Auto-Gain Approach for Use with Time-Of-Flight Examination in Minimally Invasive Surgery

P. Ritt[1], K. Höller[1], J. Penne[1], A. Schneider[2], J. Hornegger[1], and H. Feussner[2]

[1] Institute of Pattern Recognition (LME), University Erlangen-Nuremberg, Germany,
[2] Workgroup for minimal invasive Surgery MITI, Klinikum r.d.Isar, Technical University, Munich, Germany

Abstract. The use of time-of-flight cameras (TOF) in minimally invasive surgery is expected to grow over the next years. Some of the camera parameters like modulation frequency, integration time or focal point of the camera lens are still controlled by hand. In order to make the handling of a MUSTOF (Multi sensor TOF) endoscopic system more convenient the automation of these parameters with the help of pattern-recognition-methods is a desirable aim [1]. We present a new approach for the automation of the control of one of those parameters, the integration time. We achieve an improvement in time consumption over existing approaches while retaining accuracy of the distance measuring process.

1 Introduction

Distance measuring time-of-flight (TOF) cameras are already widely used in many sectors. It is easily understood that 3D views are a big gain for minimally invasive surgery (MIS) and natural orifice transluminal endoscopic surgery (NOTES), improving both, precision and convenience of such treatments. For that reason the development of the use of TOF-cameras in minimally invasive surgery has been intensified. Before commercial products can be realized there are still hurdles to overcome.
One of those hurdles is reaching a sufficient accuracy of the distance measuring process. So far, under best conditions TOF-cameras reach a distance accuracy of 1-2 mm for distances up to 50 cm. Outside the best conditions the distance measurements rapidly loose accuracy, thus it is essential to operate the TOF-cameras in best conditions. One important parameter that influences the precision is the amount of received light. The amount of received light is directly controlled by integration time, which is the time-span where the CCD-sensor receives light.
But let's first have a look at the basic principle of the TOF-camera [2][3]:

- Modulated light is sent out by the camera (active illumination), scattered by the object and received again by the camera.
- The camera measures the phase difference ϕ_d between the sent and received light.
- The phase difference is measured by sampling the received signal at 4 measurement points (fig. 1). The phase difference is calculated by
  $\phi_d = \arctan(\frac{a_0 - a_2}{a_1 - a_3})$.
- The distance d now is calculated by
  $d = \frac{c}{2f_0}\frac{\phi_d}{2\pi}$. (with the speed of light c and the modulation frequency f_0)

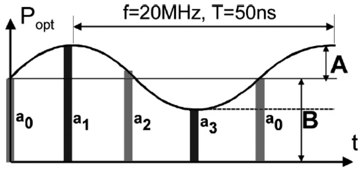

Fig. 1: Sampling points of the received signal

2 Problem description

Our measurements show that it is necessary to be within a certain range in integration time, in order to obtain accurate distance information. It can be seen on fig. 2 that a too low integration

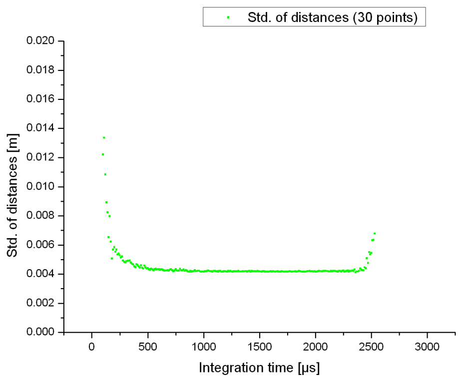

Fig. 2: Standard-deviation vs. Integration time

time results in a high uncertainty (high standard-deviation). This is caused by statistical effects of the electron-generation/photon-absorption process. A too high integration time also leads to high uncertainty. This is caused by saturation effects. The region of 'correct' integration time varies with distance and reflectivity of the observed object. For less reflectivity or further away objects, this region is shifted to higher values (longer integration time) and for higher reflectivity and closer objects to lower values (shorter integration time)(fig. 3). It is therefore necessary to find the right integration time for any observed object, which is one of the aims of our work. The adjustment in integration time also needs to be as fast as possible or at least within 1-2 seconds as it is not reasonable for a surgeon to wait any longer until she/he has access to accurate distance data. Manually adjusting the integration time has major drawbacks. Our measurements show that it takes between 5-10 seconds to adjust manually. The adjusting process also needs a

