Fuzzy Logic Based Edge Detection Methods: A Systematic Literature Review

Miquéias Amorim Santos Silva[1][a], Gracaliz Dimuro[1][b], Eduardo Borges[1][c],
Giancarlo Lucca[1][d] and Cedric Marco-Detchart[2][e]

[1]*Center of Computational Sciences, Federal University of Rio Grande, Itália avenue, Rio Grande - RS, Brazil*
[2]*Universitat Politècnica de València, Valencia, Comunitat Valenciana, Spain*

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Abstract: Edge detection, or the detection of the maximum limit between two regions with different properties, is one of the classic problems in the area of computer vision. The uncertainty associated with the nature of this detection, such as the characteristic fuzzy transition zone resulting from the image discretization processes, or even noise and illumination variations, justifies an approach based on fuzzy logic theory. In order to understand the state of the art in edge detection techniques using fuzzy logic-based methods, this work proposes a systematic review considering two bibliographic sources of scientific literature, Scopus and Web Of Science. In total, 34 works were selected through a systematic literature review, and their methods were summarized and reported in this research. From this analysis, it could be concluded that, in recent years, fuzzy logic has been employed in hybrid methods in order to improve the performance of existing techniques or reduce computational complexity. Studies with interval fuzzy logic of higher order have been employed for its greater flexibility in dealing with the uncertainty associated with the edge detection task.

1 INTRODUCTION

One of the most common approaches for detecting discontinuities in images is edge detection (Suresh and Srinivasa Rao, 2019). An edge is defined as the maximum boundary between two regions with different properties (Martin, 2002), i.e. the border between two objects or object faces in an image.

Edge detection represents an important task in several steps of computer vision and image processing such as (Wei et al., 2017); object detection (Yang et al., 2002); pattern recognition (Mohan et al., 2021) and others. Either because of the discretization intrinsic to the digital capture process, or because of some subsequent quantization process, the edge of the objects, or the faces of the objects, show a small smoothing around the actual boundary of the regions.

This uncertainty, among other characteristics of the images, makes it difficult to accurately determine the edge of objects, so different methods have been proposed throughout history, from methods based on partial derivatives such as Sobel (Sobel et al., 1968), Log (Marr and Hildreth, 1980) and Canny (Canny, 1986) in the 1970s and 1980s, up to methods based on convolutional neural networks in recent years (Jing et al., 2022).

Traditional methods have a number of problems, such as high sensitivity to noise, high complexity, and high consumption of time and processing. In general, these methods show very discontinuous results and false positives.

On the other hand, methods based on fuzzy logic (Zadeh, 1965) were developed in order to represent the imprecision and uncertainty of the information (Tripathi et al., 2021). In recent years, there has been increasing research on applications of fuzzy logic in several areas such as pattern recognition, neural networks, expert systems, artificial intelligence, control theory, automata, decision-making, medical diagnosis, and robotics. (Muthalagu et al., 2020; Orhei et al., 2020; Qiu et al., 2021).

In computer vision, in addition to applications in edge detection (Bustince et al., 2009; Lopez-Molina et al., 2010; Marco-Detchart et al., 2021b), fuzzy ap-

[a] https://orcid.org/0000-0003-4496-500X
[b] https://orcid.org/0000-0001-6986-9888
[c] https://orcid.org/0000-0003-1595-7676
[d] https://orcid.org/0000-0002-3776-0260
[e] https://orcid.org/0000-0002-4310-9060

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proaches have been frequent in noise reduction (Yuksel and Basturk, 2012), feature extraction (Shimada et al., 2005), classification and clustering (Koschan and Abidi, 2005).

Considering the importance of research in edge detection through the fuzzy theory approach, and since, to the best of our knowledge, there are no review papers devoted specifically to fuzzy methods, a specific investigation/review of these methods is needed

In this sense, the main research question which is intended to be answered is: **RQF - what is the state of the art of fuzzy edge detection methods?** In order to relate them to the rest of the literature in the area of edge detection, the following should also be answered: **RQG - what is the state of the art of edge detection methods?**

For each research question, a bibliometric analysis was sought in order to provide a set of information that would appropriately position new research activities, this being another contribution of this work, besides the summarization and description of the found methods.

This paper is organized as follows: in Section 2 (Methodology), the search terms, inclusion and exclusion criteria, as well as the number of papers found and admitted for review will be discussed. Next, in Section 3, the results and discussion are presented for each research question mentioned above, summarizing the reviewed methods with their respective bibliometric analyses. Finally, in Section 4, the conclusions are exposed.

2 METHODOLOGY

This section first introduces the concept of a systematic literature review and then presents the methodology used to answer the research problems.

2.1 Systematic Literature Review

According to (Kitchenham and Charters, 2007), a systematic literature review is a form of analysis that aims to identify, evaluate, and interpret all available relevant research on a specific research problem, topic, or phenomenon of interest. Among the various reasons for engaging in a systematic literature review, the most common are:

i. Summarize the existing evidence regarding treatment or technology;

ii. Identify gaps in current research with the goal of suggesting areas for future research;

iii. Provide a set of information that appropriately positions new research activities and;

iv. Reduce, or try to eliminate research bias.

In this context, this research seeks to summarize the existing technology regarding fuzzy edge detection methods. For this, key good practice questions for a quality review, found in (Tacconelli, 2010), were considered.

2.2 Definition of Criteria, Search in the Indexing Bases and Obtaining Primary Research

In order to answer the research problems, searches were conducted in two major bibliographic databases, Scopus (SC)[1] and Web of Science (WS) [2]. In total, 34 papers were selected by merging the results of the searches in the two databases (21 from the SC database and 16 from the WS database). This union, by definition, considers the exclusion of duplicates.

