A REVIEW OF THE USE OF THERMAL IMAGING AND COMPUTER VISION FOR PATTERN RECOGNITION

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ABSTRACT

The use of thermal imaging and computer vision has seen a sharp increase in recent years. This paper presents the current state of the art concerning these fields. Thus, a review of research articles studying the combination of these technologies for pattern recognition is established. After presenting an overview of the topic, a bibliometric analysis is selected based on 1160 articles extracted from the Scopus database, which allows assessing the temporal evolution of the publications and the study of their most relevant sources, authors, keywords, trend topics, and publishing countries. Besides, a particular focus is given to the issue of defect detection using thermal imaging and computer vision. The related articles are analyzed and classified into their primary domains. The results confirm that combining thermal imaging with computer vision techniques has become commonly used in several fields. However, the defects detection case studies using these technologies are focused on a few application fields. Thus, more contributions are required regarding this specific issue in more innovative applications. This review will help to guide future research contributions within all fields where creative uses of infrared thermal imaging and computer vision can be developed to recognize different patterns and issues.

KEYWORDS

Infrared thermal imaging, computer vision, bibliometric analysis, pattern recognition, defect detection

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1. INTRODUCTION

Thermal imaging is widely used in many fields because it is a non-contact and non-destructive monitoring and controlling method. While human eyes can detect electromagnetic radiations in the visible light spectrum, thermal imaging devices detect radiations in the infrared spectrum and translate them into thermal images where each pixel corresponds to the temperature at its exact location [1]. In recent years, applying computer vision techniques to process thermal images has gained significant interest in many fields because it helps extracting meaningful information and analyzing variable issues efficiently and accurately.
Many reviews focusing on infrared thermal imaging were established previously. However, most of these reviews focus on establishing the state of the art in using infrared imaging in specific fields [2-4]. For example, one of these reviews focuses on using infrared imaging in animal production [2]. The contribution presents an overview of the general parameters involved in thermal imagery and then focuses on recent advances in monitoring animals using this technology. Another review shows infrared imagery in plant analysis [3]. The principles of mid-infrared and near-infrared imaging are presented, and an inventory of their applications in the analysis of plant tissues is established. Besides, infrared imagery in diagnosing and monitoring knee diseases is also reviewed [4]. The research criteria are listed, and the reviewed articles are classified based on the nature of the knee disease or anomalies they study.

To fill this gap related to the lack of more general and inclusive reviews on this topic, to the authors' knowledge, this article aims to investigate the use of infrared thermal imaging and computer vision in all application fields through a general overview and an inclusive bibliometric analysis of the topic. Then, a specific analysis of the various case studies related to defect detection using the studied technologies is established.

Our research objective is to establish a review of the current state of the art concerning the different applications of infrared thermal imaging and computer vision. It can be considered as a reference work to guide future contributions within these fields. The issues discussed concern various areas where the combination of thermal imaging and computer vision has proven its efficiency for pattern recognition. Our research is mainly highlighted by combining qualitative and quantitative analysis of the reviewed research contributions.

The remainder of this paper is structured as follows: Section (2) presents an overview of different application fields of thermal imaging and computer vision. In section (3), the study's methodology and the analysis steps are presented. Section (4) shows the bibliometric analysis's main findings and highlights the selected articles' main topics related to defect detection. In section (5), a discussion of the study's main findings is presented, in addition to the conclusion of the whole work.

2. OVERVIEW OF DIFFERENT APPLICATION FIELDS OF THERMAL IMAGING AND COMPUTER VISION

Many scientific contributions discuss using infrared thermal imaging and computer vision to handle several issues linked to varied fields such as living being characterization, agriculture, medical and pharmaceutical analysis, buildings, and industry, which shows the broad application field of these technologies.

Concerning living being characterization, some articles focus on human case studies [5-11], while other articles present examples of application for animals [12-14]. The main topic studied in [5] is the detection of the age and gender of people based on their infrared images. A dataset of

3,000 thermal images combined with visible images was used to train and test different deep-learning approaches (CNNs). This allowed the classification of people based on their age and gender. Moreover, the study established in [6] concerns the Covid-19 issue. Thermal images were used to detect people with high body temperature and to indicate whether people were wearing masks or not. Besides, human action recognition (HAR) was the primary purpose of the study elaborated in [7], which used sequences of thermal images (1470 infrared videos) that were classified via deep learning approaches into 20 classes representing different actions of human beings. In the same scope, [8] presents a study concerning the body’s hyperventilation due to stress or anxiety, which can be tracked on thermal videos through computer vision techniques and respiration rate assessment. Besides, computer vision techniques can also be applied to infrared imaging for face detection purposes [9-11]. Literature reviews about this topic are established in [9] and [10], while [11] discuss the extraction of people's emotional states from thermal images of their faces.