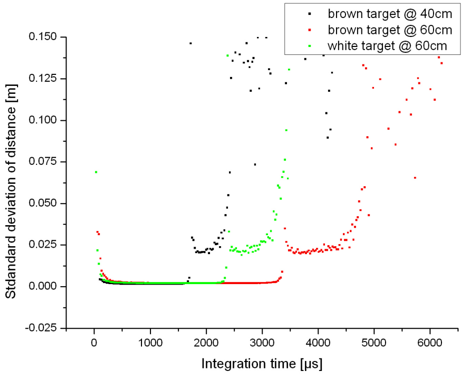

Fig. 3: Standard-deviation vs. Integration time for different distances/reflectivities

lot of attention of the surgeon or alternatively of a second person that controls integration time. So we try to discuss and provide solutions for the following questions:

- Is there a reliable way of judging which integration time is good and which is not?
- Is an automation of the integration-time-adaption possible? Can it be realized in such ways that the adaption process is fast enough in order to avoid irritations and inconveniences for the surgeon/medical staff?

3 Methods

During our experiments we found out that the amplitude image that the cameras supply is a good indication of the reliability of the distance values (fig. 4). We see that the curves for different reflectivities/distances cover very well, which means that a certain amplitude can be interpreted as an indicator for accuracy. The amplitude value is usually based on the evaluation algorithms implemented in the camera. Basically the amplitude A depends (fig. 1) on the measured values according to $A \sim \frac{1}{2} \cdot \sqrt{(a_3 - a_1)^2 + (a_0 - a_2)^2}$. Yet the amplitude range that offers a good reliability has to be measured for every camera model.

For the adjustment of the integration time, our first realizations were simply increasing integration time by a fixed step if amplitude is too low and decreasing it if amplitude is too high. This approach had two major drawbacks. It is quite slow, as the curves for low reflectivity or high distance are very shallow compared to high reflectivity or short distances (fig. 5). It would take a lot of steps for low reflectivities/high distances to reach the desired region of amplitudes. We can also see (fig. 5) a region with negative slope. If our camera somehow is in this region, the algorithm would find a too low amplitude and would therefore increase the integration time, resulting in an even lower amplitude.

Consequently the next approach involved slopes to a) estimate how big the consecutive steps need to be in order to reach a good amplitude as fast as possible and to b) determine on which side (positive slope/negative slope) of the curve it is right now. Unfortunately this didn't work very well, we needed a lot of measurement points to calculate a reliable slope, which is quite easy to

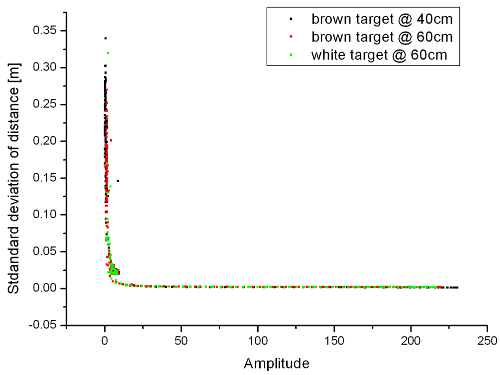

Fig. 4: Standard-deviation vs. Amplitude for different distances/reflectivities

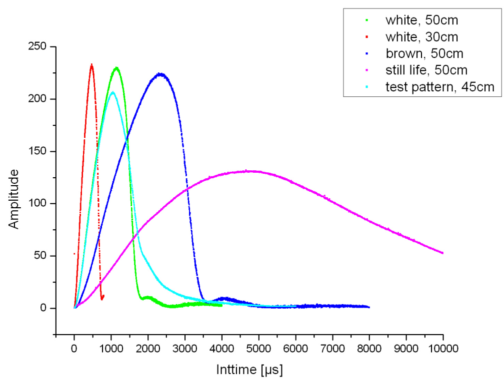

Fig. 5: Amplitude vs. Integration time for different distances/reflectivities

understand if we look at a detailed view of the integration time - amplitude curve. The points are heavily scattered, therefore it is not possible to calculate a reliable slope out of a maximum of 10 points (again every point means one frame). Even if we got a reliable slope, this could only give coarse clue for the position on the curve, as we already know that the curves have different shapes for different reflectivity/distances (fig. 5).

