Computer Aided Surgery, Vol 3, 1998

The VN-Project: Endoscopic Image Processing for Neurosurgery

W. Konen[1], M. Scholz[2], S. Tombrock[1]

[1] Zentrum für Neuroinformatik GmbH, Bochum, Germany

[2] Neurochirurgische Universitätsklinik, Ruhr-Universität Bochum, Germany

Abstract:

We develop a navigation support system for endoscopic interventions which allows to extract 3D-information from the endoscopic video data and to superimpose 3D-information onto such live video sequences. The endoscope is coupled to a position measurement system and a video camera as components of a calibrated system. We show that the radial distortions of the wide-angle endoscopic lens system can be successfully corrected and that an overall accuracy of about 0.7mm is achieved. Tracking on endoscopic live video sequences allows to obtain accurate 3D-depth data from multiple camera views.

1 Introduction

Image processing and image analysis play an important role in advanced surgery (CAS: computer aided surgery). Much work is devoted to 3D-reconstruction from CT-, MRI- or other volume data slices or to 3D-registration between different image modalities and the actual scene in the operating theatre [Cinquin+95]. 3D-registration is an important prerequisite for navigation support systems which allow for example to follow a predefined path during a surgical intervention [Horstmann94].

Endoscopic interventions become also increasingly important in many surgical areas because they provide minimal-invasive impact on the patient [Bauer+Hellwig94, Scholz+96, Scholz+97]. Especially in the area of neurosurgery and endonasal surgery they allow operation in otherwise difficult accessible areas (e.g. ventricular system). The endoscopic view adds another image modality to the surgeon's repertoire.

However, on the contrary to what one might expect, the obvious combination, namely digital image processing *within* endoscopic images, has not been assessed so far. The main roadblocks lie (a) in the difficulty to extract useful 3D-information from multiple images if the camera movement is not known, (b) in strong distortions caused by the wide-angle endoscope lens system and (c) in close-to-real-time requirements for any of the image processing tasks.

We propose in this paper a new system where the endoscope is coupled to an optical position measurement system (OPMS) which measures the endoscope position - and hence also the camera position - accurately in space and time. Using state-of-the-art camera calibration techniques (Sec. 3) and a newly developed system calibration (Sec. 4), we can map a 3D world point into the actual endoscope view. The inverse operation, namely inferring from multiple camera views of a point its 3D-coordinates, is also achieved by moving the endoscope while tracking the image motion of the (stationary) world point in the camera plane (Sec. 5).

Once these basic registration problems have been solved, they can be applied to multiple modules which give the surgeon enhanced navigation support:

- display certain landmarks from *preoperative* data (CT,MRI) - e.g. the location of a tumor - within the endoscopic image, or give appropriate navigational hints, if outside the endoscopic view,
- mark *intraoperatively* a certain landmark in the endoscope and allow to relocate it precisely and reliably when the landmark has moved out of the field of view, – or measure the distance between two or more of such intraoperatively defined marks,
- mark anatomical landmarks to refine *intraoperatively* the registration transform between the patient coordinate system and the CT coordinate system (e.g. after tissue movement).

An interesting and somewhat similar approach has been taken in the ARTMA system [Gunkel+95] where the endoscope position is measured by a Hall sensor and used to overlay certain preoperatively defined structures in the live endoscopic image. However, no camera calibration has been undertaken in this approach so that the achievable accuracy is fairly limited and does not allow to infer the depth of an intraoperatively marked point from multiple camera views.

2 System Setup

The rigid endoscope (outer diameter 5.9 mm, Wolf GmbH) used in this work consists of a circular tube (6 mm diameter) where a color CCD-camera at the rear end captures the image from the tip of the endoscope through a special lens system (distance tip - rear end: 380 mm). We developed a special device mounted on the shaft of the endoscope which holds 3 infrared LEDs (see Fig. 1). In designing this device care has to be taken to make it sufficiently small such that it does not disturb surgeon's ability to maneuver the endoscope. On the other hand it has to be sufficiently large such that a good spatial resolution can be achieved.

