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Endoscopic Orientation Correction

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Abstract. An open problem in endoscopic surgery (especially with flexible endoscopes) is the absence of a stable horizon in endoscopic images. With our "Endorientation" approach image rotation correction, even in non-rigid endoscopic surgery (particularly NOTES), can be realized with a tiny MEMS tri-axial inertial sensor placed on the tip of an endoscope. It measures the impact of gravity on each of the three orthogonal accelerometer axes. After an initial calibration and filtering of these three values the rotation angle is estimated directly. Achievable repetition rate is above the usual endoscopic video frame rate of 30Hz; accuracy is about one degree. The image rotation is performed in real-time by digitally rotating the analog endoscopic video signal. Improvements and benefits have been evaluated in animal studies: Coordination of different instruments and estimation of tissue behavior regarding gravity related deformation and movement was rated to be much more intuitive with a stable horizon on endoscopic images.

1 Introduction

In the past years, *N*atural *O*rifice *T*ranslumenal *E*ndoscopic *S*urgery (NOTES) [1] has become one of the greatest new challenges within surgical procedures and has the strong potential to eventually succeed minimal invasive surgery (MIS). Currently, MIS interventions are mainly carried out by surgeons using *rigid* laparoscopes inserted in the abdomen from the outside, while gastroenterologists apply *flexible* video-endoscopes for the detection and removal of lesions in the

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gastro digestive tract (esophagus, stomach, colon, etc.). As the currently practiced *NOTES* and *hybrid* interventions require flexible endoscopes to access the abdominal cavity as well as the surgical instruments and skills to perform the actual intervention, both disciplines and technologies are needed. Gastroenterologists have been trained and accustomed to navigate through the lumen of the colon, stomach or esophagus by pushing, pulling and rotating the flexible video-endoscope (fig. 1), regardless of orientation, rotation and pitch of the endoscope tip inside the patient and the image orientation displayed on the monitor. Surgeons, on the other hand, are used to a fixed relation between the tip of the endoscope and the inside of the patient, as neither one of them is changing their position during the intervention. However, mismatches in the spatial orientation between the visual display space and the physical workspace lead to a reduced surgical performance [2,3].

Hence, in order to assist surgeons interpreting and reading images from flexible video-endoscopy, an automated image rectification or re-orientation according to a pre-defined main axis is desirable [4]. The problem of the rotated image is even more important in hybrid NOTES procedures, where an additional micro instrument is inserted through the abdominal wall for exposition and tasks during extremely complex interventions.

In the past, there have been suggested different approaches for motion tracking [5] and image rectification [6]. Several approaches use parameters achieved from registration of intra-operative obtained 3-D data with pre-operative CT or MRI volumes. Such intra-operative 3-D data can be obtained from image-driven approaches like monocular shape-from-shading [7] and structure-from-motion [8,9], stereocular triangulation [10], active illumination with structured light [11] or application of an additional time-of-flight/photonic-mixing-device camera [12]. But even if intra-operative 3-D data can be obtained and reconstructed in real-time, e.g. via time-of-flight cameras needing no data post-processing and having frame rates higher than 30Hz, real-time computation of registration parameters is still a challenge [13] especially since colon or stomach provide less applicable feature points.

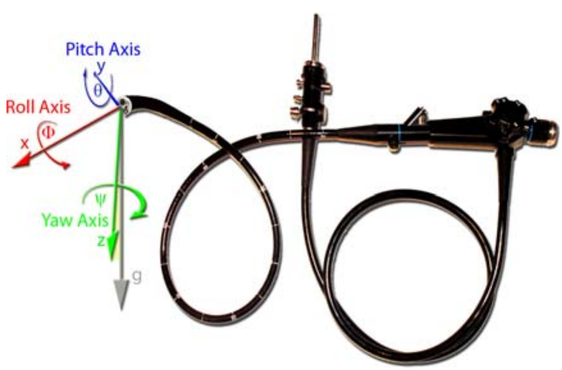

Fig. 1. Roll, pitch and yaw description for endoscopic orientation

A broad overview of possible tracking technologies has been given in [5]. These also include the idea of electro-magnetic tracking, which can be applied to an endoscope. This requires not only an additional sensor in the endoscope's tip but also an external magnetic field. This can easily be disturbed by metallic instruments and leads to several further restrictions [14]. A by far simpler approach to measure the needed orientation angle will be presented in this work and consists of integrating a Micro Electro-Mechanical System (MEMS) based inertial sensor device in the endoscope's tip to measure influencing forces in three orthogonal directions (fig. 1). If the endoscope is not moving, only the acceleration of gravity has an effect on the three axes.

