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Suppression of shock based errors with gravity related endoscopic image rectification

In: H. Feußner, R. Bauernschmitt, N. Navab, J. Hornegger, E. Mayr, S. Schookin, Y. Gulyaev, Y. Chaplygin, and S. Selishchev, Eds., Proc. 5th Russian-Bavarian Conference on Bio-Medical Engineering (RBC'09), ISBN 978-3-00-029049-7, pp. 43–47, Munich, Germany, July 2009.

Höller K., Penne J., Schneider A., Jahn J., Girgis H., Guttierrez J., Wittenberg T., Feußner H., Hornegger J.

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Abstract

Image rotation correction even in non-rigid endoscopic surgery (particularly NOTES and hybrid interventions) can be realized with a tiny MEMS tri-axial inertial sensor placed on the tip of an endoscope by measuring the impact of gravity on each of the three orthogonal axes. Achievable repetition rate for angle termination has to be above the usual endoscopic video frame rate of 25-30Hz. The measuring frequency of the accelerometer can be set up to 400 Hz. As the down sampling step can be used to minimize impact of shocks or short movements and therefore to maximize accuracy an intelligent algorithm has to be found. There are different approaches to obtain a triple of values to calculate the rectification angle for each new image: The simplest one is to pick the last triple out of the accelerometer data stream. For better noise reduction one can average over all samples. Another approach is to sort all values of each axis separately and take the median of each. If the magnitude of all three axes is taken into account, one can choose the triple with the minimum superposed force which means the magnitude nearest to gravity. Comparing all these approaches there can be shown different advantages like noise reduction (by averaging several values) and less movement influence (if samples have different impact with respect to superposed forces).

There can also be disadvantages like distortion (when chosen axis values are recorded at different measurement points) and delay (with averaging). A maximization of the advantages and a minimization of the disadvantages of all approaches can be reached by summing up separately all sensor values within an image frame and weighting them with a weighting factor depending to the closeness of the magnitude to gravity. Afterwards the sum has to be normalized by the sum of all weighting factors. It was shown that shock based errors within usual interventions are suppressed quite reliable during endoscopic image rectification.

1 Introduction

A still unsolved problem with flexible endoscopy in Natural Orifice Translumenal Endoscopic Surgery (NOTES) [1] is the missing information about the image orientation [2]. Thus, tip retro-flexion of a non-rigid endoscope causes image rotation angles up to ±180 degree [3]. Our approach for measuring this orientation angle is to integrate a Micro Electro-Mechanical System (MEMS) based inertial sensor device in the endoscope's tip [4] as shown in fig. 1 and 2. It measures influencing forces in three orthogonal directions. If the endoscope is not moving, only the acceleration of gravity has an effect on the three axes. Using an atan2 function the rotation angle Φ can be computed out of acceleration values F_y and F_z on the two axes y and z orthogonal to the endoscopic line of view in x-direction [2]:

$$\Phi = \arctan2(F_y, F_z) \quad (1)$$

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. 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, the upper acceleration limit can be chosen small enough to suppress calculation and to 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 on each axis, correction may be delayed by fractions of a second but will be stable even during fast movements. Video rate is 25-30 frames per second. Accelerometer values are refreshed every 2.5 ms which is equivalent to a rate of 400 values per second. Therefore the measuring frequency of the accelerometer is considerably higher than the image frame rate. There has to be found a method to provide one triple of acceleration values for each image frame and to use the information of all measurement values within one image frame to provide highest possible robustness and accuracy.

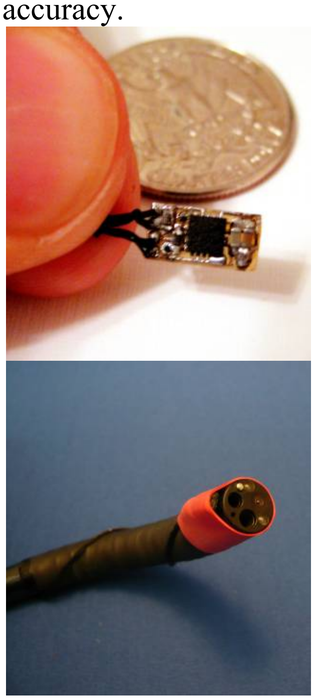

Fig. 1,2: Endorientation hardware prototype

2 Methods

The measuring frequency is up to 16 times higher than the image frame rate. For each image just one angle value is needed for image rectification.

