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Detection, localization, and segmentation of colorectal polyps in colonoscopy images by computational intelligence methods

Doctoral Theses Booklet

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Motivation

Colorectal polyps are abnormal growths that develop on the inner lining of the colon or rectum. While most polyps are benign and do not cause any symptoms, some polyps can potentially become cancerous over time. Colorectal cancer (CRC) is the third lethal cancer type and the fourth most common cause of cancer mortality worldwide (Ismail & Nagy, 2021). The prevention of CRC is one of the most important worldwide public health studies and has a high priority in computer-aided diagnostic (CAD) systems research (Bernal, Sanchez, & Vilariño, 2012).

Clinical guidelines based on medical practice as well as scientific evidence recommend that individuals who are over the age of fifty must undergo a regular examination. The conventional, classical, colonoscopy is the most precise visual inspection procedure for early colorectal cancer detection and prevention.

Even for experienced gastroenterologists, detecting polyps with the naked eye can be a challenging task, as some polyps may be very small in size or hidden in folds of the colon lining, in addition to various reasons like the inadequate intestinal preparation and doctor's visual exhaustion (Alam & Fattah, 2023), (Krenzer, et al., 2023), (Yue, et al., 2022).

Developing a computer-aided diagnosis system using computational intelligence methods for colorectal polyps' medical tasks, (i.e., colorectal polyps' detection, localization, and segmentation) is currently one of the most demanding needs in the healthcare sector. Such a system would simplify the diagnostic process and facilitate the assessment of the examined cases severity. Although none of these intelligence methods are intended to replace human diagnosis, at least, not in the near future, but they definitely help the often-overloaded medical staff to collect and organize the available data for decision support. They can draw their attention to certain phenomena, identify and

highlight potential polyps, and provide accurate measurements of polyps' size, location, and the degree of their severity (Alam & Fattah, 2023), (Krenzer, et al., 2023), (Yue, et al., 2022).

By utilizing advanced image processing and computer vision techniques, many algorithms have been developed in the scientific community of medical image processing to automatically assist gastroenterologists in detecting, localizing, and segmenting polyps during colonoscopy. These algorithms vary from polyp shape or texture-based handcrafted methods to fully automated machine learning methods based on highly efficient neural networks, as well as the hybrid methods which combine both.

One of the fundamental challenges in medical image processing is the limited number of training and testing database samples. Unlike the usual image classification tasks, the medical images cannot be processed by unskilled personnel, the preparation of the labeled ground truth masks need medical experts, that makes the creation of the medical databases very costly and time-consuming process. In addition legal, social, and ethical challenges come with managing personal data corresponding to the medical images. The above-mentioned facts clarify why the large training set based learning algorithms are not the only possibilities in medical image processing, but other approaches, such as expert knowledge based fuzzy inference are also preferable.

In the past few years, a research team has been formed at Széchenyi István University that focuses on detecting and classifying colorectal polyps within colonoscopy image segments using a fuzzy inference-based strategy. The proposed strategy was based on comprehensive consultations with expert gastroenterologists and on the utilization of plausible statistical parameters and entropies of image segments as antecedents, and finally, a fuzzy decision value was assigned to each segment.

Even though fuzzy inference is not used by other groups in this field of medical image analysis, the previous results are somewhat promising, but leave place for further development.

In my work, I aimed to achieve better, more flexible, and more plausible processing of colonoscopy images. The continuous improvement and exploring of the fuzzy inference-based method was essential. My contribution was introducing new rulebase generation methods and more fitting consequents for colorectal polyp detection purposes using the stabilized Kóczy-Hirota rulebase interpolation method.

As the classical circular Hough transform was already found to be successful in colorectal polyp localization task, to deal with the not perfectly circular shapes of the polyps and to improve the Hough transform's tolerance for shape deviation, I studied the applicability of fuzzy Hough transform, together with special preprocessing methods and a gradient-based weighting approach in its voting methodology.

As a last step, I also researched the colorectal polyp segmentation possibilities. One of the most effective, non artificial intelligent based segmentation methods is the active contours method. I tested the efficiency of two active contours methods and the necessary preprocessing steps to optimize their performance.

Research Methodology

A comprehensive literature review has been carried out to establish a robust background on the research topic, with an intense focus on the international contributions and recently developed algorithms together with the evaluation employed metrics in this interesting field.

In this dissertation, three publicly available still colonoscopy image databases CVC-Clinic (Bernal J. , et al., 2015), CVC-Colon (Bernal, Sanchez,

& Vilariño, 2012), and Etis-Larib (Silva, Histace, Romain, Dray, & Granado, 2014) were used. Each of these databases contains a specific number of images, namely 612, 380, and 195, respectively. The colonoscopy images have different sizes, the dimensions of the images are 384×288, 574×500, and 1225×966 pixels, and they have a resolution of 96, 72, and 72 dpi, respectively. Furthermore, the colour depth of the RGB color pictures is 24 bit per pixel. In addition to the frames, a ground truth mask corresponding to the region covered by the polyp/ polyps in the image is also included in each database.

