of the convolution product. Then, the estimated orientation, α, that maximizes the result is given by the expression:

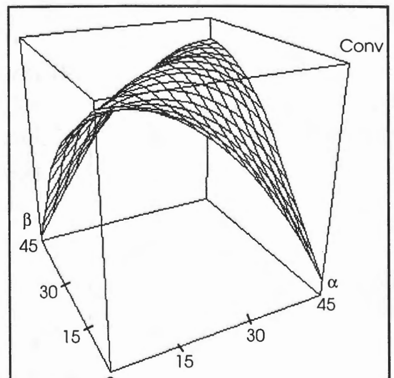

Fig.4. Result of Convolution.

$$\alpha = \begin{cases} \mathrm{arctg}\left[\dfrac{16.666667\,\mathrm{tg}\,\beta}{18-4.28764\,\mathrm{tg}\,\beta}\right] & \text{if } 0 \le \mathrm{tg}\beta \le \dfrac{1}{3} \\ \mathrm{arctg}\left[\dfrac{7.666666\,\mathrm{tg}^2\beta+6\,\mathrm{tg}\,\beta-1}{-7.51112\,\mathrm{tg}^2\beta+20.149\,\mathrm{tg}\,\beta-0.358164}\right] & \text{if } \dfrac{1}{3} \le \mathrm{tg}\beta \le \dfrac{1}{2} \\ \mathrm{arctg}\left[\dfrac{11.6667\,\mathrm{tg}^2\beta}{-10.0785\,\mathrm{tg}^2\beta+22.7613\,\mathrm{tg}\,\beta-1}\right] & \text{if } \dfrac{1}{2} \le \mathrm{tg}\beta \le \dfrac{2}{3} \\ \mathrm{arctg}\left[\dfrac{0.207685\,\mathrm{tg}^2\beta+17.2786\,\mathrm{tg}\,\beta-5.09288}{-3.27825\,\mathrm{tg}^2\beta+13.6494\,\mathrm{tg}\,\beta+2.02232}\right] & \text{if } \dfrac{2}{3} \le \mathrm{tg}\beta \le 1 \end{cases}$$

In figure 5 it is shown the response of our operator. It is shown the estimated orientation in front of the real orientation:

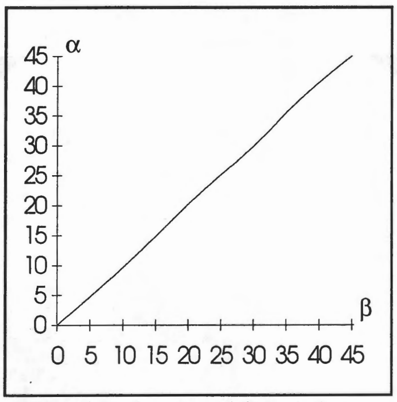

Fig.5. Estimation of Orientation.

The mean angular error using this operator is 0.24°, so, we get a higher accuracy than the one obtained using classic methods.

5. TRACKING SYSTEM

In order to center the camera field of view onto the interest area, a tracking vision system is used. The vision system detects and tracks the surgical instruments. The camera probe is held by a robot. The position errors detected by the vision system according to the operation mode desired by the surgeon, are used to control the camera movement. The control strategy to generate the robot trajectories, and the robotic handling system will not de discussed in this paper, it can be found a good solution in (Casals, 1996).

By observing laparoscopic images, it can be seen that the intrusive surgical tools, present a very structured aspect, in fact, they are the only presence which present real straight lines. Figures 6a and 6b present two examples of such images. Surgical tools are used to determine the interest area of the intervention. To identify the position and orientation of these tools, it must be detected an important presence of some concrete orientation. This goal is achieved by detecting a great amount of pixels in the image which present the same (or very approximate) orientation.

The operator presented in last section is used to determine the mentioned orientation. It presents two main advantages: first, it has been demonstrated that it has higher precision than classical ones, and second, it is more invulnerable to noise.

Laparoscopic images are noisy by nature. The operator presented in this paper is less vulnerable to noise than the classical ones. The standard deviation of the noise in the convoluted image is given by the expression:

$$\sigma_H = \frac{3}{2} \cdot \frac{\sqrt{\pi}}{T} \cdot \sigma$$

being σ the standard deviation of the noise in the original image, and T the diameter of the operator. Since the diameter of our operator has been fixed to 6, this means that the noise has been reduced by $\frac{\sqrt{\pi}}{4}$ in the final result.

Figures 6c and 6d, present the results of our method, using the described operator in this paper.

In order to achieve real time operation, once the surgical tools have been detected there is no need to work with the complete image, and only a working window is considered. There have not been also considered all possible orientations of the tools, once these have been identified. This is possible due to the fact that the movement of these tools does not present fast changes either in position or in orientation. So, in permanent operation, the amount of data to be considered has been considerably reduced an this permits to operate in real time.