The summary of all the included information and documents that went through each exclusion step, which will be discussed below, is shown in Table 1, where we show for each search question, the considered inclusion terms, where ABS() refers to the terms found in the abstract and TITLE() refers to the terms found in the title. In the number of occurrences, we have the total number of papers found by each database, where inc is the number of papers found in that search, and for each exclusion step (exc) the total number of elected papers.

One can see in Table (1) that four exclusion steps were considered:

i. Step one:

a) Exclusion of papers published before the year 2017.

ii. Step two:

a) Elimination of those that were not written in the English language;

b) Deletion those that have not been published in the computer science or related field and;

c) Elimination papers that had a title that demonstrated the lack of relevance of that study to this review work.

iii. Step three:

a) Deletion of the works flagged as portrayed by the journal and;

b) Analysis of the abstract, eliminating articles that were outside the scope of this review.

[1] www.scopus.com
[2] www.webofscience.com

iv. Step four:

a) Analysis of the methodology and exclusion of those with no validation of the proposed segmentation method.

2.3 Bibliometric Analysis

Bibliometric analysis is defined as the quantitative disclosure of the characteristics of a set of works, with the objective of managing knowledge and scientific information on a specific theme or subject (Aria and Cuccurullo, 2017). One can cite as observable parameters that are commonly analyzed from the articles and papers selected: their references, authors, number of citations, and most relevant journals.

To perform the bibliometric analysis of the papers in this research, we decided to use the bibliometrix tool through the Rstudio software (Aria and Cuccurullo, 2017). Each set of papers, which were selected in order to answer one of the problems of this research, was submitted to bibliometric analysis, evaluating the keywords, authors, affiliation, abstract, citations, and country of origin, reporting only the information relevant to the research problem.

3 RESULTS AND DISCUSSION

This section presents the results of each bibliometric analysis of each group of papers, the summary of the methods found in each set of papers, and a short discussion aiming to synthesize the obtained information.

3.1 State of the Art in Edge Detection (RQG)

In order to identify the state of the art of edge detection methods in the literature, we have chosen the papers that are summarized in Table 2. The biliometry performed aimed to understand the frequent terms, as well as those that have gained relevance in the last 6 years.

First, the absolute numbers of citations that each work received were extracted from the metadata, to determine those with greater relevance to the research topic. In addition, the most cited papers are those that, potentially, best summarize the state of the art until that year of publication, and have a higher ratio between the number of citations and the time elapsed since publication.

In this case, the articles (Magnier et al., 2018; Kaur and Kaur, 2017; Yogesh et al., 2018) appear as the most cited, in the first three positions. Evaluating the number of citations/year, from publication to the present moment, we observe that the works (Suresh and Srinivasa Rao, 2019; Magnier et al., 2018) have the highest scores. In the case of (Suresh and Srinivasa Rao, 2019) it is the most recent work with the highest citation/year ratio.

Through the word cloud of the keywords of all the papers, if we disregard terms such as: "edge detection", "segmentation", "image processing" and other terms that are synonyms or homonyms to them since they are expected words considering the search terms, we find related and recurrent terms that may indicate the methods or applications that have been developed in the studied period. Figure 1 summarizes the most frequent terms found, among them, we can observe terms related to fuzzy logic, machine learning, genetic algorithms, and other classical segmentation and edge detection techniques.

Figure 1: Word clouds of key terms of RQG edge detection methods.

The occurrence of terms related to classical segmentation and edge detection techniques such as Canny, Sobel, and Watersheed in the keywords may indicate a movement towards improving the performance of these techniques that have already been exhaustively studied. Further evidence of this could be found through another analysis, where the terms were considered by year. In this case, words like "edge", "detection" and "segmentation" were the most frequent in the abstracts of the papers in the year 2020, where performance-related terms also started, which had a higher frequency in the year 2022. From these papers, it is interesting to extract especially the methods reviewed by the authors regarding the state of the art in the area of edge detection. Therefore, in the following, we will present a summary of the techniques, grouped by approach.

Gradient-Based Methods: A digital image is a discrete representation of the variation of light in the real world, so each numerical value carried by the pixel represents the intensity of light or color at that

Table 1: Terms of inclusion and exclusion and number of selected papers.

Research question	**Terms of Inclusion**	**Number of occurrences**	
		SCOPUS	**WEB OF SCIENCE**
RQG	*(ABS(edge PRE/ detection)* *OR* *ABS(image PRE/ segmentation))* *AND* *TITLE(survey or review)*	inc: 768 1^a exc: 518 (i) 2^a exc: 244 (ii) 3^a exc: 15 (iii) 4^a exc: 15 (iv)	inc: 1,475 1^a exc: 1,038(i) 2^a exc: 248(ii) 3^a exc: 3(iii): 4^a exc: 3 (iv)
RQF	*ABS (fuzzy* *AND* *(edge PRE/ detection))* *AND* *TITLE (fuzzy OR edge OR segmentation)*	inc: 870 1^a exc: 247 (i) 2^a exc: 7 (ii) 3^a exc: 6 (iii) 4^a exc: 6(iv)	inc: 717 1^a exc: 224 (i) 2^a exc: 21(ii) 3^a exc: 13(iii) 4^a exc: 13(iv)

Table 2: Papers in edge detection (RQG).

