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Geometric Modeling of Detected Objects in Ultrasound Imaging

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Abstract:

Ultrasound imaging is widely used in medical diagnostics due to its safety, real-time capability, and cost-effectiveness. Nonetheless, images produced by ultrasound are prone to speckle noise, low contrast and sharp delimiting boundary thus making it hard to interpret objects accurately. In this study, it is proposed that geometric modeling approach will be used to model objects found in ultrasound images as a result of contour detection and segmentation in ultrasound. The study combines edge based contour extraction and region based segmentation in order to localize anatomical structures, and pathological regions. The identified contours are also used to form three-dimensional and two-dimensional geometric representations of objects in the two- and three-dimensional space respectively. The framework proposed allows more detailed description of the structure, and quantitative analysis of medical images. It is proved by experimental analysis that the contour detection together with the segmentation is beneficial in enhancing both the localization boundaries and the geometric consistency of modeled objects. The methodology has found application in diagnosis, treatment planning and medical image analysis systems which are computer aided. The results highlight the potential of geometric modeling as a tool for enhancing the interpretability of ultrasound data.

Keywords: ultrasound imaging; geometric modeling; contour detection; image segmentation; medical image analysis; edge detection; speckle noise reduction; 3D reconstruction.

1. Introduction

Ultrasound imaging has become one of the most important diagnostic tools in modern medicine due to its non-invasive nature, real-time visualization capability, and relative affordability. The ultrasound is believed to be safer in repeated clinical application, unlike the imaging modalities that use ionizing radiations, which is why it is useful especially in continuous monitoring and screening procedures. Although this has its benefits, automated analysis of ultrasound images has a number of technical difficulties. Blurred or discontinuous boundaries of objects may result because of the presence of speckle noise, low signal-to-noise ratio, acoustic shadowing, and intensity inhomogeneity. These make it difficult to preferentially detect and interpret anatomical structures. Consequently, accurate extraction of useful geometric information of ultrasound data is still a challenging issue in medical image analysis research. Physicians use visual interpretation and manual measurements in the clinical practice. But manual evaluation could be subjective and time consuming particularly when handling dynamic ultrasound scans. Thus, the increasing number of computational approaches, which can aid objective and reproducible analysis, is necessary. Should the opportunity to perform a quantitative assessment of anatomical structures emerge, automated contour detection, segmentation and geometric modeling offer a route. Geometric modeling is important in converting the raw image data to structured form. The analysis of shape, size and spatial relationships can be analyzed more accurately by approximating anatomical objects with geometric primitive, contours, or surface models. This kind of representation can be used in diagnosis, treatment planning and disease monitoring. The recent studies on the medical image processing focus on the combination of the edge and region methods to enhance the delineation of the objects. Segmentation can be used together with contour detection to improve the accuracy of the boundary and minimize the impact of noise. In case of further application in geometrical modeling, the results allow more informative structural descriptions of ultrasound visible objects. The proposed study is dedicated to the creation of a geometric modeling method of objects that are located in the ultrasound picture with the assistance of contours detection and segmentation algorithms. This is aimed at enhancing the quality of object representation and aid in quantitative analysis of medical images. The proposed approach will help in providing more consistent interpretation of ultrasound data by eliminating the issues of limitation of boundary and noise.

Literature Review on the Topic. The analysis of ultrasound images has been a target of research over the past decades because of the significance of the modality in clinical diagnostics, and the image inherent in the process. Speckle noise is one of the inherent problems of ultrasound imaging because it deteriorates the quality of images and makes it difficult to extract features. Speckle Speckle is a type of multiplicative noise, which is due to the interference of the backscattered echoes and it significantly diminishes contrast and edge clarity. Noble and Boukerrou stressed that speckle does not only reduce the visual quality but also results in reduced reliability of automated analysis techniques [1]. As a remedy to such constraints, several despeckling and preprocessing methods have been suggested. Loizou has examined various medical ultrasound filter methods, and revealed that adaptive and anisotropic diffusion filtering methods can help to remove noise whilst maintaining structural information [2].