On the other hand, the processing of infrared images through computer vision and AI methods allowed characterizing anomalies affecting some animals or defining indexes related to their state is also investigated in [12-14]. This concerns the definition of cattle’s behavioral characteristics through their thermal images [12], the detection of their bodies' temperatures through eye thermal image segmentation and thresholding [13], and the definition of an index characterizing heifers’ thermal comfort using their infrared images [14].

In agriculture, infrared imaging and computer vision techniques are used for different purposes. Thermal images are analyzed in [15] to estimate crop temperature at greenhouses through machine vision, while [16] investigates several techniques for assessing fruit maturity, including infrared imaging. Besides, in the study established in [17], 3D RGB and thermal point data clouds allow characterizing forest canopies using unmanned aerial vehicles, while [18] investigates the use of the combination of thermal imaging and computer vision for inspecting pipes used in the fertilizers' industry. The clogging in these pipes generated by the dust accumulation is detected using artificial intelligence neural network models.

Several articles also focus on fault diagnosis topics using thermal imaging and machine vision. In the study established in [19], anomalies in industrial materials are detected through the segmentation of their thermal images and computer vision techniques. This allowed the detection of cracks, holes, and other deficiencies inside the materials. In the same scope, the study established in [20] focuses on detecting faults affecting heating water pipes using thermal imaging. Thus, image segmentation and anomaly detection techniques are used, and defects are classified into three categories: insulation damage, insulation fall-off, or pipeline leakage. Besides, in another study, porcelain insulators were also diagnosed to detect whether they are affected by faults using thermal imaging and machine learning [21]. Thus, image processing techniques such as geometrical and morphological operations are applied to the thermal images, which are then processed through machine learning approaches (e.g., Support Vector Machine) to classify the different insulators' fault types. Thus, a new model for internal damage detection in concrete structures is also presented [22]. It uses thermal image segmentation and deep learning approaches.

Several articles also focus on using human imaging and computer vision to assess buildings' characteristics and energy efficiency. The study in [23] presents a building energy model based on thermography and computer vision. A 3D model is built based on 2D visible images and thermal images indicating the transmittance of the structure walls. Besides, a new method for occupancy sensing is presented in [24] to optimize the functioning of energy-based equipment (such as heating and ventilation …). This new method is based on multiple thermal imagers that allow reaching a high sensitivity regarding human occupancy inside the buildings. In the same scope, state-of-the-art energy-related models for buildings are presented in [25]. This review also includes the methods based on thermal imaging for buildings' energy modeling and the main algorithms used for related data processing. Besides, a building inspection method based on infrared imaging through autonomous helicopters is presented in [26], highlighting some segmentation methods used to detect building anomalies.

Besides, in the medical and pharmaceutical field, thermal imaging and computer vision are used in several studies. The freeze-drying process is also characterized through these technologies [27]. This operation, commonly used in pharmaceutical methods, is studied through a thermal image processing pipeline, including image segmentation, which locates objects whose temperature should be measured, and object tracking, which aims to follow its movements. In the same scope, the study established in [28] presents another thermal imaging case study related to phacoemulsification, a cataract surgery technique used in the medical field. Besides, a survey about breast screening using infrared imaging and image processing techniques is presented [29]. The study includes several steps, such as image acquisition, segmentation approaches, feature extraction, and the classification step, to establish a complete diagnosis of the breast and to detect its eventual anomalies. Besides, thermal imaging is also studied in biopharmaceutical formulations [30], including the pre-processing step, the images' segmentation, and their quantification by extracting pixels' main features.

Natural phenomena can also be diagnosed using thermal imaging and computer vision. For example, tridimensional spatial characteristics of volcanic plumes were reconstructed using thermal images collected from ground-based cameras [31]. Four infrared cameras were used for this purpose. Image segmentation techniques were then applied to the collected images to locate the object of interest. A space-carving technique was also used to assess the volcanic plume's volume. Besides, another study presents a method for early detection of sinkholes using thermal imaging and computer vision techniques [32]. In this study, infrared cameras are mounted on unmanned aerial vehicles. The classification is based on the temperature gradient between sinkholes and other ground regions. The sinkholes present a lower thermal energy, and the pattern classification allows recognition using deep learning approaches.

Some specific applications are also studied in other articles, such as the food industry, where chemical features and computer vision techniques applied to digital images are used to characterize the heating patterns of packaged foods after their sterilization in microwaves [33]. Another example is related to the in-vessel industry, where thermal images were used to establish a diagnosis of the related equipment. Thus, a state of the art about similar diagnosis methods and the next steps toward new implementations are presented [34]. In another context, infrared imaging is presented as an alternative for production line quality diagnosis in industrial processes [35]. Knowledge-based machine vision systems are used for classifying devices through their thermal images.