Reference	**Paper title**
(Kaur and Kaur, 2017)	An Edge detection technique with image segmentation using Ant Colony Optimization: A review
(Castillo et al., 2017)	Review of Recent Type-2 Fuzzy Image Processing Applications
(Yogesh et al., 2018)	A comparative review of various segmentation methods and its application
(Magnier et al., 2018)	A review of supervised edge detection evaluation methods and an objective comparison of filtering gradient computations using hysteresis thresholds
(Magnier, 2018)	Edge detection: a review of dissimilarity evaluations and a proposed normalized measure
(Agrawal and Bhogal, 2019)	A review—Edge detection techniques in dental images
(Aggarwal et al., 2019)	Review of Segmentation Techniques on Multi-Dimensional Images
(Zhu and Li, 2019)	Survey on the image segmentation algorithms
(Suresh and Srinivasa Rao, 2019)	Various image segmentation algorithms: A survey
(Ghosh et al., 2020)	Different EDGE Detection Techniques: A Review
(Budzyn and Rzepka, 2020)	Review of edge detection algorithms for application in miniature dimension measurement modules
(Chakrapani et al., 2021)	A Survey of Sobel Edge Detection VLSI Architectures
(Isa et al., 2021)	Review of Edge-based Image Segmentation on Electrical Tree Classification in Cross-linked Polyethylene (XLPE) Insulation
(Mubashar et al., 2022)	Have We Solved Edge Detection? A Review of State-of-the-art Datasets and DNN based Techniques
(Yadav and Pandey, 2022)	Image Segmentation Techniques: A Survey
(Jing et al., 2022)	Recent advances on image edge detection: A comprehensive review

point. The contours of objects in the image can be interpreted as a transition zone between these intensities so that more intense transitions have a much greater chance of being an edge than smoother transitions. That is, given a direction in the image, the rate of change or discrete difference between pixels highlights the likely edges of the objects (Marco-Detchart et al., 2021a).

It was through this reasoning that the first edge detectors emerged (Agrawal and Bhogal, 2019). There are two approaches to gradient-based detection: first-order derivative-based, and second-order derivative-based.

The best-known gradient-based detection methods are first-order fixed operations; first-order oriented operations that use the maximum energy of the orientation; or two-direction operations.

To facilitate understanding regarding the development of the techniques throughout history, we have summarized in a timeline the publication dates of the articles describing the first version of each method described in this section, which can be seen in Figure. 2. The following are some of the classical gradient-based methods and their main differences (Aggarwal et al., 2019).

The Canny Detector (Canny, 1986), to this day one of the most widely used, was proposed considering a Gaussian smoothing followed by a gradient operation and finally thresholding. In the studies in (Jing et al., 2022), we found other methods based on first-order derivatives, inspired by Canny, such as Infinite size Symmetrical Exponential Filters (D-

ISEF), a color-boundary and first-order derivative of anisotropic Gaussian (FDAG).

Sobel's detector (Sobel et al., 1968) calculates the gradient value at each pixel position in the image using a fixed operator. In turn, Prewitt (Prewitt et al., 1970) has a similar technique to Sobel, but unlike Sobel it has no adjustment coefficients, varies by a constant value, and calculates the magnitude of the gradient with the image orientations.

The method proposed by Roberts (Roberts, 1980) first appears in the literature in 1963, as the product of his doctoral thesis. This method calculates the derivative by taking the root of the difference between diagonally adjacent pixels. It focuses on invariant properties that edges exhibit.

The LoG (Marr and Hildreth, 1980), or Gaussian Laplacian, is based on a Gaussian filtering followed by a Laplacian operation. It is based on a second-order operator, which seeks to identify the maximum and minimum points of the variation of intensities so that by finding these points that cross to zero, the edge candidates in the image are found. The Gaussian filter step is important because it is a second-order method and therefore extremely sensitive to noise.

Region Segmentation-Based Methods: Another set of methods for edge detection is based on region segmentation. In these methods, regions are segmented, such as clustering and automated thresholding methods, and edges are detected as the boundary of these regions. According to (Mubashar et al., 2022), the regions formed by the textures in high-complexity images can be used as a facilitator in the process of detecting the edges between them.

The region-based approach outperforms direct detection methods such as gradient methods. Others, such as frequency domain filtering and statistics can be classified as either region segmentation or direct edge detection methods, depending on how the detection modeling is done. These works can be found in (Jing et al., 2022; Mubashar et al., 2022).

Through the emergence of texture descriptors and other local information such as brightness gradient, texture gradient, and color gradient, the *probabilistic contour* (Pb) method emerged (Arbelaez et al., 2010).

Methods Based on Machine Learning and Neural Networks: Combining the Pb method with a logistic regression it was possible to develop a model for edge detection in the image (Jing et al., 2022). The method has been extended over the years, for example by bringing in the multi-scale probabilistic contouring method and a multi-scale spectral clustering.

Currently, new machine learning-based techniques have emerged, in particular those based on Convolutional Neural Networks (CNN's). Other methods based on machine learning are presented in (Jing et al., 2022), this is the case of *Holistically-nested edge detection* better known as HED that was proposed to improve the performance of the convolutional neural network, inspired other methods as, *Convolutional Encoder-Decoder Network* (CEDN), *Richer Convolutional Features* (RCF), *Learning to Predict Crisp Boundaries* (LPCB).

In 2019, the *bi-directional cascade network* (BDCN) method emerges, which proposes detection at different scales. More recently, techniques such as: *Fined*, *Edge Detection TransformER* (EDTER), and *Pixel Difference Networks* (PiDiNet) have been proposed, to handle edge detection without the need for such a large database for model training.

Fuzzy Logic Based Methods: Since Russo (Russo, 1998) first presented a fuzzy inference system modeling to efficiently extract edges in high noise images in 1998, the application of fuzzy theory in edge detection has increased, justified by the fuzzy nature of object edges in a digital image, which makes fuzzy theory suitable for solving such problems (Russo, 1998).