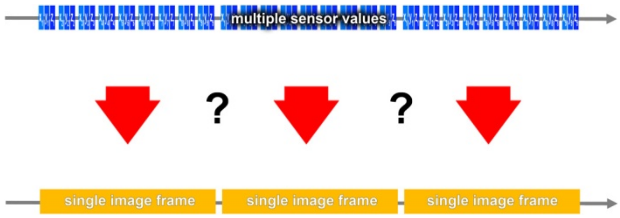

Fig. 3: Down sampling: Different possible approaches

This means that the rate for angle calculation should be synchronized to the video frame rate (fig. 3). The desired down sampling procedure for accelerometer values can be realized by different approaches which will be explained in the following steps:

2.1 Using the last triple

Using the last triple (fig. 4) is the easiest way. It is the method which uses the newest sensor value. But there is no noise reduction at all. There is a high movement influence, especially if this one value is an extraordinary bad one.

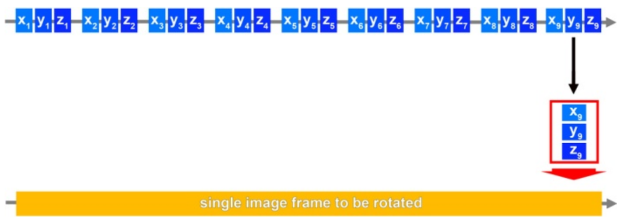

Fig. 4: Choose last triple value to calculate the rotation angle of the new image frame

2.2 Using the mean value

Using mean values (eq. 2, fig. 5) is a quite simple but relatively efficient way of down sampling with a kind of low pass filter:

$$\begin{pmatrix}F_x\\F_y\\F_z\end{pmatrix} = \frac{1}{n}\sum_{i=1}^{n}\begin{pmatrix}F_{x_i}\\F_{y_i}\\F_{z_i}\end{pmatrix} \qquad (2)$$

It already provides some noise reduction, but there is still some movement influence, as every value has the same impact regardless of its quality.

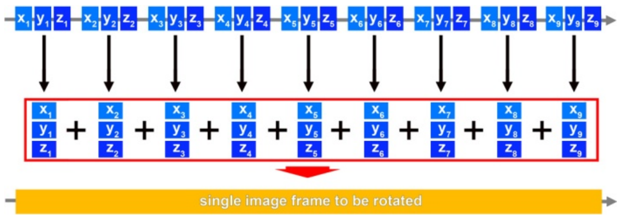

Fig. 5: Average all sensor triples to calculate the rotation angle of the new image frame

2.3 Using the median

Quite similar to the mean value is the median. If all recorded values are sorted for each axis separately one can determine a new triple by taking the individual median values triple F_{xi}, F_{yj} and F_{zk}. The median is not taken of the angle as a whole but of each axis separately (fig. 6).

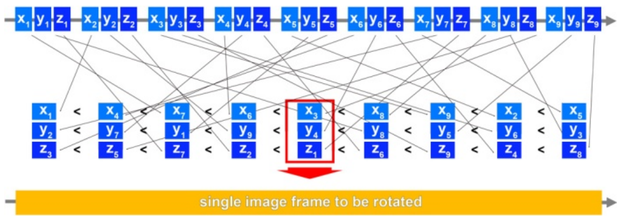

Fig. 6: Choose median of each sensor axis to calculate the rotation angle of the new image frame

It provides a quite good noise reduction, but there is still some distortion due to the fact that those values are recorded at different time.

2.4 Using the best triple

If the magnitude of all three axes is taken into account, one can choose the triple F_{xi}, F_{yi} and F_{zi} with the minimum superposed force which means the magnitude F nearest to gravity g:

$$|F| = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{3}$$

Taking the best Triple (eq. 3, fig. 7) provides values with less movement influence. But as there is no filtering there is no noise reduction.