The positions of the LEDs are measured continuously by the OPMS which is a part of the EasyGuide^{TM} Neuro (Philips). The OPMS basically consists of a stereo camera rig, stationary in the operating theatre. The system measures the 3D-position of the LEDs and determines the 6 degrees of freedom of the rigid endoscope in the coordinate system of the camera rig. The OPMS achieves a spatial resolution of 0.4-0.8 mm and an overall accuracy of 1-1.5 mm within its volume of operation. The OPMS data are transfered via serial interface to the PC at a rate of about 8 Hz.

The video output of the endoscope camera is connected to a TV monitor and to a standard PC-framegrabber, which allows the live display of the color image on the PC's VGA-monitor, optionally with cursor and certain marks overlayed. Alternatively, we may grab a sequence of frames via PCI burst mode into the main memory (up to 16 Hz for 512x512 images).

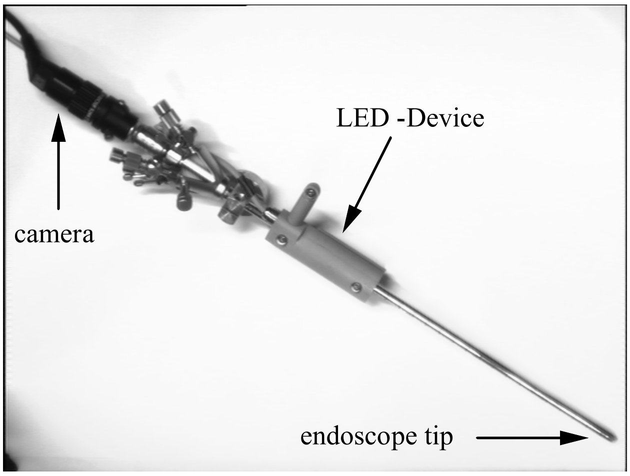


Fig. 1: Rigid endoscope with LED device

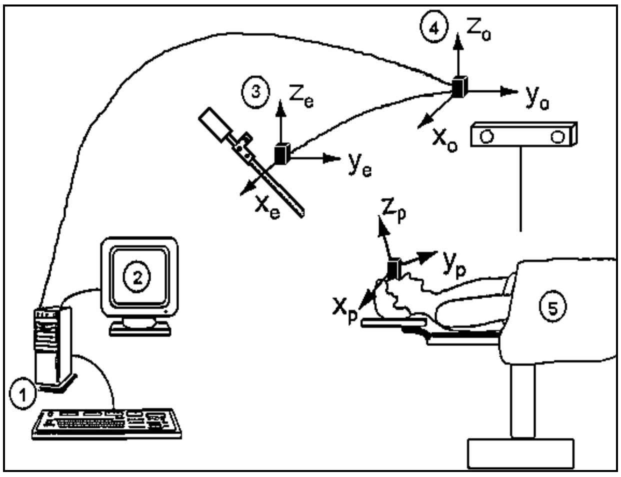


Fig. 2: Schematic drawing of the intraoperative system setup: The coordinates of the endoscope (3) are measured by the OPMS (4) and transmitted to the PC (1).

3 Camera calibration

The basic camera calibration procedure estimates the 6 extrinsic parameters $\{\mathbf{R}, \mathbf{t}\}$ which map a point from the world coordinate system into the camera coordinate system, the 4 intrinsic parameters of a camera (focal length f, piercing point (u_o,v_o), scaling factors s_x) and finally image distortion parameters $(\kappa_1, \kappa_2,...)$. When the camera is moved, only the extrinsic parameters change, while the intrinsic and the distortion parameters remain constant. The mapping of a world point $\mathbf{X}_w=(x_w,y_w,z_w,1)$