As reported by (Jing et al., 2022), detectors based on joining techniques like *divergence and fuzzy entropy minimization* (FED) and detectors based on morphological gradient and type-2 fuzzy logic have been proposed (Type-2 Color). Hybrid techniques and fuzzy versions of neural networks have been created, improving the performance of other approaches and in some cases decreasing the computational complexity.

In the studies of (Ghosh et al., 2020) we can identify hybrid methods that use neural networks and fuzzy logic type-1, type-2, and type-3, which are extensions of fuzzy logic with more degrees of uncertainty associated, they are called *Hybrid approach neuro-fuzzy-1, neuro-fuzzy-2 and neuro-fuzzy-3* (Neuro-fuzzy's). As well as the use of fuzzy logic to improve classical methods such as Canny (C&I-TYPE2), and a hybrid method that uses Sobel, fuzzy logic type-1, and fuzzy interval system type-2 (T2FLS).

Figure 3 presents the chronology of the found fuzzy methods, through the two proposed research questions. Observe the predominance of applications of fuzzy logic type-1, type-2, and type-3 and the use of this approach in conjunction with other techniques, evidencing a clear research trend.

3.2 Fuzzy Logic-Based Edge Detection Methods (RQF)

Considering the current state of edge detection methods and the importance of fuzzy logic-based methods,

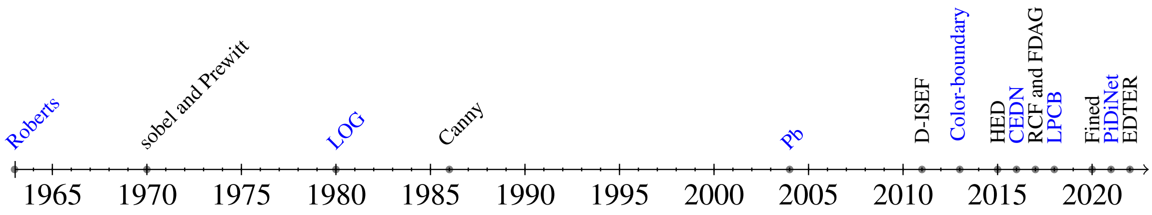

Figure 2: Chronology of non-fuzzy methods RQG.

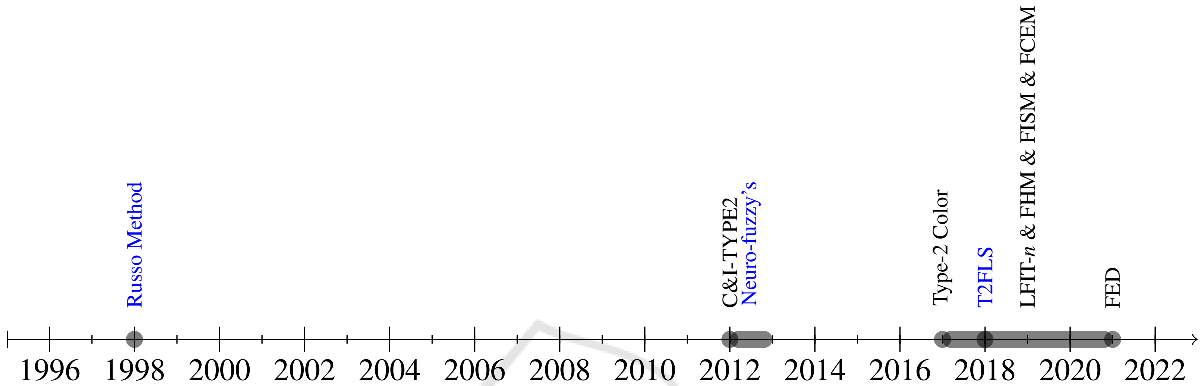

Figure 3: Chronology of fuzzy methods RQF.

evidenced in the previous section, it was possible to perform a bibliometric analysis of these articles in order to obtain some useful information in understanding the state of the art of fuzzy logic-based methods.

It is important to emphasize that some works focused on the review of segmentation methods, in general, using fuzzy logic, were included in this review. This is justified by the fact that the process of edge detection is a method of segmentation of the boundary between two or more regions, i.e., a particular case of the segmentation area in general and, therefore, high-impact works that were not specific to edge detection but returned from consultations and went through the exclusion processes were admitted.

Table 3 summarizes the papers returned from the search, organized by publication date. In the first column, we show the reference and, next to it, the title of the work.

Next, we present the relevant results of the bibliometric analysis, with the objective of presenting the most important papers and the common terms among the papers. This may allow a better understanding of the research carried out in this area, with the help of the description of the methods, to understand the gaps in the literature regarding this theme.

By extracting the metadata of the papers, it was possible, as described in the previous chapter for general edge detection methods, to determine the most cited papers among the selected ones. The paper with the highest number of absolute citations was the paper by (Castillo et al., 2017). In the second and third positions, in absolute numbers of citations, we have the works (Kumar et al., 2019; Gonzalez et al., 2017a).

Analyzing the ratio of citations per year, we have that the three most cited papers in absolute number, are also those with the highest citations/year ratio without losing the hierarchical order. Of these works, two are about edge detection using type-2 interval fuzzy logic, and the second position is relatively recent.