The research methodology can be well organized by briefly listing the practical steps that were implemented and investigated in the dissertation as follows.

❖ Utilizing computational intelligence methods through simple measured data that are easy to interpret by medical experts is very advantageous for computer-aided diagnosis systems. Based on the concept of fuzzy reasoning, if the rulebase is derived from plausible statistical parameters of the image being analyzed, it can be easily comprehended and accepted by society. Thus, a further development for a fuzzy inference-based strategy was carried out. Simple statistical parameters and entropies of image segments were used as rulebase antecedents.

- Investigating the impact of determining the rulebase parameters on the efficiency of the detecting of the polyp segment using stabilized Kóczy-Hirota fuzzy rule interpolation. The performance of the proposed method was evaluated using the true positive rate (TPR), the false positive rate (FPR), the true negative rate (TNR) and the false negative rate (FNR) metrics.
- Introducing more consequent classes in the colorectal polyp's detection approach to better align with real-world scenarios, and examining the effect of the refinement of the consequent categories in stabilized Kóczy-Hirota

fuzzy rule interpolation. The number of the consequents was extended from two classes, (i.e., "with-polyp", or "without-polyp"), to a more refined set distribution based on the polyp content of the image segment. Other metrics, namely accuracy (ACC), Matthews correlation coefficient (MCC) and F_1 score were introduced for a more detailed evaluation.

- ❖ Applying classical circular Hough transform was proven to be effective for some types of colorectal polyps. However, the polyps are very rarely perfectly circular, so more tolerance to shape uncertainty is needed. That was the reason why the switching from the classical circular Hough transform to the fuzzy circular Hough transform for the colorectal polyp's localization purposes was proposed.
  - Depending on statistical data from the three colonoscopy databases, the performance of four edge detection algorithms (Canny, Prewitt, Roberts, and Sobel) was compared, and the most ideal one that gave the most polyp contour related and least unnecessary edge points, i.e., the lowest number of points to be transformed, was selected. Two metrics based on normalized gradients of contour and non-contour edges were developed to establish this selection.
  - According to a statistical study that has been performed during this research, in the colonoscopy images the polyp contours usually belong to gradient domain of neither too large, nor too small gradients, though they can also have stronger or weaker segments. To prioritize the gradient domain typical for the polyps, a relative gradient-based thresholding as well as a gradient-weighted voting approach was introduced.
  - Characterizing the roundness of the objects to be detected was applied for evaluating the improvement of the shape deviation tolerance of the classical and fuzzy Hough transforms using the maximum radial displacement and the average radius.

❖ Considering the importance of segmenting detected polyps for achieving precise diagnosis, it was worth searching systematically, how colonoscopy databases are responding to two of the most influential variational segmentation methods, the geodesic and Chan–Vese active contour methods.

- As the quality of colonoscopy databases varies, preprocessing steps were taken before evaluating 14 filtered images as inputs for the active contour methods.
- The performance of the segmentation techniques was measured using the Sørensen-Dice Similarity Coefficient. The effects of the initial mask shape and its size together with the number of iterations, contraction bias and smoothness factor were studied.

Finally, it is worth mentioning that all steps formulated in the dissertation have been implemented by computer simulation in a MATLAB environment. All image processing, analyzing, and visualizing were performed using the powerful image processing toolbox as well as codes developed for the given purpose by me and our research group.

Thesis statements

Thesis 1

I suggested two novel rulebase generation methods for the application of fuzzy inference with stabilized Kóczy-Hirota rule interpolation in colorectal polyp detection, a median-centered and a histogram-fitted method. Both methods depend on the statistics of the training set. The median-centered method connects the characteristic points of a triangular membership function, i.e., the edges of its support and the core point to the minimum, maximum and median of the distribution of the training set, respectively. The histogram-fitted method generates triangular rules where the core of the fuzzy membership function is the highest point of the 100-bin, equal-width histograms of the normalized

measured data of each antecedent and each consequent in the training set. The support edges extend to the domain where the histogram values first cross a given percentage (1%, 5%, or 10%) of its peak value, starting from both sides of the interval [0;1].

A. I compared the results of the two proposed rulebase generation methods to the original, mean-centered method. For three publicly available databases, I calculated the true positive rate, the false positive rate, the true negative rate and the false negative rate for antecedent numbers being 2/3, 1/2, and 1/3 of the original 99 antecedents. I concluded, that the results of the three methods are comparable to each other for the studied numbers of antecedents.

B. Among the histogram-fitted rulebases, the lowest percentage one, with the widest support gave the best results.

Thesis 2

Based on the multiple peaks visible on the 100-bin, equal-width histograms of the distributions of the normalized measured data for many antecedents, I proposed to increase the number of consequents during the fuzzy decision process to improve the binary "with polyp"-"no polyp" classification of tiles of colonoscopy images. Instead of polyp area percentage of 0% or above 0% classes, I studied a 3-output class case with borderlines at 0% and 50%, and a 4-output class case with borderlines at 0%, 20%, and 50%.