[1] into the camera coordinate system, $\mathbf{X}_c=(x_c,y_c,z_c,1)$, and then into the framebuffer pixel coordinates (x_f,y_f) is described by the following equations:

$$(3.1)\quad \mathbf{X}_c = D\,\mathbf{X}_w \qquad \text{with 4x4-matrix } D = \begin{pmatrix} \mathbf{R} & \mathbf{t} \\ 0 & 1 \end{pmatrix}$$

$$(3.2)\quad (X_u, Y_u) = \frac{f}{z_c}(x_c, y_c)$$

$$(3.3)\quad (X_d, Y_d)\,(1 + \kappa_1 r^2 + \kappa_2 r^4 + \ldots) = (X_u, Y_u) \qquad \text{with} \quad r = \sqrt{X_d^{\,2} + Y_d^{\,2}}$$

$$(3.4)\quad x_f = s_x X_d + u_0$$

$$(3.5)\quad y_f = s_y Y_d + v_0$$

We use in this paper the well-known camera calibration procedure from [Tsai87] which provides a versatile and robust estimation of the camera parameters.

The noncoplanar calibration procedure requires multiple images of a calibration pattern with known geometry. As calibration pattern we use a plane of rings placed on a regular lattice with 1,25 mm ring-to-ring distance (The left part of Fig. 3 shows an example of an original calibration image).

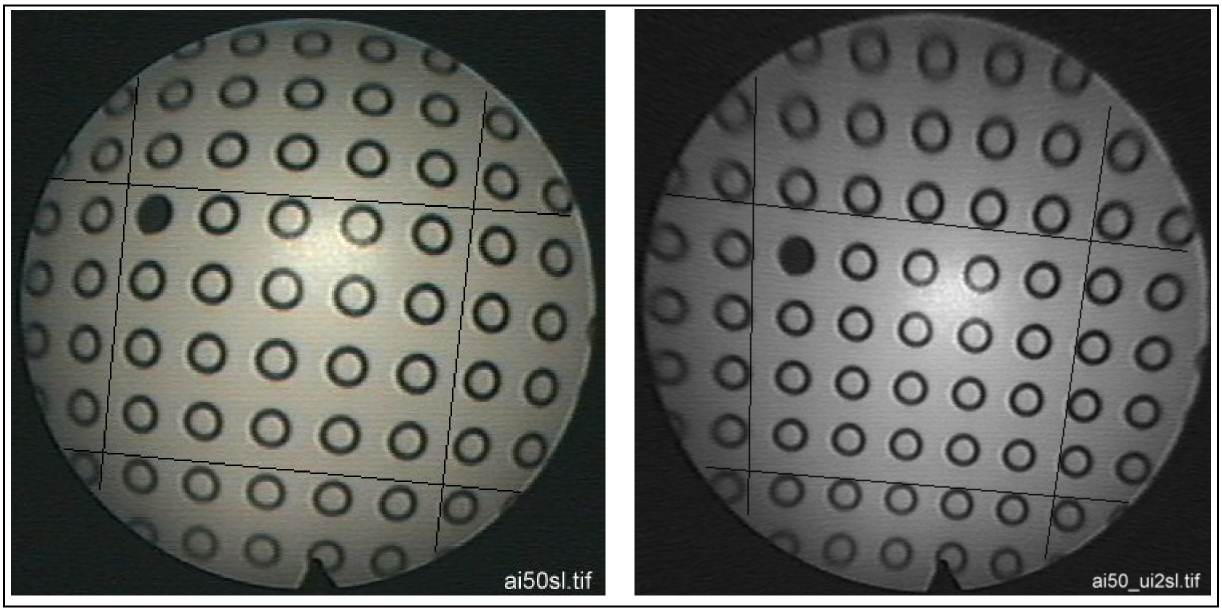


Fig. 3: Left: The calibration pattern as viewed through the endoscope (distorted image). The straight lines are not part of the image but superimposed to show the distortion effects. Right: The calibration pattern after correcting the distortion effects using the κ_1-distortion model. All rings are lying on straight lines, as they should. The (κ_1,κ_2)-distortion model achieves the same result.

The calibration pattern is attached to a micrometer screw which allows to move it with an accuracy of < 10µm. For the calibration we took a sequence of 15 images where the calibration pattern was shifted by 0.5 mm between consecutive positions.

