The use of time of flight camera for soft tissue tracking during minimally invasive hip arthroplasty

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Abstract:
Time of flight (TOF) cameras can guide surgical robots or provide soft tissue information for augmented reality in the medical field. In this study a method to automatically track the soft tissue envelope of a minimally invasive hip approach in a cadaver study is described. An algorithm for the TOF camera was developed and 30 measurements on 8 operational siti (direct anterior approach) were carried out. The results were compared to a manual measurement of the soft tissue envelope. The TOF camera showed an overall recognition rate of the soft tissue envelope of 75 %. Comparing the results from the algorithm to the manual measurements a significant difference was found (p>0.005).Recognizing the soft tissue envelope remains challenging. By further optimizing the algorithm and improving the measurement technique a a robotic navigation device for minimally invasive hip surgery could be developed.

Keywords: Soft tissue motion tracking, Robotic navigation, Minimally invasive hip arthroplasty.

1 Introduction

In robot assisted surgery, soft tissue motion tracking is important for intraoperative surgical guidance, motion compensation, and observing active constraints [1]. It is important to avoid critical anatomical structures such as nerves and blood vessels. Therefore, it is necessary to develop complementary techniques for accurate 3D surface structure reconstruction and motion estimation in situ in real time [2].
Time of Flight (TOF) cameras were introduced for 3D mapping for robotic navigation [3-4], computer graphics [5], as well as for gesture recognition [6-7]. In the medical field they are used for model-based human pose estimation, 3D endoscopy [8], respiratory motion detection, and gait analysis [6, 9-10]. 3D simultaneous localization and mapping is important for robot navigation and object recognition, as the specific environment in which it is moving can be reconstructed [3, 11]. This object recognition information can be used for guiding a surgical robot, also providing soft tissue information. Photonic mixing device (PMD) cameras combine fast imaging and high lateral resolution with depth information of the captured scene. This makes the camera suitable for applications in the medical field.
In this study we describe a method to automatically track the soft tissue envelope of a minimally invasive hip approach in a cadaver study with a time of flight camera. The benefit by detecting the borders of the surgical situs is to provide boundaries conditions to the movement of a robot inserted into the hip cavity. Soft tissue damages could be avoided by tracking the soft tissue envelope.

2 Materials and Methods

Measurement setup:
A TOF-PMD camera (CamCube2, PMD Technologies GmbH, Siegen, Germany) was used in 30 measurements on 8 cadavers on which minimally invasive hip arthroplasty was performed as described by Nogler et al [12]. The camera uses modulated near-infrared light to illuminate the scene and uses the phase delay between emitted and reflected signal to estimate the distance between the object and the camera [6, 13].
All measurements were taken "freehand" (without using a tripod) with the TOF-PMD camera and without specifying the registration angle. The camera recorded a dataset of 250 frames for each cadaver (Resolution 200x200 pixels, 962kB). The integration time was set to 50 µs, according to the registration distance [14], and the modulation frequency was set to 20 MHz. Using the application programming interface of the PMD camera (PMDSK2 V.2.2.1, PMD

Technologies GmbH, Siegen, Germany) an algorithm was developed in MATLAB® (MATLAB® R2011b, MathWorks®, Natick-MA, USA) to recognize the boarders of the soft tissue envelope of the surgical approach.

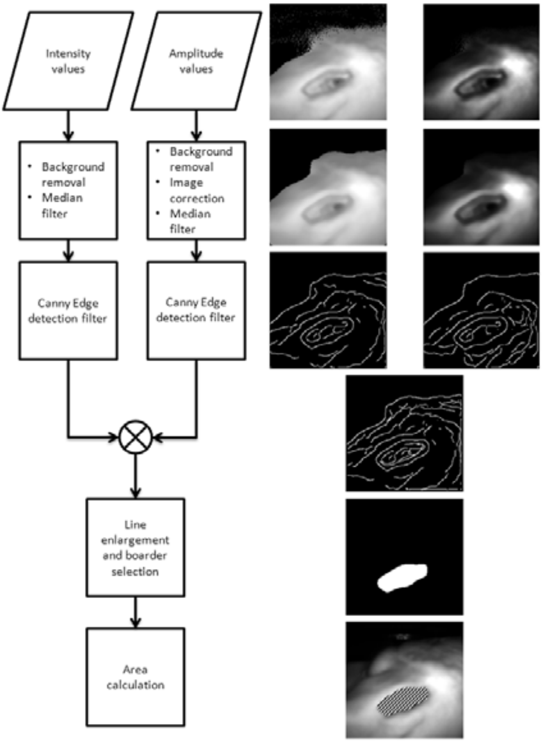

Figure 1: Flow chart of the image processing algorithm

Image filtering:

For each frame recorded by the camera an intensity, an amplitude, and a distance map is generated and the 3D coordinates of each pixel in relation to the camera are calculated (Fig 1). By scaling the new values, so that 1% of the image was saturated at low (lower limit) and high intensities (upper limit), the contrast of the output image was enhanced. The background filter proposed in this study eliminates the values that are out of a predefined range (calculated median of each frame ± 80%). The amplitude data was corrected by using the statement described by Oprisecu et al. [15].The intensity and amplitude maps are filtered by a median filter with a kernel size of 9x9 to reduce the variability for each pixel (Fig 1, Step 1).

Contour extraction:

Amplitude and intensity values are filtered for each frame by a Canny edge detection filter to extract the contours of the soft tissue envelope (Fig 1, Step 2). The contours of the images were improved with a logic operation described by Danciu et al [16]. We used a AND combination in a 5 x 5 neighbourhood between intensity and amplitude values (Fig 1, Step 3). The borders detected by the edge detection filter were enlarged with a line with a minimum length of 3 pixels. The border was cleared from attaching pixels by eroding it with a diamond shape element of size 3.

The region of interest for the soft tissue envelope was selected by using a threshold function on the size of the calculated area. The area was calculated by determining the minor and major axis length of the recognized regions. All areas were taken into consideration which stayed within an area of ± 10% of the area of an ellipse (Fig 1, Step 4).

A temporal filter was introduced to increase detection of the operational situs, which takes the average of two frames across two or more successive time steps. Position and camera rotation is corrected by calculating the rototranslation of the frames.

Area calculation and measurement validation:
After selecting the 3D points of the operational situs area by the mask operation, the area can be calculated by using the Delaunay Triangulation (Fig 1, Step 5). The area calculated by the algorithm was compared to 30 manual measurement of the size of the soft tissue envelope, which was approximated to an ellipse, as well as to a rhombus. A ruler was used in the manual measurements to determine the maximum extensions of the approach. A similar measurement method is used in wound care treatment to determine the size of a wound[17].
To evaluate the suitability as a soft tissue tracking device the recognition rate was reported as a percentage out of the recorded dataset of 250 images for each measurement and each operational situs. The minimum and maximum values of each measurement as well as the median were reported. Evident errors (outliers) in recognizing the operational situs were reported.
To evaluate the performance of the algorithms, the mean out of 250 images for each dataset were reported together with the standard deviation. Statistical analysis was performed using SPSS® (V20, IBM® Corporation, New York, United States). Pair-wise post-hoc comparisons of the three groups were carried out with the Sidak procedure.
The time for executing the MATLAB® script was reported. The script run on a Computer Workstation (Intel® CoreTM2 Duo CPU E8400 @ 3.00 GHz and with 3.21 GB of RAM).

3 Results

The measurements with the TOF-PMD camera on 8 different surgical approaches resulted in an overall recognition rate of the operational situs of 75 % (Figure 3). The overall performance was 75% (31.2–100%). In three cases more than one area was recognized. They can be easily detected, as the value of the area deviate markedly from the other areas (outliers). The best performance was obtained in surgical situs 7, where the median recognition rate was 98 % (48–100%). In four surgical siti the maximum recognition rate was 100%, in four siti the minimum was below 40 %. The median recognition rate was always higher than 50% except for surgical situs 5.
The measurements obtained with the TOF-PMD camera were statistically significant different compared to the ellipse approximation ($p>0.001$) and the rhombus approximation ($p>0.005$) (Table 1). Considering the rhombus approximation the area was always underestimated, while using the ellipse approximation the entrance area was overestimated.
The time for processing 250 images was 29 min, which translated to a calculation time of 7 sec for each frame on average. Processing the frames of the measurement with the worst recognition rate (32.1%) was 22 min, with an average calculation speed of 5.3 sec for each frame on average.