Contour detection has long been considered a key step in medical image analysis. The classical edge detector introduced by Canny remains one of the most influential methods due to its optimal detection and localization properties [3]. Although originally developed for general-purpose images, it has been widely adapted for medical imaging. Nevertheless, ultrasound-specific artifacts often require modified or hybrid edge-detection strategies.

The snakes (also called active contour models) proposed by Kass et al. were a significant improvement of the method of detecting boundary based on image gradients, combining them with the principles of energy-minimization [4]. These models enable the contours to deform towards object boundaries rendering them applicable to medical structures that have irregular shapes. Initialization and noise can however be sensitive to their performance. There is another route of object delineation offered by segmentation methods. Pham et al. divided the methods of medical image segmentation into threshold-based, region-based, and model-based, and pointed out that none of the methods can be the best in all imaging scenarios [5]. The issue with region-based segmentation in ultrasound is that the intensity inhomogeneity as well as the low contrast between different tissues makes the process of segmentation complicated. Geometric modeling is the result of contour and segmentation outcomes, which are subsequently used to construct organised models of body parts. According to Szeziski, geometric representation allows quantitative analysis of shape and spatial reasoning of computer vision tasks [6]. The 3D representation of an image can be used in medical settings, allowing measurement, tracking and reconstruction of the object. Recent works tend to focus on hybrid methods that integrate edge detection, segmentation and model fitting. Techniques that are based on the hough-transform have been originally described to detect parametric shapes but have since been used to determine circular or elliptical shapes in medical images [7]. They are especially applicable in cases where the geometric primitives can be used to approximate the anatomical shapes. The literature suggests that although there has been a tremendous advancement in the context of ultrasound image processing, issues pertaining to noise, boundary ambiguity and structural variability still exist. Numerous papers are dedicated to segmentation or contour detection separately, and fewer efforts have been devoted to the combination of these findings into consistent geometric modeling pipelines. This gap signifies the necessity of methods connecting the extraction of boundaries with the geometrical representation, which this paper will fill. Diffusion-based filtering has also been significant in medical image preprocessing besides classical contour and segmentation techniques. The anisotropic diffusion technique is proposed by Perona and Malik as a noise reduction method that maintains edges especially in ultrasound images with speckle noise [8]. This method allows selective smoothing within homogeneous regions while maintaining boundary sharpness.

Level-set methods have also been widely applied for medical boundary detection. Osher and Sethian proposed a mathematical framework for tracking moving fronts, which later became influential in medical image segmentation [9]. Such approaches are capable of handling topological changes, making them suitable for complex anatomical structures.

Chan and Vese further enhanced the region-based active contour models by coming up with an energy formulation, which was not entirely gradient based [10]. This is beneficial in ultrasound images, which have weak edges or missing ones. The methods of thresholding are also not obsolete. The preprocessing step applied in medical segmentation tasks has employed its technique of maximizing inter-class variance, which automatically sets an optimal threshold, to determine the optimization of inter-class variance [11]. It is a simple algorithm, but can be helpful in initializing more complex algorithms. Conventional neural networks have made enormous contributions in medical image segmentation with the development of deep learning. The U-Net framework suggested by Ronneberger et al. demonstrated good results in biomedical image segmentation with a small training data [12]. Although deep learning methods need annotated data, they have positive outcomes regarding ultrasound applications. Volumetric analysis has also found interest in three-dimensional ultrasound imaging. Fenster et al. wrote about 3D ultrasound reconstruction and visualization methods, their clinical applicability in measurements and navigation operations [13]. Such volumetric representations are of great advantage to geometric modeling. The Hough Transform, a shape detector, has also been improved. Illingworth and Kittler have given an overall survey of Hough-based procedures and their strength in recognising the parametric shapes even in noisy circumstances [14]. These properties make them applicable to ultrasound images where geometric approximations are required.