The estimated calibration and distorsion parameters yield a good camera calibration with an accuracy better than 0,15mm.

---

[1] Here and in the following we adopt the notation of projective geometry where points in 3D-space are represented by 4D-vectors (e.g. $\mathbf{X}_w$). In this 4D-space the rigid body transforms are *lineare mappings,* represented by 4x4 matrices (e.g. D).

With the estimated distortion parameters we can invert Eq. (3.3) numerically and warp the distorted image using bilinear interpolation to obtain an undistorted image (Fig. 3, right part). We found that the camera model is able to correct the strong distortion of the endoscope very well. Since this is the case, we conclude that the underlying assumption of the central projection model is valid for the endoscopic lens system.

4 System calibration and overall accuracy

The next important step is the system calibration, namely the precise registration of the LED device coordinate system relative to the camera coordinate system. Details for this procedure may be found in [Konen+97]. Here it is sufficient to say that practical experience has shown that n=4-5 images of a stationary calibration pattern from different viewpoints are sufficient to obtain a good system calibration. Thus we have a fast calibration procedure which can be conducted easily by technical personal.

What is the overall accuracy of the calibrated system, consisting of endoscope, LED device and OPMS? We can assess the accuarcy by the following *"spin-me-around test"*: We manually mark a certain landmark **P** in at least k=2 different camera views. Knowing the k camera positions from the OPMS, we can obtain the 3D-representation $\mathbf{P}_o$ in the OPMS-system using standard triangulation techniques. For any subsequent endoscopic view, we map $\mathbf{P}_o$ in the actual camera view and overlay it onto the endoscope image. If camera and system calibration are correct, the overlayed mark will be always on top of the landmark **P**, no matter how we "spin around" the endoscopic viewpoint or where the landmark **P** appears in the endoscope image. Table 1 shows that the residual error $<\Delta f> \approx 0.7$ mm is in the order of the intrinsic error of the OPMS (> 0.5mm), i.e. the accuracy of the calibration is close to its theoretical limit.

Table 1: Average error $<\Delta f>$ as residual distance between **P** and the overlay mark in the live endoscope image. (Averaging has been done with respect to 10 images where the landmark **P** appears at various distances from the piercing point.) Δs is the approximate movement of the camera between the k multiple views to determine $\mathbf{P}_o$. Δf_{OPMS} is the observable jitter of the overlay mark when the endoscope is fixed. This jitter stems from noise in repeated OPMS measurements and gives a lower bound on the intrinsic OPMS error.

meas.	k	Δs [mm]	$<\Delta f>$ [mm]	Δf_{opms} [mm]
A2	2	5	0,74	0,5
A3	3	5	0,62	0,5
B2	2	10	0,6	0,5
B3	3	10	0,54	0,5
C2	2	10	0,82	0,5
C3	3	10	0,97	0,5
average:			**0,72**	

Note that it is very important to have an accurate distortion model in order to achieve this accuracy. If we neglect distortion effects (by setting $\kappa_1=0$) and if **P** is far away from the piercing point, the error goes up to 3.5 mm instead of 0.7 mm.

A second note concerns the the ergonomic requirements for the use of the system in the operating theatre: Although good camera and system calibration are important for good accuracy, these two procedures need *not* to be done each time the system is used in the operating theatre: The *camera calibration* remains valid as long as the same camera is used and the *system calibration* remains valid unless the LED device is detached from the endoscope, which is normally unnecessary in the clinical routine.

5 Tracking

It was our goal in the spin-me-around test to determine the 3D-position of a visual landmark from multiple 2D-views (triangulation). We can eliminate the necessity to perform *multiple* clicks on a certain landmark **P** if the systems tracks the landmark automatically. Then the surgeon simply points initially at the landmark, the system tracks it while the endoscope is moving until some stopping criterion is met and finally reports the 3D-coordinates $\mathbf{P}_0$ and displays the overlay mark. We implemented a fast tracking algorithm which can analyze up to 8 frames per second and works well in realistic sequences of endoscopic surgery (low contrast, diffuse borders). We obtain good results when tracking landmarks on neuroanatomical tissue and achieve in the *spin-me-around test* a similar accuracy (0.9 mm) as in the manually-assisted case (0.7 mm).