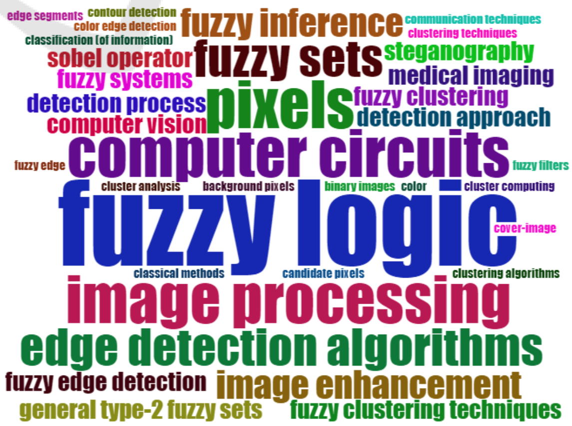

Figure 4: Word cloud of key terms of fuzzy methods.

Through the word cloud, it is possible to identify, disregarding obvious terms such as those used in the search, or synonyms and homonyms, the terms that have raised the interest of researchers in the area, when using a fuzzy treatment in solving the problem of edge detection and image segmentation. In Figure 4, one can observe terms such as: "Medical Imaging", "Computer Circuits", "General Type-2 fuzzy sets", "Classical Methods" and "Sobel Operator". This word cloud was obtained through the frequency of the terms in the keywords, which are terms chosen by the authors to describe their work, using the software R Studio.

The metrics presented in the results of these works in comparison with classical methods show that the approach plays a key role in improving the performance of classical and other existing methods.

The found methods can be divided into four classes:

i. Methods based on *interval fuzzy logic of the type-n* (LFIT-*n*) (Baghbani et al., 2019; Raheja and Kumar, 2021; Gonzalez et al., 2017a; Kaur and Kaur, 2017; Castillo et al., 2017; Gonzalez et al., 2017b);

ii. *Hybrid methods* (FHM), in combination with neural networks or improving the performance of classical edge detection techniques (Balabantaray et al., 2017; Kumawat and Panda, 2021; Moya-Albor et al., 2017; Dhargupta et al., 2019; Kaur and Kaur, 2017; Dorrani et al., 2020);

iii. Methods that are based on *fuzzy inference systems* (FISM) (Dhivya and Prakash, 2019) e;

iv. Methods that are based on *fuzzy clustering methods* (FCEM) (Flores-Vidal et al., 2018).

4 CONCLUSION

Edge detection represents an important task in several steps in computer vision, such as (Wei et al., 2017); object detection (Yang et al., 2002); pattern recognition (Mohan et al., 2021); or image retrieval (Pavithra and Sharmila, 2018).

Recently, research in this area has been gaining momentum due to its importance in several applications, such as augmented reality (Orhei et al., 2020); image colorization (Sun et al., 2019) and medical image processing (Qiu et al., 2021) among others. Because of the fuzzy nature of the edges of an object in a digital image, many methods have been developed over the years, and more recently, with the use of fuzzy theory, which has been improving and performing applications in various areas.

Considering the advancement of research in edge detection through fuzzy theory approaches, and the lack of review papers dedicated to these methods, a specific investigation of these techniques is justified.

In this sense, this work presented a review of edge detection methods in order to understand the state of the art of fuzzy edge detection methods. For this, searches were performed in two major databases, Scopus and Web Of Science, and defined the terms of inclusion and exclusion, so that of 3,830 papers that returned from the searches, only 34 went through the exclusion steps. The methods were reviewed and organized by category according to the proposed approach by the method.

Classical methods can be divided into four classes: methods based on gradient; methods based on segmentation of regions; methods based on machine learning and Neural Networks and; methods based on Fuzzy Logic that in turn, through the specific search can be divided into four subclasses: methods based on interval fuzzy logic type-*n*; hybrid methods, in combination with neural networks or improving the performance of classical techniques for edge detection; those based on fuzzy inference systems and; based on clustering methods.

The fuzzy set theory proposed by Zadeh (Zadeh, 1965) as well as the Roberts method (Roberts, 1980) of edge detection, has its first works in the mid-1970s. Despite the nature of edge detection fitting clearly in a fuzzy theory approach, fuzzy applications in this task only appeared for the first time in the late 1990s using fuzzy inference systems, with the method of Russo (Russo, 1998).

Even after this initiative, little has been explored over the years, with the first relevant papers around the year 2012. A bibliometric analysis was also conducted, where the metadata of the documents was analyzed, in order to understand, in conjunction with the summary of the methods whether there are gaps or trends in research regarding the studied topic.

Through the analysis, it could be concluded that in recent years, from the year 2012, fuzzy logic has been employed in hybrid methods in order to improve the performance of existing techniques or reduce computational complexity. Studies with interval fuzzy logic of higher order have been employed for its greater flexibility in dealing with the uncertainty associated with the edge detection task.

As future work, a review dedicated to the performance of the methods is proposed, comparing works that used the same metrics and databases in order to evaluate the gain that these different techniques have in relation to other non-fuzzy methods. This quantitative evaluation is necessary considering the number of methods proposed in the last ten years, and the scarcity of review work in this regard.

Table 3: Works in edge detection based on fuzzy logic (RQF).