When dealing with this problems we noticed that the curves for different reflectivities/distances

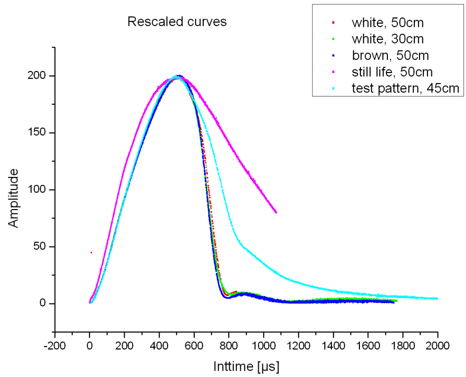

Fig. 6: Rescaled curves: Amplitude vs. Integration time for different targets/distances

look somehow similar. We found out that the curves are linear scaled on the integration time axis up to a certain degree. So if we rescale the curves to a reference curve they are nearly congruent (fig. 6). This can be used for adjusting the integration time, our algorithm does the following steps to calculate the correct integration time.

1. Before we can even use our algorithm, we need a reference curve. So we direct the camera to a static scene (typically similar to the later use of the camera) and record the amplitude values for consecutive integration time values (for example, 100 μs, 200 μs, 300 μs...). For a reliable curve, we measure a few frames for every integration time and calculate the mean value of the amplitude data. In the end we get a curve with (typically a few hundred) n pairs $(I_x; A_x), 0 < x \leq n$, consisting of an integration time I_x and the belonging to its amplitude A_x. This is our reference curve.
2. In the auto gain process we need a reliable data pair on our (now unknown) curve which consinsts of an integration time I_m and the measured amplitude A_m. This is done by a multiple measurement of the amplitude at the constant integration time I_m with following calculation of the mean value. Before this the integration time is risen until a certain minimum amplitude is reached. This is necessary because the measurement points are heavily scattered for low amplitudes and therefore have got a high inaccuracy.
3. In the next step the amplitude A_m of our data pair is compared to the amplitudes of the reference curve. The amplitude A_b that matches our measured amplitude best (that means, which is closest to the measured amplitude) is identified and the belonging to its integration time I_b is read out.

4. The scaling factor s is calculated. It is the ratio of the integration time used for the measurement and the read out integration time. $s = \frac{I_m}{I_b}$
5. Now the target amplitude is compared with the amplitudes in the reference curve, again the amplitude closest to the target amplitude is identified and the belonging to its integration time I_b read out.
6. The target integration time I_t can now be calculated according to $I_t = s \cdot I_b$.

4 Results

The knowledge of the scaling factor s allows to jump directly to the appropriate integration time I_t, without having to do any intermediate steps. The reference curve usually needs only to be obtained once for every camera-endoscope setup.
With the help of the described procedure it is possible to speed up the auto gain process. Our experiments have shown that manually adjusting the integration time normally takes 5-10 seconds, depending on how much the integration time needs to be changed. First automatic approaches took about 10-20 seconds. Our method normally needs 9-12 frames to adjust to the right integration time, 3 frames under good conditions (only small adjustment needed), which results in 1-3 seconds and for good conditions below 1 second.

5 Outlook

The method is still limited to a region of about 1 meter around the distance in which the reference curve was obtained, as the curves are only scaled in first approximation by a constant factor. With bigger differences in distance the non-linearities grow and limit the accuracy of the method. At this point development is still necessary, we are confident that we are able to adapt the usability to a wider distance range.

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