Automatic Positioning of a Surgical Microscope

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Abstract: A procedure for interactive navigation of a fully motorized surgical microscope is presented. This procedure uses preoperative MRT- or CT-images to generate a 3D-model of the patient which then acts as the basis for navigation during surgery. The relation between tracking system, microscope and 3D-model is established using a simple calibration method based on the Horn [Ho87] algorithm. It enables positioning the microscope by defining target points either directly on the patient using an optical marker or on his 3D-model. After reaching the target position the microscope focuses automatically by calculating the focus score of the current field of view as function of the working distance. Thus, not only the surgeon will be discharged from positioning the microscope but he can also continue his work almost immediately. Manual interaction becomes unnecessary.

1 Introduction

In order to simplify orientation and diagnosis for the surgeon, special need exists for central visualization of pre- and intraoperative images in operating rooms. Because of that, the surgical microscope as the crucial assistance system in neurosurgical applications serves as starting point for new developments.

The success of microsurgical procedures depends significantly on recognizing small details (microstructures). An intense magnification is necessary in such procedures. The surgeon faces several rapidly changing situations during a surgery. First, a large field of view is used to get an overview of the surgical area. Next, a vast modification of working distance or focus position is required.

Despite its central function in neurosurgical operations, microscopes still have two main deficits: 1) Preoperative images are usually used for intraoperative orientation but not to navigate microscopes themselves. 2) Manual repositioning complicates or even prevents small and precise movements. They are very important because tissue is observed multiply enlarged. In this view even very small motions can move tissue out of focus. Weight and inertia of microscopes reinforce this problem. Moving microscopes with constant working distance around a target point situated inside the body (pivotation) is hardly practicable and
very time-consuming.

In addition to this, positioning microscopes manually interferes with the surgeon’s workflow and increases the procedure’s duration. This makes the replacement of the surgical instruments necessary every time. Manual contact is also a substantial infection risk because of increased danger of sterility loss.

In 1995, a microscope fixed to an industrial robot arm was used to specify observed tissue and to visualize it in a reconstructed 3D model of the patient’s brain [Gi95]. The robot was positioned manually by the surgeon using a force feedback sensor.

The development of the Zeiss MKM enabled motorized positioning of a microscope [Gr97]. The system consisted of a small microscope fixed to a robot arm, too. However, the advantage of exact positioning was eliminated by disadvantages regarding the system’s handling in several medical procedures [GFT99]. It was suited only for open, neurosurgical procedures but not for surgeries where the system’s position must be modified frequently. The system is not available on the market anymore.

Each repositioning of a microscope varies its field of view, so that it can loose the focus, if the working distance is not adapted. Even slight changes can cause this problem. Indeed, this can easily be corrected manually, but it complicates the handling. The surgeon’s workflow is interrupted and it removes the advantages of automatic positioning at least partially. Due to these facts, an automatic and fast focusing represents a crucial aspect of automated microscope positioning.

A variety of autofocus methods have already been mentioned in [Bo96, HK92, Ge00, SCN92, Ye93]. Usually, a focus score is calculated which is maximal for the best focused image. Unimodality, accuracy, repeatability and the range of an extremum are very important criteria for a reliable autofocus, because the calculation of focus score must be done online. Only the gradient of this focus score gives some indication how to adapt the working distance. An offline calculation, where entire values of the working distance are considered, would provide an optimal result but microscopes cannot be used while the autofocus is in process [Hi05].

In this work, the combination of automatic positioning based on preoperative images and autofocus to identify the optimal working distance as well as the handling of the system are presented. This application enables the surgeon to change the field of view fast and precisely during microsurgical procedures without being interrupted by manual interactions.

## 2 System description

A commercially available HI-R 1000 microscope (Fig. 1 left) produced by Möller-Wedel GmbH Germany is used for automatic, intraoperative visualization of the operation area. It has six degrees of freedom and is fully motorized. All four axes of the tripod are equipped with stepper engines and encoders. The two axes to roll and pitch the microscope are controlled by servomotors without external encoders. An additional not motorized joint is
placed at the end of the parallelogram-arm (axis four) which compensates the motions of joints two and three in order to keep the microscope suspension parallel to axis one. The joints’ positions are calculated using the kinematics [FBS08a] for exact positioning. A Polaris tracking system produced by NDI tracks the microscope’s position with an accuracy of 0.35mm.

An external firewire camera (DFK 31AF03 produced by TheImagingSource) is mounted to the video interface of the microscope (Fig. 1 right) and records the current field of view. The recorded images are then used to calculate the focus score on an external computer because a separate autofocus function is not provided by the microscope.

Figure 1: Left: Microscope HI-R 1000 with tripod FS4-20 produced by Möller-Wedel Germany. Axes 1-3 and 5-7 are motorized; axis 4 compensates motions of joints 2 and 3 in order to keep axes 1 and 5 parallel. Right: Firewire camera is mounted to the video interface of the microscope whose image is used to calculate the focus score of the current field of view.

Preoperative MRT- or CT-images are used to generate a 3D-model of the patient using the marching cubes algorithm [LC87]. Target points can then be defined in the 3D-model, which will later be focused automatically by the microscope.