References	Paper title
(Gonzalez et al., 2017b)	Edge detection methods based on generalized type-2 fuzzy logic systems
(Castillo et al., 2017)	Review of Recent Type-2 Fuzzy Image Processing Applications
(Moya-Albor et al., 2017)	An Edge Detection Method using a Fuzzy Ensemble Approach
(Gonzalez et al., 2017a)	Edge detection method based on general type-2 fuzzy logic applied to color images
(Balabantaray et al., 2017)	A Quantitative Performance Analysis of Edge Detectors with Hybrid Edge Detector
(Flores-Vidal et al., 2018)	A New Edge Detection Approach Based on Fuzzy Segments Clustering
(Bueno et al., 2018)	Two-phase flow bubble detection method applied to natural circulation system using fuzzy image processing
(Baghbani et al., 2019)	A method for image edge detection based on interval-valued fuzzy sets
(Flores-Vidal et al., 2019)	A new edge detection method based on global evaluation using fuzzy clustering
(Dhargupta et al., 2019)	Fuzzy edge detection based steganography using modified Gaussian distribution
(Bhogal and Agrawal, 2019)	Image Edge Detection Techniques Using Sobel, T1FLS, and IT2FLS
(Kumar et al., 2019)	Information hiding with adaptive steganography based on novel fuzzy edge identification
(Dhivya and Prakash, 2019)	Edge detection of satellite image using fuzzy logic
(Dorrani et al., 2020)	Image Edge Detection with Fuzzy Ant Colony Optimization Algorithm
(Kumawat and Panda, 2021)	A robust edge detection algorithm based on feature-based image registration (FBIR) using improved canny with fuzzy logic (ICWFL)
(Raheja and Kumar, 2021)	Edge detection based on type-1 fuzzy logic and guided smoothening
(Tripathi et al., 2021)	Edge Detection on Medical Images Using Intuitionistic Fuzzy Logic

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DECLARATIONS

The authors declare that there is no financial or personal conflict directly or indirectly related to this work.

REFERENCES

Aggarwal, P., Mittal, H., Samanta, P., and Dhruv, B. (2019). Review of Segmentation Techniques on Multi-Dimensional Images. In *2018 International Conference on Power Energy, Environment and Intelligent Control, PEEIC 2018*, pages 268–273. Institute of Electrical and Electronics Engineers Inc.

Agrawal, A. and Bhogal, R. (2019). A review—Edge detection techniques in dental images. *Lecture Notes in Computational Vision and Biomechanics*, 30:1359–1378. Publisher: Springer Netherlands.

Arbelaez, P., Maire, M., Fowlkes, C., and Malik, J. (2010). Contour detection and hierarchical image segmentation. *IEEE transactions on pattern analysis and machine intelligence*, 33(5):898–916.

Aria, M. and Cuccurullo, C. (2017). bibliometrix : An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, 11(4):959–975.

Baghbani, R., Jamasb, S., and Khodabakhshi, M. B. (2019). A method for image edge detection based on interval-valued fuzzy sets. *JOURNAL OF INTELIGENT & FUZZY SYSTEMS*, 37(2):2275–2288. Place: NIEUWE HEMWEG 6B, 1013 BG AMSTERDAM, NETHERLANDS Publisher: IOS PRESS Type: Article.

Balabantaray, B. K., Sahu, O. P., Mishra, N., and Biswal, B. B. (2017). A Quantitative Performance Analysis of Edge Detectors with Hybrid Edge Detector. *JOURNAL OF COMPUTERS*, 12(2):165–173. Place: PO BOX 40, OULU, 90571, FINLAND Publisher: ACAD PUBL Type: Article.

Bhogal, R. K. and Agrawal, A. (2019). Image Edge Detection Techniques Using Sobel, T1FLS, and IT2FLS. In SC., S. and A., J., editors, *INFORMATION AND COMMUNICATION TECHNOLOGY FOR INTELLIGENT SYSTEMS, ICTIS 2018, VOL 2*, volume 107 of *Smart Innovation Systems and Technologies*, pages 303–317, GEWERBESTRASSE 11, CHAM, CH-6330, SWITZERLAND. SPRINGER INTERNATIONAL PUBLISHING AG. ISSN: 2190-3018 Type: Proceedings Paper.

Budzyn, G. and Rzepka, J. (2020). Review of edge detection algorithms for application in miniature dimension measurement modules. *Journal of Machine Engineering*, 20(4):74–85. Publisher: Editorial Institution of Wrocaw Board of Scientific.

Bueno, R., Masotti, P., Justo, J., Andrade, D., Rocha, M., Torres, W., and de Mesquita, R. (2018). Two-phase flow bubble detection method applied to natural circulation system using fuzzy image processing. *Nuclear Engineering and Design*, 335:255–264. Publisher: Elsevier Ltd.

Bustince, H., Barrenechea, E., Pagola, M., and Fernandez, J. (2009). Interval-valued fuzzy sets constructed from matrices: Application to edge detection. *Fuzzy Sets and Systems*, 160(13):1819–1840.

Canny, J. (1986). A computational approach to edge detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, PAMI-8(6):679–698.

Castillo, O., Sanchez, M. A., Gonzalez, C. I., and Martinez, G. E. (2017). Review of Recent Type-2 Fuzzy Image Processing Applications. *INFORMATION*, 8(3). Place: ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND Publisher: MDPI Type: Review.

Chakrapani, S., Y., Rao, V., N., and Kamaraju, M. (2021). A Survey of Sobel Edge Detection VLSI Architectures. In A.J., O., S., A., B.H., H., and H.A., A., editors, *Journal of Physics: Conference Series*, volume 1804. IOP Publishing Ltd. ISSN: 17426588 Issue: 1.

Dhargupta, S., Chakraborty, A., Ghosal, S. K., Saha, S., and Sarkar, R. (2019). Fuzzy edge detection based steganography using modified Gaussian distribution. *MULTIMEDIA TOOLS AND APPLICATIONS*, 78(13):17589–17606. Place: VAN GODEWIJCKSTRAAT 30, 3311 GZ DORDRECHT, NETHERLANDS Publisher: SPRINGER Type: Article.

Dhivya, R. and Prakash, R. (2019). Edge detection of satellite image using fuzzy logic. *Cluster Computing*, 22:11891–11898. Publisher: Springer.