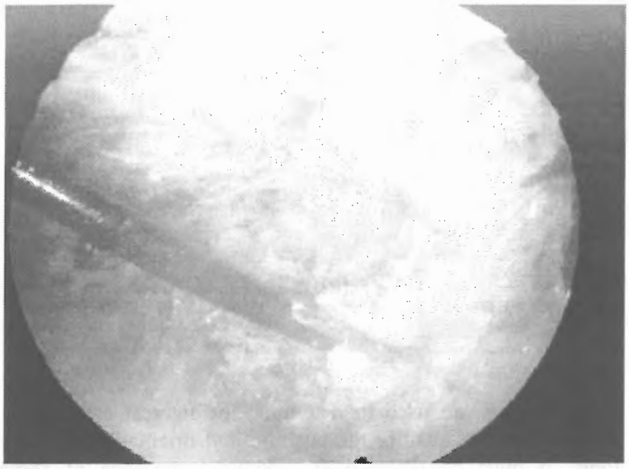

Fig.6a Surgical tool

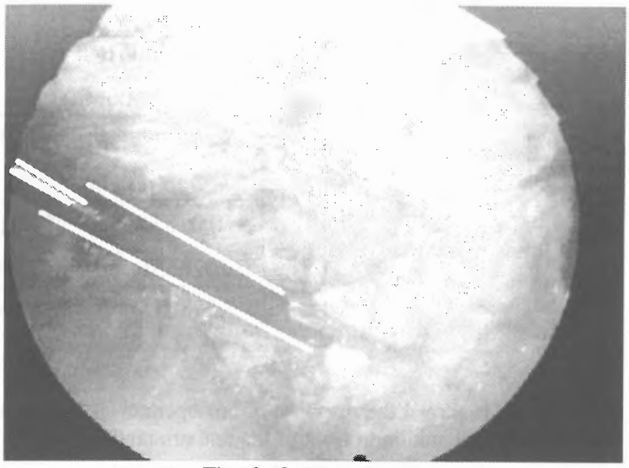

Fig. 6c Operator result

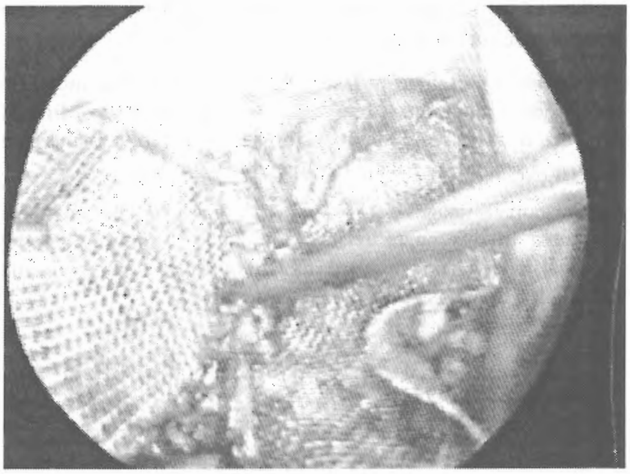

Fig.6b Surgical tool

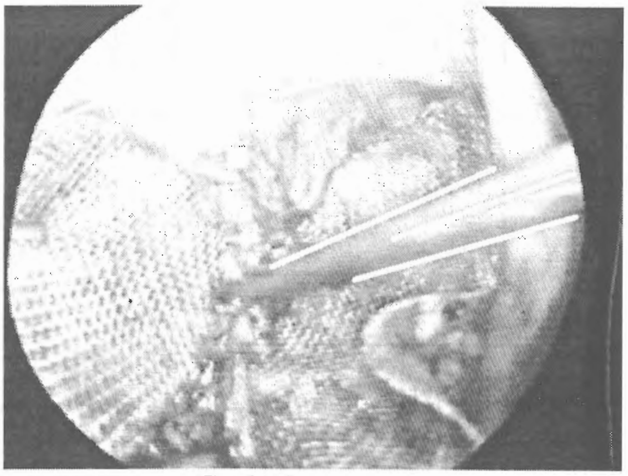

Fig. 6d. Operator result

6. CONCLUSIONS

A new operator that determines edge orientation has been presented. In order to reduce the errors obtained using classic template mask operators due to its discrete set of masks, our operator uses a continuous set of masks. Masks obtained are also circularized. The accuracy obtained with this new operator is higher than the one using classical operators. The angular resolution so obtained has been 0.25°.

These adaptive circular operators have been applied as a compass for determining the orientation of surgical tools in laparoscopic surgery. The orientation obtained is used to achieve a good centering of the camera field of view onto the interest zone. A specialized image processor has been developed in order to achieve real time operation.

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