3 Methods

It can be assumed that the image-based repositioning will simplify the handling of the microscope and that the time needed can be reduced. Two properties must be taken into consideration to ensure a reliable application: 1) Tracking system and microscope must be calibrated to guarantee accurate positioning; 2) The microscope should focus the field of view itself after each positioning as the working distance can be changed.

The calibration method consists of two parts. Positions of voxels, joints and optical markers should be determinable in all three parts of the system - 3D volume, microscope and
tracking system. In the first step, a passive marker is mounted on the microscope and cannot change its position relative to the lens. The tracking system can determine the focus position by tracking this marker and calculating the relation to its own coordinate system. The registration of a 3D volume and tracking system is more complicated. No marker geometry exists which can make a relationship between 3D volume and tracking system.

In the second step, a relation between transformations of a real point in both coordinate systems can be calculated using the Horn algorithm [Ho87]. Therefore, the underlying real point have to be static so that the transformations can be calculated exactly.

### 3.1 Autofocus

A surgeon has to react to different situations during surgery. At the beginning, usually a broad field of view is necessary to get an overview of the operation area. Afterwards, the procedure requires several variations of working distance and focus position. In any case, it is important that the field of view remains focused. So, the autofocus represents a crucial aspect of automatic positioning of a microscope as otherwise the surgeon has to refocus the field of view manually.

The HI-R 1000 microscope does not provide an autofocus function itself. Because of that, an external firewire camera is used to capture the current view of the microscope. These images are used to determine the image sharpness by calculating the focus score on an external PC. Therefore, the following properties must be complied by the algorithm calculating the focus score:

1. Local maxima or minima should not appear, if the working distance is varied monotonity,
2. high noise immunity and
3. the best focused image is described by the maximal focus score.

Two methods for calculating the focus score are described in the next sections.

#### 3.1.1 1D Fourier Transformation with Pearson Correlation

A 1D Fourier Transformation is applied to the image column by column. The resulting frequency vectors are combined to vector \( v_i = (v_0, v_1, \ldots, v_n) \) with \( n \) number of columns of the image [BAA04]. An important aspect of this algorithm is, that a reference image with maximal unsharpness must be chosen before the algorithm can be started. Unfortunately, this image is not known at the beginning, so that a blurry out of focus image is generated artificially. Therefore, the image of the current view is blurred with a Gaussian function (1) which results in a good approximation of an out of focus image.

\[
f(x, y) = \frac{1}{2\pi\sigma^2} e^{-0.5 \left( \frac{x^2 + y^2}{\sigma^2} \right)}
\] (1)
Afterwards, each image can be compared with the reference image by calculating the Pearson Correlation $FS_{PC}$ (2) of the two vectors of the reference image $v_r$ and the currently observed image $v_i$.

$$FS_{PC} = \frac{\sum v_i v_r - \frac{1}{n} \sum v_i \sum v_r}{\sqrt{\left(\sum v_i^2 - \frac{1}{n} (\sum v_i)^2\right) \left(\sum v_r^2 - \frac{1}{n} (\sum v_r)^2\right)}}$$

The algorithm assumes that the best focused image and the blurred reference image are most dissimilarly. This means that the image with the minimal Pearson Correlation has the maximal focus score.

3.1.2 Calculating the gradient using Sobel operators

Sobel operators are a simple method to detect edges in an image. Folding the image with a sobel operator calculates the derivative of the image’s intensity at every pixel. The operators $S_x$ and $S_y$ for detecting horizontal respectively vertical edges consist of a 3x3 matrix.

$$S_x = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix} ; \quad S_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

Assuming that significant variations of magnification in the original image $B$ describe the area with maximal intensity, the Sobel operator can be used to visualize high frequencies in the microscope’s image as grey level.

Folding the image $B$ and the Sobel operators $S_x$ and $S_y$ and summarizing their squares describes a function which is maximal for focused images [Ye93] (4).

$$FS_{Sobel} = \sum_{\text{height}} \sum_{\text{width}} S_x(x, y)^2 + S_y(x, y)^2$$

In Fig. 2, a focused and an out of focus image of an identical scene are presented. Both images have been folded using $S_x$. It is obvious that the folding of the out of focus image hardly contains any information, whereas the folding of the focused image could clearly detect the containing edges.

3.1.3 Comparison of computing methods

A video sequence has been recorded using the microscope in order to evaluate the two computing methods. Therefore, the focus score of all images of this video has been calculated offline. The video shows a static model of a human knee in front of a monochrome
background. At the beginning the working distance is minimal so that the object is very blurry and can hardly be recognized. The working distance is increased to the maximum and afterward decreased back to the minimum, so that the object is focused twice. The progress of the focus score of both methods is shown in Fig. 3. There you can see that both methods recognize the focused image almost identically but the Fourier Transformation cannot determine an explicit maximum. The Sobel operator detects the focused image a few frames too early. The increasing respectively decreasing flanks are not monotonically so that detecting the maximum can be difficult.

A weighted combination of both methods is presented in Fig. 4. Now, both maxima are detected very well and represent the best focused frames of the video. Increasing as well as decreasing flanks are now strictly monotonically so that gradient search can be used to autofocus the microscope.