Dorrani, Z., Farsi, H., and Mohamadzadeh, S. (2020). Image Edge Detection with Fuzzy Ant Colony Optimization Algorithm. *INTERNATIONAL JOURNAL OF ENGINEERING*, 33(12):2464–2470. Place: 16, AHURAMAZDA ST, ALVAND AVE, TEHRAN, 15169, IRAN Publisher: MATERIALS & ENERGY RESEARCH CENTER-MERC Type: Article.

Flores-Vidal, P. A., Gomez, D., Olaso, P., and Guada, C. (2018). A New Edge Detection Approach Based on Fuzzy Segments Clustering. In Kacprzyk, J., Szmidt, E., Zadrozny, S., Atanassov, K., and Krawczak, M., editors, *ADVANCES IN FUZZY LOGIC AND TECHNOLOGY 2017, VOL 2*, volume 642 of *Advances in Intelligent Systems and Computing*, pages 58–67, GEWERBESTRASSE 11, CHAM, CH-6330, SWITZERLAND. SPRINGER INTERNATIONAL PUBLISHING AG. ISSN: 2194-5357 Type: Proceedings Paper.

Flores-Vidal, P. A., Olaso, P., Gomez, D., and Guada, C. (2019). A new edge detection method based on global evaluation using fuzzy clustering. *SOFT COMPUTING*, 23(6, SI):1809–1821. Place: 233 SPRING ST, NEW YORK, NY 10013 USA Publisher: SPRINGER Type: Article.

Ghosh, C., Majumder, S., Ray, S., Datta, S., Mandal, and S.N. (2020). Different EDGE Detection Techniques: A Review. *Lecture Notes in Electrical Engineering*, 686:885–898. ISBN: 9789811570308 Publisher: Springer Science and Business Media Deutschland GmbH.

Gonzalez, C., Melin, P., and Castillo, O. (2017a). Edge detection method based on general type-2 fuzzy logic applied to color images. *Information (Switzerland)*, 8(3). Publisher: MDPI AG.

Gonzalez, C., Melin, P., Castro, J., and Castillo, O. (2017b). Edge detection methods based on generalized type-2 fuzzy logic systems. *SpringerBriefs in Applied Sciences and Technology*, 1(9783319539935):21–35. Publisher: Springer Verlag.

Isa, M., Rohani, M., Ismail, B., Rosmi, A., Isa, M., Mustafa, W., Kamarol, M., Mansor, N., and Nazar, N. (2021). Review of Edge-based Image Segmentation on Electrical Tree Classification in Cross-linked Polyethylene (XLPE) Insulation. In *Journal of Physics: Conference Series*, volume 1878. IOP Publishing Ltd. ISSN: 17426588 Issue: 1.

Jing, J., Liu, S., Wang, G., Zhang, W., and Sun, C. (2022). Recent advances on image edge detection: A comprehensive review. *Neurocomputing*, 503:259–271. Publisher: Elsevier B.V.

Kaur, S. and Kaur, P. (2017). An Edge detection technique with image segmentation using Ant Colony Optimization: A review. In *Proceedings of 2016 Online International Conference on Green Engineering and Technologies, IC-GET 2016*. Institute of Electrical and Electronics Engineers Inc.

Kitchenham, B. and Charters, S. (2007). Guidelines for performing systematic literature reviews in software engineering.

Koschan, A. and Abidi, M. (2005). Detection and classification of edges in color images. *IEEE Signal Process. Mag.*, 22(1):64–73.

Kumar, S., Singh, A., and Kumar, M. (2019). Information hiding with adaptive steganography based on novel fuzzy edge identification. *DEFENCE TECHNOLOGY*, 15(2):162–169. Place: PO BOX 211, 1000 AE AMSTERDAM, NETHERLANDS Publisher: ELSEVIER SCIENCE BV Type: Article.

Kumawat, A. and Panda, S. (2021). A robust edge detection algorithm based on feature-based image registration (FBIR) using improved canny with fuzzy logic (ICWFL). *VISUAL COMPUTER*. Place: ONE NEW YORK PLAZA, SUITE 4600, NEW YORK, NY, UNITED STATES Publisher: SPRINGER Type: Article; Early Access.

Lopez-Molina, C., Bustince, H., Fernández, J., Couto, P., and De Baets, B. (2010). A gravitational approach to edge detection based on triangular norms. *Pattern Recognition*, 43(11):3730–3741.

Magnier, B. (2018). Edge detection: a review of dissimilarity evaluations and a proposed normalized measure. *MULTIMEDIA TOOLS AND APPLICATIONS*, 77(8):9489–9533. Place: VAN GODEWIJCKSTRAAT 30, 3311 GZ DORDRECHT, NETHERLANDS Publisher: SPRINGER Type: Review.

Magnier, B., Abdulrahman, H., and Montesinos, P. (2018). A review of supervised edge detection evaluation methods and an objective comparison of filtering gradient computations using hysteresis thresholds. *Journal of Imaging*, 4(6). Publisher: MDPI Multidisciplinary Digital Publishing Institute.

Marco-Detchart, C., Bustince, H., Fernández, J., Mesiar, R., Lafuente, J., Barrenechea, E., and Pintor, J. M. (2021a). Ordered directional monotonicity in the construction of edge detectors. *Fuzzy Sets and Systems*, 421:111–132.

Marco-Detchart, C., Lucca, G., Lopez-Molina, C., De Miguel, L., Pereira Dimuro, G., and Bustince, H. (2021b). Neuro-inspired edge feature fusion using Choquet integrals. *Information Sciences*, 581:740–754.

Marr, D. and Hildreth, E. (1980). Theory of edge detection. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, 207(1167):187–217.

Martin, D. R. (2002). *An empirical approach to grouping and segmentation*. University of California, Berkeley.