6 Conclusion and outlook

We have shown that advanced image processing techniques can be applied successfully to endoscopic surgery. A good calibration for the wide-angle and strongly distorting endoscopic lens system has been obtained (accuracy 0.2 mm). We have coupled the endoscope to an OPMS which determines its 3D-location in space and which allows to overlay 3D-points or arbitrary 3D-structures directly in the live camera image with high accuracy (0.7-0.9 mm). Inversly, landmarks in the camera image can be tracked when the endoscope is moving, their 3D-position can be obtained and reported to other systems. This is to our knowledge the first time that direct image processing on the image modality of endoscopic video sequences is performed.

The system has meanwhile been tested in extensive preclinical studies and also during neurosurgical interventions (Fig. 6). The results are reported in detail in the article by [Scholz+98] in this issue. Overall, the system showed convincing results and achieved a similar accuracy as in the laboratory case. Further work will go into optimization of the system and into development of further modules to aid the surgeon. It is our believe that advanced image processing methods will play an increasingly important role in endoscopic surgery where the surgeon faces new challenges due to continuing miniaturization. Thus he needs new tools for improved navigation support.

This work has been supported in part by grants from the Ruhr-Universität Bochum for interdisciplinary research (FORUM).

7 Literature

[Cinquin+95] P. Cinquin, E. Bainville et al., *Computer assisted medical interventions,* IEEE Engineering in Medicine and Biology, 1995.

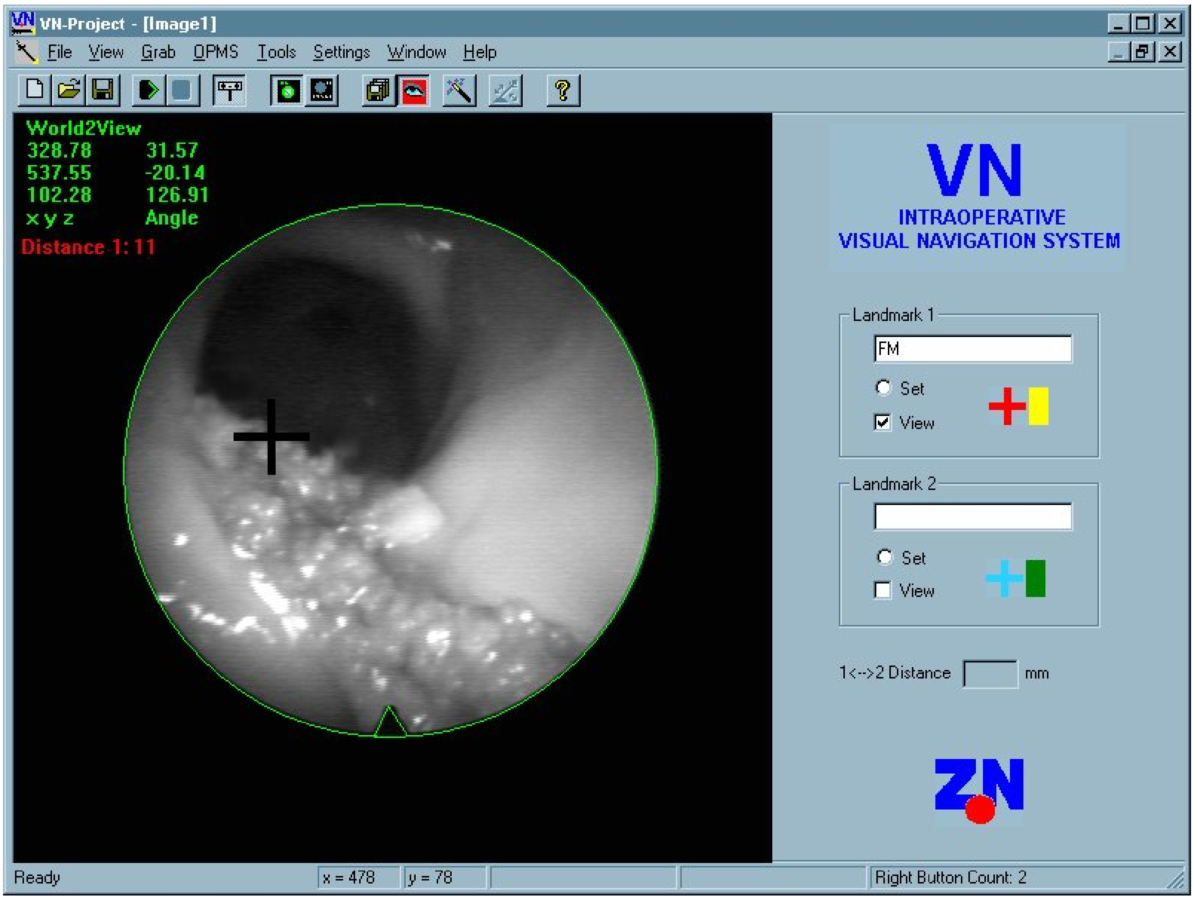
[Horstmann94] G.A. Horstmann, H.F. Reinhardt, *Micro-stereometry, a frameless computerized navigating system for open microsurgery,* Comput. Med. Imaging Graph. **18**, 229-233, 1994.