In some articles, general approaches for image processing are presented and applied to thermal images. For example, the study in [36] presents a pre-processing method concerning image denoising. It is based on deep learning and allows encountering high noise that may be present in thermal images. Besides, several studies present some object detection and target tracking techniques and their application to thermal images [37-38]. YOLO models (You Only Look Once) were applied to infrared images to extract features and locate objects on thermal and infrared images and videos [37]. Besides, an object tracker is proposed to be applied to infrared images using a combination of generative and discriminative approaches [38], both basic approaches for machine and deep learning models.

The examples presented in this section are varied, which shows the wide use of infrared thermal imaging and computer vision. In the following section, we present the methodology adopted to establish a bibliometric analysis that allows extracting the most relevant information from the articles related to this topic. Besides, the methodology includes the following research steps that aim to focus on the special issue of defect detection using infrared thermal imaging and computer vision.

3. METHODOLOGY

To establish the bibliometric analysis of scientific articles studying different issues using thermal imaging and computer vision, the research criteria we adopt are:

- Research database: Scopus.
- Keywords: "infrared OR thermal," "image OR imaging," AND "computer vision."
- Keywords' location: Title, abstract, or keywords.
- Publishing year: Before or within 2022.
- Document types: Articles and Reviews.

As a result, 1160 articles are found. Their citation, bibliographical information, abstracts, and keywords are all exported as a CSV file to be analyzed in Biblioshiny for Bibliometrix, a bibliometric analysis tool. Detailed information about this tool is given by Aria and Cuccurullo [39]. Using the Biblioshiny for Bibliometrix tool, the general information we could extract from the database is presented in Table 1.

Table. 1. General information about the articles' database used for the bibliometric analysis

Number of documents	1160
Number of sources	496
Number of authors	3492
Articles' writing languages	Chinese, English, Japanese, Korean, Portuguese, Russian, Slovenian, Spanish
Publication years	Between 1986 and 2022
Average citation per year	Up to 97

Then, to focus on the specific issue of defect detection using infrared thermal imaging and computer vision, we add the extra-keyword "defects" to the research criteria. Thus, 22 articles are found using this new restricting criterion. These articles will be analyzed in the following section. First, they are classified into their primary fields, and then their main ideas are presented. Figure 1 presents a diagram summarizing the whole research methodology used in this paper.

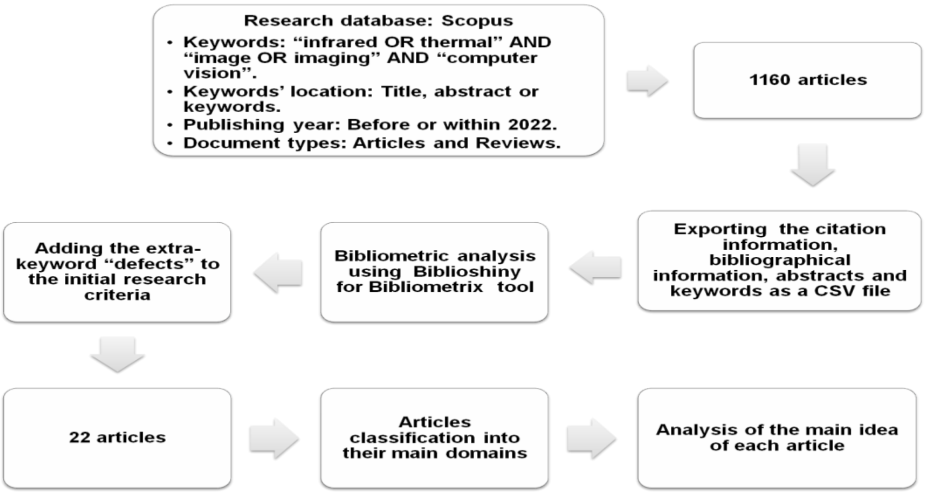

Figure 1. The workflow of the analysis adopted in the paper

4. MAIN FINDINGS

4.1. Global Bibliometric Analysis

The study’s main bibliometric results concern the analysis of the temporal evolution of the publications over the years and the analysis of the sources, authors, affiliations, and publishing countries that contributed the most in the research field, in addition to the identification of the most relevant keywords and the trend topics in each temporal period.

First, the results show that the number of articles concerning infrared thermal imaging and computer vision per year has shown a vital increase recently. The number of publications increased from 51 in 2017 to 192 in 2022. Thus, the publication rate has increased sharply in the last few years. Figure 2 presents the temporal evolution of the publications concerning the studied topic.