Mohan, K., Seal, A., Krejcar, O., and Yazidi, A. (2021). Facial Expression Recognition Using Local Gravitational Force Descriptor-Based Deep Convolution Neural Networks. *IEEE Transactions on Instrumentation and Measurement*, 70:1–12.

Moya-Albor, E., Ponce, H., and Brieva, J. (2017). An Edge Detection Method using a Fuzzy Ensemble Approach. *ACTA POLYTECHNICA HUNGARICA*, 14(3, SI):149–168. Place: BECSI UT 96-B, BUDAPEST, H-1034, HUNGARY Publisher: BUDAPEST TECH Type: Article.

Mubashar, M., Khan, N., Sajid, A., Javed, M., and Hassan, N. (2022). Have We Solved Edge Detection? A Review of State-of-the-art Datasets and DNN based Techniques. *IEEE Access*, pages 1–1. Publisher: Institute of Electrical and Electronics Engineers Inc.

Muthalagu, R., Bolimera, A., and Kalaichelvi, V. (2020). Lane detection technique based on perspective transformation and histogram analysis for self-driving cars. *Computers & Electrical Engineering*, 85:106653.

Orhei, C., Vert, S., and Vasiu, R. (2020). A Novel Edge Detection Operator for Identifying Buildings in Augmented Reality Applications. In Lopata, A., Butkienė, R., Gudonienė, D., and Sukackė, V., editors, *Information and Software Technologies*, volume 1283, pages 208–219. Springer International Publishing, Cham.

Pavithra, L. and Sharmila, T. S. (2018). An efficient framework for image retrieval using color, texture and edge features. *Computers & Electrical Engineering*, 70:580–593.

Prewitt, J. M. et al. (1970). Object enhancement and extraction. *Picture processing and Psychopictorics*, 10(1):15–19.

Qiu, B., Guo, J., Kraeima, J., Glas, H. H., Zhang, W., Borra, R. J. H., Witjes, M. J. H., and van Ooijen, P. M. A. (2021). Recurrent Convolutional Neural Networks for 3D Mandible Segmentation in Computed Tomography. *Journal of Personalized Medicine*, 11(6):492.

Raheja, S. and Kumar, A. (2021). Edge detection based on type-1 fuzzy logic and guided smoothening. *Evolving Systems*, 12(2):447–462. Publisher: Springer Science and Business Media Deutschland GmbH.

Roberts, J. (1980). *Machine Percept 3D Solids*. Dissertations-G.

Russo, F. (1998). Edge detection in noisy images using fuzzy reasoning. *IEEE Transactions on Instrumentation and Measurement*, 47(5):1102–1105.

Shimada, T., Sakaida, F., Kawamura, H., and Okumura, T. (2005). Application of an edge detection method to satellite images for distinguishing sea surface temperature fronts near the Japanese coast. *Remote Sensing of Environment*, 98(1):21–34.

Sobel, I., Feldman, G., et al. (1968). A 3x3 isotropic gradient operator for image processing. *a talk at the Stanford Artificial Project in*, pages 271–272.

Sun, T.-H., Lai, C.-H., Wong, S.-K., and Wang, Y.-S. (2019). Adversarial Colorization Of Icons Based On Structure And Color Conditions. *MM 19: Proceedings of the 27th ACM International Conference on Multimedia*.

Suresh, K. and Srinivasa Rao, P. (2019). Various image segmentation algorithms: A survey. *Smart Innovation, Systems and Technologies*, 105:233–239. ISBN: 9789811319266 Publisher: Springer Science and Business Media Deutschland GmbH.

Tacconelli, E. (2010). Crd's guidance for undertaking reviews in health care. *Lancet Infectious Diseases - LANCET INFECT DIS*, 10:226–226.

Tripathi, N., Kumrawat, D., Gottimukkala, V.K., Jeevaraj, S., Godfrey, and W.W. (2021). Edge Detection on Medical Images Using Intuitionistic Fuzzy Logic. *Communications in Computer and Information Science*, 1376 CCIS:236–246. ISBN: 9789811610851 Publisher: Springer Science and Business Media Deutschland GmbH.

Wei, Y., Liang, X., Chen, Y., Shen, X., Cheng, M.-M., Feng, J., Zhao, Y., and Yan, S. (2017). STC: A Simple to Complex Framework for Weakly-Supervised Semantic Segmentation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 39(11):2314–2320.

Yadav, R. and Pandey, M. (2022). Image Segmentation Techniques: A Survey. *Lecture Notes on Data Engineering and Communications Technologies*, 90:231–239. Publisher: Springer Science and Business Media Deutschland GmbH.

Yang, M.-H., Kriegman, D., and Ahuja, N. (2002). Detecting faces in images: a survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 24(1):34–58.

Yogesh, Dubey, A., Arora, R., and Ahmed, A. (2018). A comparative review of various segmentation methods and its application. In Khatri S.K., Kapur P.K., S. B., editor, *2017 6th International Conference on Reliability, Infocom Technologies and Optimization: Trends and Future Directions, ICRITO 2017*, volume 2018-January, pages 645–650. Institute of Electrical and Electronics Engineers Inc.

Yuksel, M. and Basturk, A. (2012). Application of Type-2 Fuzzy Logic Filtering to Reduce Noise in Color Images. *IEEE Comput. Intell. Mag.*, 7(3):25–35.

Zadeh, L. (1965). Fuzzy sets. *Information and Control*, 8(3):338–353.

Zhu, Y. and Li, P. (2019). Survey on the image segmentation algorithms. *Springer Series in Geomechanics and Geoengineering*, 1(216039):475–488. Publisher: Springer Verlag.