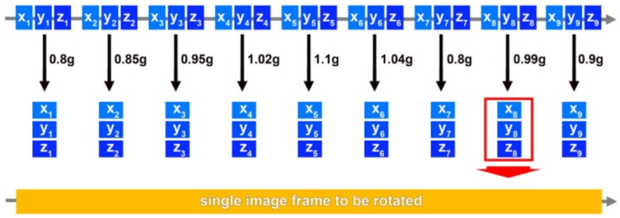

Fig. 7: Choose best triple to calculate the rotation angle of the new image frame

2.5 Using a weighted sum

A combination of all different approaches is to sum up separately all n sensor values F_{xi}, F_{yi} and F_{zi} within an image frame with $i = 1,\ldots,n$ and weighting them with a weighting factor w_i with maximal weight w_0:

$$w_i = \frac{1}{\frac{1}{w_0} + \left| \sqrt{F_{x_i}^2 + F_{y_i}^2 + F_{z_i}^2} - g \right|} \tag{4}$$

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

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \sum_{i=1}^{n} \left(\begin{pmatrix} F_{x_i} \\ F_{y_i} \\ F_{z_i} \end{pmatrix} \cdot w_i \right) \cdot \left(\sum_{i=1}^{n} (w_i) \right)^{-1} \tag{5}$$

Using the weighted Sum (eq. 5, fig. 8) provides less movement influence with quite good noise reduction.

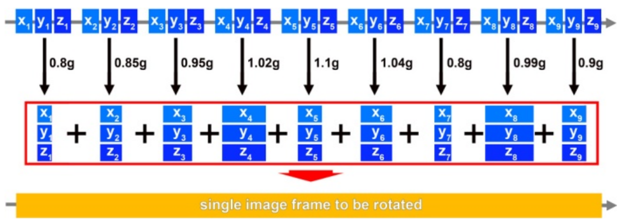

Fig. 8: Sum up weighted values to calculate the rotation angle of the new image frame

3 Discussion: Implementation Aspects

One main aspect in choosing the appropriate filter algorithm for rotation angle computation (fig. 9) is the implementation characteristics of the target platform. In our approach acquisition of acceleration measurements, filtering and down sampling is done on a small 8-Bit microcontroller. First it has to be taken into account if it is possible to synchronize the measurements to the frame acquisition or if the acceleration measurement is done free running. We decided to keep the hardware design simple by using free running measurement. In the case of using last triple there is only a simple last-in-first-out buffer needed to provide down sampling.

The use of mean values can be treated as a simplified way of FIR-filtering. This results in very small computational requirements as long as the tap length of the filter is not too big. In our case we limit the tap length to 16 taps. With a tap length based on a multiple of two the computational effort is reduced significant.

The implementation of the best triple or the weighted sum method requires much more attention. First you have to keep in mind that all calculations should be done with fixed-point, e.g. integer math to avoid unneeded computational complexity. Squaring the acceleration vector components for magnitude calculation could be done easy and fast with the available hardware multiplier. The square root calculation must be done with dedicated integer math like a CORDIC implementation. Efficient calculations for division to complete the weighted sum calculation can be found in the Atmel AVR200 application note. Another aspect for the best triple and weighted sum approaches is the data management. First you have to calculate the magnitude of an incoming acceleration vector and for the weighted sum method the weighting factor.

The data storage itself could be realized with a ring buffer structure. To avoid the need to synchronization we calculate the output value on demand. This results in searching the ring buffer for the best triple every time the host software asks for an actual measurement. For the weighted sum method the calculation of equation 5 is done every time the host needs an actual measurement.

4 Outlook

For further research the quality of the presented down sampling algorithms must be evaluated. The evaluation will be done in two steps. First the algorithms will be tested with synthetic inertial sensor data. By adding defined noise, simulating possible distortions, it is possible to evaluate the capabilities of the different approaches to standard situations, e.g. collision or continuous tremor. Second the algorithms will be tested in a surgery simulation with several probands.

Fig. 9: Rectified view of a needle grasping tool

Literature

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