[Bauer+Hellwig94] B.L. Bauer, D. Hellwig, *Minimal invasive endoscopic neurosurgery - a survey,* Acta Neurochir. **61** (Suppl), 1-12, 1994.

[Scholz+96] M. Scholz et al, *MRI-guided endoscopy in the brain: a feasibility study,* Minim. Inva. Neurosurg. **39**, 33-37, 1996.

[Scholz+97] M. Scholz et al., *Endoskopische Neuronavigation - eine präklinische Studie mit dem Easy Guide Neuro System,* Endoskopie heute **3**, 28-34, 1997.

[Gunkel+95] A.R. Gunkel, W. Freysinger, W.F. Thumfart, M.J. Truppe, *Application of the ARTMA Image-Guided Navigation System to Endonasal Sinus Surgery,* Proc. Computer Assisted Radiology, 1146-1151, Berlin, 1995.



```
World2View
328.78    31.57
537.55    -20.14
102.28    126.91
x y z     Angle
Distance 1: 11
```

Landmark 1: FM
☑ View

Landmark 2:
☐ View

1<-->2 Distance ☐ mm

Ready | x = 478 | y = 78 | Right Button Count: 2

Fig. 6: View through the endoscope into the ventricular system (Foramen Monroi). A point on the border of the Foramem Monroe is marked (the cross), its 3D-coordinates have been established and can be used for further navigation. When the landmark disappears out of the field of view, an arrow on the circumference shows the direction where the landmark can be found and the thickness of the arrow indicates the depth of the landmark with respect to the current endoscope position. Two or more landmarks can be stored and the 3D-distance between pairs of landmarks is computed automatically by the system.

[Tsai87] R.Y.Tsai, *A versatile Camera Calibration Technique for High Accuracy 3D Machine Vision Metrology Using Off-the-Shelf TV Cameras and Lenses,* IEEE Journal of Robotics and Automation, Vol. RA-3, No.4 , 323-344, 1987.

[Konen+97] W. Konen, M. Scholz, S. Tombrock, S. Tölg, M. Brauckmann, L. Adams, *An Image-Based Navigation Support System for Neuroendoscopic Surgery,* in: R. Ahlers (ed.), 5. Symposium Bildverarbeitung 1997, Technische Akademie Esslingen, 1997.

[Scholz+98] M. Scholz, W. Konen, S. Tombrock, B. Fricke, M. von Düring, A. Harders, *corresponding article in this issue,* 1998.