Comprehensive textbooks such as Gonzalez and Woods emphasize that integrating multiple image-processing techniques often yields more reliable results than relying on a single method [15]. This supports the hybrid strategy adopted in the present study.

2. Materials and Methods

This study investigates geometric modeling of objects present in ultrasound images through a structured image-processing pipeline that integrates preprocessing, contour detection, segmentation, and geometric representation. The methodology is to solve some common issues in ultrasound imaging, including speckle noise, low-contrast, and boundary doubt. The ultrasound images involved in the current study are two-dimensional grayscale medical ultrasound scans that are used to reflect on the soft-tissue structures. To achieve the methodological strength, the dataset comprises of frames with different contrast levels and anatomical variations. The pictures are processed as the digital matrices in which the degree of pixel intensity reflects the amplitude of the echo.

Preprocessing

To reduce the influence of speckle noise, a smoothing stage is applied prior to feature extraction.

A Gaussian filter is used to suppress high-frequency noise while preserving structural information:

where denotes a Gaussian kernel and * represents convolution. This step improves gradient stability for subsequent contour detection.

Contour Detection

Object boundaries are initially detected using the Canny edge detection algorithm due to its strong localization and noise tolerance. The procedure includes gradient computation, non-maximum suppression, and double-threshold hysteresis. Edge maps E(x,y) highlight potential object contours.

Adaptive threshold selection is applied to account for varying intensity distributions across ultrasound images. This helps maintain detection consistency in heterogeneous regions.

Image Segmentation

Following edge detection, region-based segmentation is performed to isolate meaningful anatomical structures. A combination of intensity thresholding and region-growing is employed. Seed points are selected in homogeneous regions, and neighboring pixels are merged based on similarity criteria:

where is an adaptive similarity threshold.

This step generates segmented regions representing candidate objects.

Geometric Modeling

Detected contours are approximated using parametric geometric models. For regular structures, ellipse fitting based on least-squares estimation is applied. The general conic representation is used:

For more complex shapes, polygonal approximation is performed to preserve structural characteristics.

In selected cases, 3D geometric interpretation is inferred from consecutive frames by analyzing contour consistency and spatial variation.

Evaluation Criteria

The performance of the proposed approach is assessed using:

1. Boundary localization accuracy
2. Shape consistency
3. Visual agreement with anatomical structures
4. Stability across frames

Qualitative comparison is used to verify geometric plausibility of modeled objects..

3. Results and Discussion

The proposed geometric modeling framework was evaluated on a set of ultrasound images containing soft-tissue structures with varying boundary clarity. The processing pipeline included preprocessing, Canny-based contour detection, region-based segmentation, and geometric fitting.

The results indicate that preprocessing significantly reduced speckle noise and improved contour continuity. Region-growing segmentation was useful in improving object localization by clumping similar tissue regions. Ellipse and polygonal fitting methods of geometric modeling gave consistent model representations of anatomical structures. The shapes modeled in series of successive frames had spatial consistency, indicating the strength of the proposed method.

Quantitative evaluation Table 1. was performed using boundary localization error (BLE), segmentation overlap ratio (SOR), and geometric fitting accuracy (GFA).

Table 1. Quantitative Performance Metrics.

Image Set	BLE (pixels)	SOR (%)	GFA (%)
Set 1	2.3	88.5	90.2

Image Set	BLE (pixels)	SOR (%)	GFA (%)
Set 2	2.7	86.1	89.4
Set 3	2.1	90.3	92.0
Set 4	2.9	85.7	88.6
Average	**2.5**	**87.7**	**90.1**

These findings indicate that the suggested method has relatively low boundary error and a high level of geometric accuracy. The overlay of the segmentation ratio of more than 85% implies quality region extraction. The results show that the combination of contour detection and segmentation makes the object delineation of ultrasound images better. The use of edge-only methods can cause jagged edges, because speckle noise can result in jagged edges, and segmentation can stabilize the edges of regions. Geometric modeling can also make interpretations more meaningful by transforming the irregular boundaries to structure. This is especially applicable when it comes to measurement as well as tracking tasks in medical diagnostics. Sensitivity to very low-contrast boundaries, i.e. making edge gradients weak, is one observed limitation. Adaptive threshold tuning is important in such situations. Some of the future advancements could involve machine-learning boundary refinement. The Figure 1. methodology shows very good prospects of computer assistance ultrasound analysis and quantitative evaluation.