2 Method

2.1 Technical Approach

To describe the orientation of the endoscope relating to the direction of gravity, an Cartesian "endoscopic board navigation system" with axes $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{z}$ (according to the DIN 9300 aeronautical standard [15]) is used as body reference frame [16]. The tip points in x-direction which is the boresight, the image bottom is in z-direction and the y-axis is orthogonal to both in horizontal image direction to the right. Rotations about these axes are called roll Φ (about x), pitch Θ (about y) and yaw Ψ (about z). Image rotation has only to be performed about the optical axis x which is orthogonal to the image plane. Gravity $\boldsymbol{g}$ is considered as an external independent vector. Since there is no explicit angle information, only the impact of gravity on each axis can be used to correct the image orientation. Equation (1) expresses, how rotation parameters Φ, Θ and Ψ of the IMU (Inertial Measurement Unit) have to be chosen to get back to a corrected spatial orientation with $\boldsymbol{z}$ parallel to $\boldsymbol{g}$:

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\Phi) & \sin(\Phi) \\ 0 & -\sin(\Phi) & \cos(\Phi) \end{pmatrix} \cdot \begin{pmatrix} \cos(\Theta) & 0 & -\sin(\Theta) \\ 0 & 1 & 0 \\ \sin(\Theta) & 0 & \cos(\Theta) \end{pmatrix} \cdot \\ \cdot \begin{pmatrix} \cos(\Psi) & \sin(\Psi) & 0 \\ -\sin(\Psi) & \cos(\Psi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} = \begin{pmatrix} -\sin(\Theta)g \\ \sin(\Phi)\cos(\Theta)g \\ \cos(\Phi)\cos(\Theta)g \end{pmatrix} \tag{1}$$

with $F_{x,y,z}$: measured acceleration

Using the two-argument function arctan2 to handle the arctan ambiguity within a range of $\pm\pi$ one finally can compute roll Φ for $F_x \neq \pm g$ and pitch Θ for all values:

$$\Phi = arctan2(F_y, F_z) \tag{2}$$

$$\Theta = \arcsin\left(\frac{-F_x}{g}\right) \tag{3}$$

As g determines just 2 degrees of freedom with this approach yaw Ψ cannot be computed. If $F_x = \pm g$ ($\rightarrow \Theta = \pm\pi \rightarrow F_y = F_z = 0$) roll Φ is not determinable either. To avoid movement influence, correction is only applied if superposed acceleration additional to gravity g is below boundary value ΔF_{absmax}:

$$|\sqrt{F_x^2 + F_y^2 + F_z^2} - g| < \Delta F_{absmax} \quad (4)$$

First, a preceded 3×3 calibration matrix, which incorporates misalignment and scaling errors [17,18], has to be retrieved by initial measurements. Moreover a peak elimination is the result of down sampling the measuring frequency, which is considerably higher than the image frame rate (up to 400Hz vs. 30Hz). This is realized by summing up separately all n sensor values F_{x_i}, F_{y_i} and F_{z_i} within an image frame with $i = 1, ..., n$ and weighting them with a weighting factor w_i with maximal weight w_0:

$$w_i = \frac{1}{\frac{1}{w_0} + |\sqrt{F_{x_i}^2 + F_{y_i}^2 + F_{z_i}^2} - g|} \quad (5)$$

Afterwards the sum has to be normalized by the sum of all weighting factors w_i:

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \sum_{i=1}^{n} (\begin{pmatrix} F_{x_i} \\ F_{y_i} \\ F_{z_i} \end{pmatrix} \cdot w_i) \cdot \sum_{i=1}^{n} (w_i)^{-1} \quad (6)$$