3.2 Application

If the surgeon controls the microscope manually, each repositioning will interrupt his actual work and he will have to lay his instruments aside. Afterwards, he has to reorientate himself and move the instruments back into the operation area.

With the help of the new method, the surgeon will not have to turn away from the scene if the positioning is done automatically and he can continue the surgery almost immediately.
Another advantage arises from the opportunity to save coordinates of focused tissue so that these target points can be focused later once again. Switchings between different viewing directions and target points can easily be done.

Already before surgery starts, the advantages of the motorized system can be used where two scenarios are distinguished utilizing this system:

1. In preparation of the surgery, the surgeon can mark relevant points in the 3D model which can later be focused automatically. This is useful to observe tissue with the microscope which is known to be of interest.

2. The surgeon can have slices of preoperative MRT- or CT-images presented which correlate with the position focused by the microscope. This simplifies consulting additional information of the currently observed tissue and acts as precondition to present these slices directly in the microscope at the correct position and true to scale.

In preparation of the surgery, preoperative MRT- or CT-images are loaded to a software tool in order to generate 3D model. In Fig. 5 a data set of a knee joint model is visualized and the surgeon can now define target points either in the model or in individual slices of the CT-images.

After having registered tracking system and microscope at the beginning of surgery, the surgeon can now choose one of the previously defined target points which will then be focused automatically by the microscope. Therefore, a small menu is presented in the
current field of view (Fig. 6) from which the target point can be selected using a small remote control fastened to the surgeon’s instrument ([FBS08b]). Additionally, the preoperative MRT- or CT-slices corresponding to the target point which have been used in preparation of the surgery (bottom of Fig. 5) are displayed.

4 Results

The quality of the autofocus function depends on the microscope’s magnification. The more the field of view is magnified the more decreases the observed tissue area. Due to this, the field of view becomes more homogeneous and the difference of two images taken at different working distances is minor. This complicates the determination of the absolute maximum of the focus score.

In Fig. 7, the focus score of three different magnifications is presented as a function of the working distance. The calculation has been done offline using a video sequence of a knee model which has been recorded with a firewire camera (Fig. 1 b)). Therefore, the working distance has been varied in equidistant steps beginning at 22.5 cm. Predictably, the absolute maximum is recognizable explicitly with small and medium magnification (zoom 41 and 75). Even with intense magnification (zoom 143) the absolute maximum of the focus score represents the best focused image but this function also has a local maximum which makes an autofocus difficult.

Positioning microscopes using an optical marker causes a human induced error already in the calibration process because of inaccurate marker positioning. This error is mainly influenced by the precision with which the marker can be detected in workspace which is
Figure 5: The software visualizes a knee joint model built from CT-images. This model as well as the presented slices can be used to define target points preoperatively.

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</table>

Table 1: Mean positioning error in mm

about 0.35mm for the used tracking system [WTF04].

The positioning error of the microscope has been calculated using root mean square deviation. The mean deviation $\sigma$ between focused point $p_i$ and the real target point $t_i$ has been computed by

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (p_i - t_i)^2}.$$ (5)

Two test series with 29 target points each have been performed in order to examine the positioning accuracy. First, the target points $t_i$ have been defined in workspace using a passive marker. Afterwards, the microscope moved to each point successively and focused it. At each target it was checked visually that the object was focused correctly. The mean deviation of all $p_i$ in x-, y- and z-direction as well as the absolute, mean deviation from $t_i$ is presented in Tab. 1.
5 Conclusion

A procedure for interactive navigation of a fully motorized surgical microscope has been presented in this work. This procedure uses preoperative MRT- or CT-images to generate a 3D-model of the patient which then represents the basis for navigation during surgery. Target points can now be defined in these images prior to surgery and later the microscope can be positioned automatically at a point chosen by the surgeon.

The relation between tracking system, microscope and 3D-model is established using a simple calibration method based on the Horn algorithm [Ho87]. It enables positioning the microscope by defining target points either directly on the patient using an optical marker or on his 3D-model. The results have shown that a positioning accuracy of about 1.0mm can be achieved. It should be examined whether this error can be reduced taking the weight force of the parallelogram-arm into consideration.

After having reached the target position, the microscope is focused automatically by calculating the focus score of the current field of view as function of the working distance. Thus, not only the surgeon will be discharged from positioning the microscope but he can also continue his work almost immediately. Manual interaction becomes unnecessary.

It can be assumed that the time needed for repositioning the microscope during surgery is reduced significantly. Appropriate measurements remain to be done. However, it might be problematical if several objects are placed in the field of view with different working distances because a defined area of the field of view must be used for computing the focus score. This can occur if tissue inside a resection cavity should be focused or if surgical instruments are located above the relevant area of the field of view during auto focusing. First experiments have shown that the function of the focus declines but it is still possible to focus the field of view automatically if the tissue, which should be focused, predominates.
Figure 7: Comparison of the focus score depending on the microscope’s zoom factor. Zoom 41 represents the smallest magnification and zoom 143 the most intense one.

in the field of view.

References