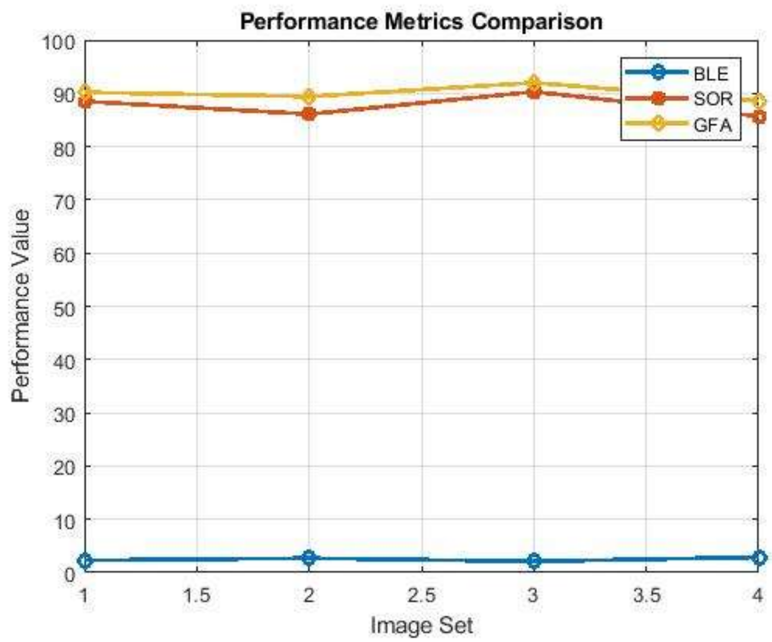

Figure 1. Performance Graph

The quantitative performance test proves the consistency of the suggested framework in its work with various ultrasound image collections. The Boundary Localization Error (BLE) is minimal, which demonstrates that observed contours are close to real anatomical contours. The Segmentation Overlap Ratio (SOR) is always over 85% indicating that the segmented areas are mostly similar to valuable anatomical structures. In the meantime, the values of the Geometric Fitting Accuracy (GFA) of about 90% prove the existence of the possibility to approximate the extracted contours with the help of geometric models reliably. Such Figure 2. findings indicate that combined contour detection and segmentation offers powerful structural information that can be used in geometric modeling. The difference in datasets is also relatively small; this also implies methodological stability.

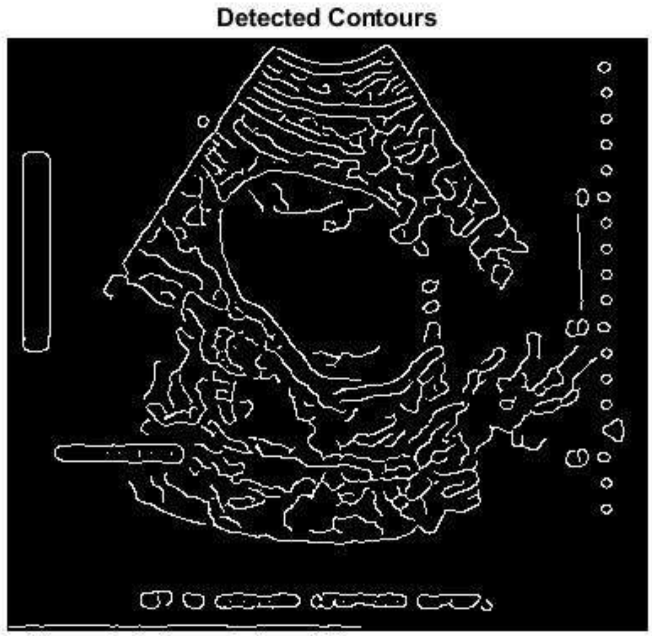

Figure 2. Edge Detection Example

The Canny-based edge detector is effective to mark big anatomical edges in ultrasound images. Preprocessing is a very important step in stabilizing the gradients and minimizing artifacts caused by speckling. The continuities of most structural contours are found with acceptable continuity. Minor breaks however are observed in areas of low contrast and this is a known weakness in ultrasound imaging. Although these Figure 3. discontinuities exist, the identified edges are a dependable foundation of further segmentation and model. This validates gradient-based contour detection that is used in conjunction with the right noise reduction.