To avoid bouncing or jittering images as a result of the angle correction, additional filtering is necessary. Hence, prior to angle calculation, each axis is filtered with a Hann filter to smooth angle changes and with a minimum variation threshold ΔF_{axmin} to suppress dithering. As long as superposed acceleration calculated in equation (4) remains below boundary value ΔF_{absmax}, roll Φ and pitch Θ can be calculated using equations (2) and (3). Otherwise they are frozen untill ΔF_{absmax} is reached again. If these boundaries are chosen correctly, the results will be continuous and reliable since nearly all superposed movements within usual surgery will not discontinue or distort angle estimation. Both original and rotated image are

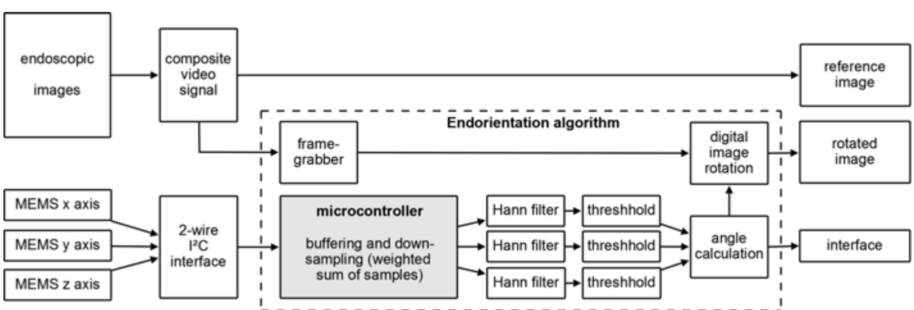

Fig. 2. Block diagram of rotation correction with the "Endorientation" algorithm

displayed for security reasons. For potential use with other devices the calculated angle is also transmitted to an external communication interface (fig. 2).

2.2 Image Rotation

The measurement data is transferred as a digital signal via a two-wire I^2C interface along the flexible endoscope tube. The endoscopic video signal is digitalized via an external USB video capture device with an adequate resolution to provide the usual quality to the operator. By this design the "Endorientation" algorithm is divided into two parts. One part running on a small 8-Bit microcontroller and one parting running as an application on a workstation. Everytime the capture device acquires a new frame the software running on the workstation requests the actual acceleration values from the software on the microcontroller. The three acceleration values are used to calculate the rotation angle according to the equations above. The rotation of the frame is performed via the OpenGL library GLUT[19]. The advantage of this concept is the easy handling of time-critical tasks in the software. We can use the sensor sample rate of 400Hz doing some filtering without getting into trouble with the scheduler granularity of the workstation OS. The information of the endoscope tip attitude is available within less than 30ms. Our "Endorientation" approach can be performed in real-time on any off-the-shelf Linux or Windows XP/Vista workstation.

2.3 Clinical Evaluation

In a porcine animal study, the navigation complexity of a hybrid endoscopic instrument during a NOTES peritoneoscopy with the well established transsigmoidal access [20] was compared with and without Endorientation. The endoscopic inertial measurement unit was fixed on the tip of a flexible endoscope (fig. 3). Additionally a pulsed DC magnetic tracking sensor was fixed on the hybrid instrument holder for recording the position of the surgeon's hands. To