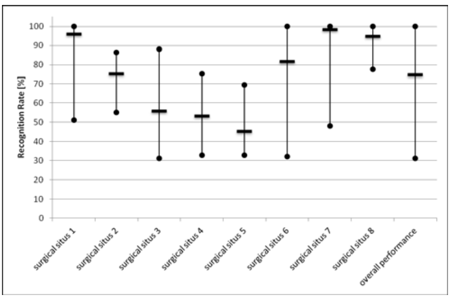

Figure 2: Median, minimum and maximum percentage of recognized regions out of 250 frames of the operational situs reported in %.

Surgical Situs	Ellipse [mm²]	Rhombus [mm²]	TOF [mm²]
1	22.8 ± 2.1	14.5 ± 1.3	17.7 ± 1.7
2	37.3 ± 2.1	23.7 ± 1.4	15.7 ± 2.1
3	43.2 ± 1.8	27.5 ± 1.1	29.9 ± 5.4
4	31.7 ± 0.8	20.2 ± 0.5	26.2 ± 0.7
5	32.0 ± 1.4	20.4 ± 0.9	22.5 ± 1.9
6	31.9 ± 2.0	20.3 ± 1.2	22.2 ± 6.8
7	33.0 ± 0.5	21.0 ± 0.3	28.5 ± 5.9
8	55.8 ± 5.2	35.5 ± 3.3	31.7 ± 4.4

Table 1: Comparison of the area calculation between the TOF-PMD camera and a manual measurement with an approximation to an ellipse and to a rhombus

4 Discussion

This study evaluates the suitability of a TOF-PMD camera for recognizing the surgical situs of a minimally invasive hip surgery. The algorithm was developed on MATLAB® as a script file, which means that the different functions were not optimized for the specific purpose. Optimizing the algorithm's memory usage and including only the necessary libraries will increase the processing speed notably. The algorithm consists of filters and simple image processing techniques, which should make it particularly fast.

The measurements obtained with the TOF-PMD camera were statistically significant different compared to the ellipse approximation ($p>0.001$) and the rhombus approximation ($p>0.005$). In the approximation to a rhombus the area was always underestimated, while using the ellipse approximation the entrance area was overestimated. Staying between this two limits, which are a rough estimation of the soft tissue envelope sizes, proves that the algorithm recognized the operation situs successfully. Additionally, the soft tissue envelope size can be calculated, which might be helpful in characterizing soft tissue damages of different approaches. Since there is currently no alternative measurement system available to perform such a task, this could be another possible application.

There are still some problems left to solve before a TOF-PMD camera can be used in an intraoperative setting. In this study the suitability of a TOF-PMD camera was evaluated in order to track the soft tissue in a dynamic environment. This was achieved by moving the camera while registering the approach to the hip. The challenge of measuring the shape of soft tissue envelopes intraoperatively was simplified by standardizing all operational siti to an ellipse-shape. In reality, retractors would be introduced, and the shape of the operational situs would vary to an extent depending on the number of retractors inserted into the hip cavity.

The delineation of the soft tissue envelope is recognized automatically in almost 75% of the images, with no manual corrections necessary. However, there might be some inaccuracies due to the low resolution of the TOF-PMD camera. The area calculation depends on the mask size. Using the line enlargement function increases the probability of recognizing a closed border line of the operational situs, but it could also lead to a larger area, which could modify the result of the area calculation. The filling operator cannot deal with gaps in the detected boarders, which explains part of the unrecognised soft tissue envelopes.

The low resolution of the TOF-PMD camera can be addressed by combining it with a high resolution CCD camera [18]. The area of the operational situs could be calculated more precisely with a higher image resolution and the colour information could be used to increase the detectability of the soft tissue envelope.

5 Conclusion

We presented a method for automatically recognizing the operational sits and calculating its area in minimally invasive hip arthroplasty. The TOF-PMD camera appears to be a suitable tool for recognizing the operational situs automatically in a real-time application. Further improvements could result in a robotic navigation device usable intraoperatively for minimally invasive hip surgery.

6 References

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