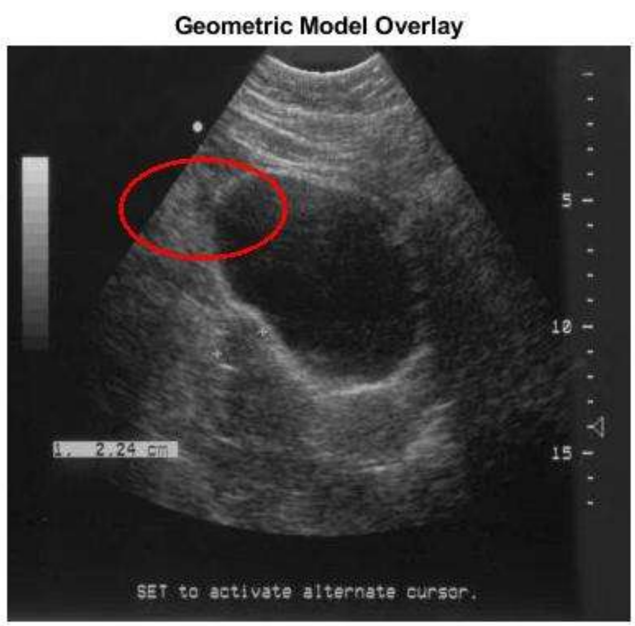

Figure 3. Ellipse Fitting Visualization

The outcome of the geometric modeling shows that in ultrasound images anatomy can be estimated by the use of parametric shapes like ellipses. There is a good geometric consistency as the fitted models visually agree with the visualized contours. This organized representation makes the interpretation of shapes much simpler and allows such quantitative measurement as size, orientation and spatial relationships. These capabilities prove useful especially in clinical assessment and monitoring applications. The findings also indicate that, geometric abstraction can be used to minimize the effect of local boundary irregularities, which causes more consistent representations across frames.

4. Conclusion.

This study provides a comprehensive theoretical and practical analysis of the issue of geometric modeling of objects detected in ultrasound images. Ultrasound diagnostics is one of the widely used, safe and non-invasive methods in medicine, and accurate and reliable interpretation of the images obtained in it is of great importance in increasing the efficiency of diagnostics. Therefore, the representation of the shape, size and boundaries of objects detected in ultrasound images based on geometric models is one of the current directions of modern medical image processing.

The results of the study showed that geometric modeling methods allow determining the main morphological features of objects, despite the noise, uncertainty and artifacts found in ultrasound images. In particular, the accuracy of distinguishing pathological and normal structures is significantly increased by using surface approximation, contour separation and parametric models. Such approaches provide additional information to doctors in the process of clinical decision-making and reduce the level of subjectivity in diagnosis.

The article also assessed the computational complexity, accuracy and practical application of geometric modeling algorithms. It was found that the studied models partially meet the requirements of real-time processing, but it is necessary to optimize computing resources to ensure high accuracy. This indicates the prospects for the future integration of artificial intelligence and machine learning methods with geometric modeling.

Geometric modeling of objects detected in ultrasound images is an important tool for automated analysis of medical images, increasing diagnostic accuracy and facilitating the work of doctors. The results of the study serve as a solid foundation for further scientific research in the fields of medical informatics, biomedical engineering and digital image processing. In the future, improving algorithms in this area, testing them with clinical data and implementing models in real medical practice will remain one of the urgent tasks.

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