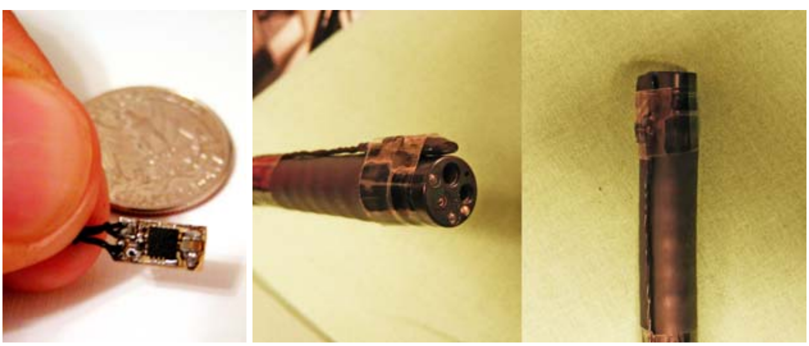

Fig. 3. Prototyping with external sensor on the endoscope's tip

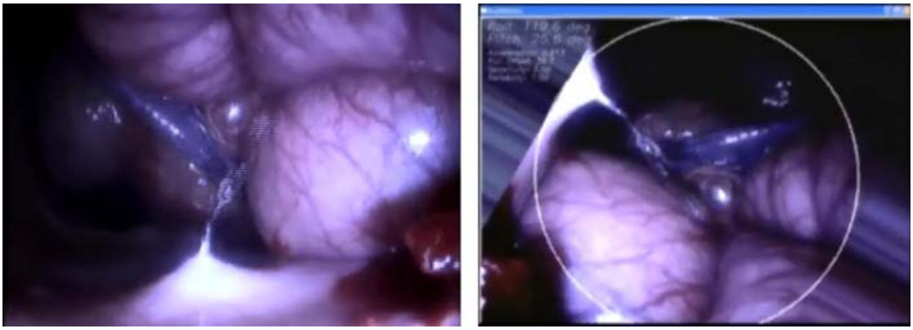

Fig. 4. Original (l) and rotated (r) image with needle incision and fluid injection

evaluate the benefit of automated MEMS based image rectification, four different needle markers were inserted through the abdominal wall to the upper left and right and the lower left and right quadrants. Under standardized conditions these four needle markers had to be grasped with a trans-abdominal introduced endoscopic needle holder. Displaying alternately originally rotated and automatically rectified images path and duration were recorded and analyzed.

3 Results

3.1 Technical Accuracy

With the employed sensor there is a uniform quantization of 8 bit for a range of ±2.3g for each axis. This implies a quantization accuracy of 0.018g per step or 110 steps for the focused range of ±g. This is high enough to achieve a durable accuracy even to a degree within relatively calm movements. This is possible as roll angle Φ is calculated out of inverse trigonometric values of two orthogonal axes. Single extraordinary disturbed MEMS values are suppressed by low weighting factors w_i. Acceleration occurs only in the short moment of changing movement's velocity or direction. For the special case of acceleration with the same order of magnitude as gravity, ΔF_{absmax} can be chosen small enough to suppress calculation and freeze the angle for this short period of time. By choosing a longer delay line for the smoothing Hann filter and a higher minimum variation threshold ΔF_{axmin}, correction may be delayed by fractions of a second but will be stable even during fast movements.

3.2 Clinical Evaluation

In the performed experiments, it could clearly be shown that grasping a needle marker with an automatically rectified image is much more easier and therefore faster than with the originally rotated endoscopic view (fig. 4). In comparison to the procedure without rectification the movements are significantly more accurate with by factor 2 shorter paths and nearly half the duration. The details of verified clinical benefits are described in [21]. Obviously the two parameters *duration* and *path length* are strongly correlated and can be regarded as a significant measure for the complexity of surgical procedures. Since both are decreased with the application of image rectification, the complexity of the complete procedure can be reduced.

4 Discussion

As described in the previous section, an automatic rectification (or re-orientation) of the acquired endoscopic images in real-time assists the viewer in interpreting the rotated pictures obtained from a flexible videoscope. This is especially important for physicians, who are used to naturally rectified endoscopic images related to a patient-oriented Cartesian coordinate system within their surgical site. In contrast, gastroenterologists have learned by combination of long experience, anatomical knowledge and spatial sense how to use and interpret an endoscope-centered (tube-like) coordinate system during their exploration of lumenal structures, even if the displayed images are rotating. Our described experiments included surgeons originally unrelated to flexible endoscopes. For future research, we will also include gastroenterologists, who are experienced reading and interpreting rotated and non-rectified image sequences. Possibly, in the future of NOTES, dual monitor systems will be needed to support both specialists during the intervention.

The hardware costs for of-the-shelf communication converter, capture device, MEMS sensor and circuit board are below $250. More reliable hardware will increase this amount by some factors, Linux/XP/Vista workstation and an additional Display have to be added. Integrating the sensor board in a flexible endoscope is surely possible but probably more expensive as well. However, there are several two channel endoscopes available. One of their working channels could be used for the MEMS sensor. In conclusion, we have shown that it is simple and affordable to additionally provide rotated images with fixed horizon for better orientation. The main complexity while using the second working channel could be to fix the sensor in the lumen, to prevent rotation in the working channel and to get the possibility to change the sensor with an instrument.

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