A. The true positive rates are the best for the histogram-fitted rules with HSV version of the images. However, in these cases, the true negative rates became very low. These results are not much influenced by the number of antecedents used and the number of consequent classes.

B. The accuracy is the best in the case of the original 99-antecedents, 2-consequents, mean-centered case for RGB versions of the images.

C. The Matthews Correlation Coefficient (MCC), as well as the F_1 score are the best in the case of HSV version of the images, 3-consequents, 66-antecedents and mean-centered rules.

Thesis 3

In order to increase the classical Hough transform's tolerance to deviations from circle, I proposed to apply fuzzy Hough transform in the colorectal polyp localization task instead of the classical one, and I compared their performance.

A. As the detection success also depends on the size of the colorectal polyp and its roundness, I introduced the roundness error together with the radial displacements and the average radius of the polyp to test the different types of Hough transforms' tolerance degree to the deviation from the circle.

B. Using artificial images, I showed that if the Hough transform's fuzzyness parameter increases, or the local maximum threshold of the transformed image decreases, or the size of the object decreases, the tolerance for shape deviations increases as well.

   For classical Hough transform the tolerance increases with increasing the size of the object.

Thesis 4

For colorectal polyp localization purposes, I developed a novel gradient-weighted voting approach for classical and fuzzy circular Hough transforms.

A. As a preprocessing method for Hough transforms, I studied four different edge detection algorithms. I developed and applied two evaluation metrics using the number of pixels in the polyp contours, and the number of edge pixels detected by the algorithms both in the full image and in the environment of the polyp contour for all the images of 3 publicly available databases. The Prewitt edge detection

algorithm proved to be the optimal choice for colorectal polyp localization purposes.

B. In order to further decrease the number of unnecessary edge points to be processed by Hough transforms, I suggested an experimentally validated gradient-based thresholding method. I proposed two different gradient threshold domains based on the typical gradient domain of the polyp edge points, a wider and a thinner one with relative gradient values [0.06, 0.3], and [0.08, 0.2]. The wider gradient threshold was proven to give more reliable results. Using this method, the runtime of the algorithms decreased by about 50% compared to the full Hough transforms. The thinner threshold further decreased the runtime, but it removed so many valuable edge points which made the detection of the polyp impossible for several images.

C. I introduced a gradient-weighted voting approach to both classical and fuzzy circular Hough transforms based on the probability distribution of the polyp contour pixels' gradients of images form 3 publicly available databases. The normalized gradient values serve as weights of the edge points in the Hough transformation step. For 8 grades of fuzzyness and 5 local maximum thresholds of the global maximum of the votes, I performed the Hough transforms for both the original and the gradient-weighted voting processes with wide and thin gradient thresholds. The gradient-weighted voting mechanism improved the ratio of the circles near the polyp among all the circles for the Hough transforms, especially for the fuzzy Hough transform.

   For general practice, I suggest using 80% of the global maximum of the votes as local maximum threshold and the application of fuzzy

Hough transform with fuzzyness parameter $\sigma = 7$ together with the wide gradient-weighted voting process.

Thesis 5

For colorectal polyp segmentation purposes, I systematically evaluated the performance of the geodesic and Chan–Vese as two variational segmentation methods using image samples of 3 publicly available databases (including some special problematic cases).

A. I tested the outputs of different pre-filtering techniques as potential inputs for both segmentation methods using Sørensen-Dice Index (SDI) metric. I found that the background-subtracted, mean, median, Gaussian, and Wiener filtered images are the best candidates for improving the segmentation results.

B. I investigated the effect of the initial mask shape on the segmentation results using Sørensen-Dice index metric. Circular and rectangular initial masks were evaluated. I concluded that for the geodesic method in 91.67% of the cases the rectangular masks were more beneficial, while for the Chan Vese method, in 50% of the cases. The Chan-Vese method demonstrated lower sensitivity to the shape of the initial mask than the geodesic method.

   The Geodesic method with the rectangular initial mask provided the best Sørensen-Dice index for most of the cases. If the Chan-Vese method gave better result, the difference between the geodesic and Chan–Vese Sørensen-Dice indices was very small.

C. I studied the influence of the initial mask size together with the smoothness factor, contraction bias, and the number of iterations on the segmentation results. The geodesic approach achieved the best performance using an initial mask encompassing the boundaries of the polyp to be segmented with a contraction bias value which makes the

contour shrink towards the polyp area, while the Chan–Vese approach accomplished the best results using an initial mask located within the polyp region with a contraction bias value which makes the contour expand towards the polyp. The suitable number of iterations ranged from 100 to 300 depending on different image and polyp sizes, although other factors including the strength of colorectal polyp edges or presence of veins also played a significant role.

D. I concluded that, in most of the cases, the Chan–Vese method performed better than the geodesic method in matching the actual contour of the polyps, but it depended more on the effectiveness of the pre-processing procedure.

Publications

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