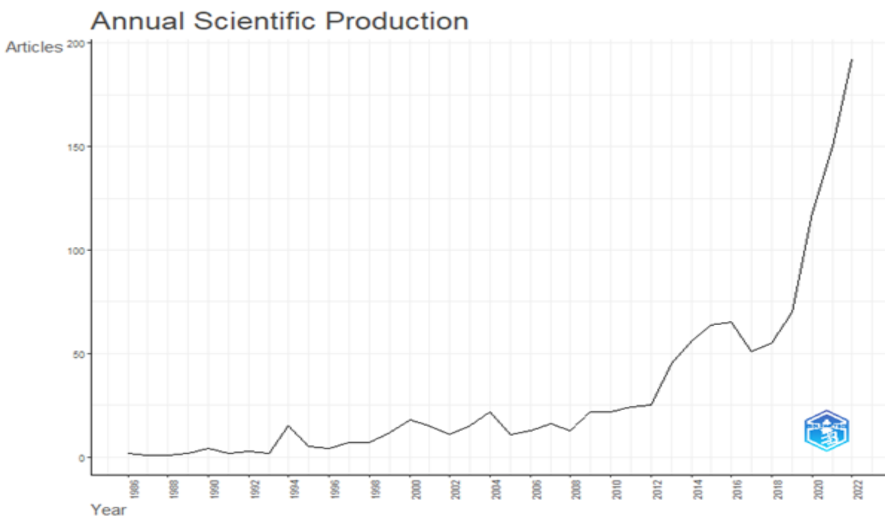

Figure 2. Temporal evolution of the annual number of publications related to the studied topic

The results also show that the global number of sources where the studied articles were published is 496 sources. However, some journals are more dominant. The journal "Infrared Physics and Technology" is where most articles related to our studied topic are published (50 articles).
The bibliometric analysis also includes the authors' study and the affiliations that contributed the most to the studied topic, which are the most relevant. The results show that Li. Y is the author who contributed the most, with 24 publications on the database. At the same time, Tianjin University is the affiliation that contributed the most to the studied articles' establishment through 48 contributions.

Concerning the spatial repartition of the scientific contributions related to the studied topic, China is the country that publishes the most on the topic of thermal infrared imaging and computer vision. The country presents a total number of 338 publications concerning the studied topic: 296 of these publications are SCP (Single Country Publication), which means they are published only by China, while the remaining 42 publications are MCP (Multiple Country Publication), which means they are published through collaborations between several countries. Table 2 summarizes the above results by listing the ten most relevant sources, authors, affiliations, and countries contributing to the studied topic.

Table. 2. Ten most relevant sources, authors, affiliations, and countries contributing to the studied topic

Rank	**Sources**	**Number of articles**
1	Infrared physics and technology	50
2	Sensors	33
3	Computers and electronics in agriculture	28
4	Guangxue xuebao/acta optica sinica	21
5	Nongye gongcheng xuebao/Transactions of the Chinese society of agricultural engineering	20
6	IEEE Access	19
7	Remote sensing	18
8	Hongwai yu jiguang gongcheng/Infrared and laser engineering	16
9	Applied sciences	15
10	Sensors	14
Rank	**Authors**	**Number of articles**
1	Li Y	24
2	Zhang Y	22
3	Wang X	19
4	Liu Y	18
5	Li X	17
6	Zhang Z	17
7	Wang Y	16
8	Wang J	15
9	Zhang J	15
10	Liu Z	14
Rank	**Affiliation**	**Number of articles**
1	Tianjin university	48
2	Nanjing university of science and technology	44

3	China agricultural university	43
4	Zhejiang university	34
5	Wuhan university	30
6	Anhui agricultural university	29
7	Anhui university	29
8	Jiangsu university	26
9	University of science and technology of China	26
10	National university of defense technology	25
Rank	**Country**	**Number of articles**
1	China	338
2	USA	109
3	Spain	40
4	Korea	39
5	India	37
6	Italy	24
7	Canada	21
8	Germany	20
9	United Kingdom	20
10	Brazil	18

In addition, bibliometric analysis allows for identifying the most cited articles in the studied database. The results show that [40] is the most cited paper, presenting 2310 citations. This is mainly due to its innovative approach compared to the research contributions published before 2000. The approach presented in the article concerns a real-time monitoring system for detecting and tracking multiple people outdoors, which uses infrared imaging and computer vision techniques.

The study also includes the evaluation of the keywords' frequency to identify the most relevant ones. The results show that "computer vision" is the most frequent keyword in all the articles, presenting 248 occurrences. For a more global idea, the graphic presented in Figure 3 shows the "Words' Cloud Map" of the 100 most relevant keywords. In this representation, the more the keyword is frequent in the studied articles, the more its size is important in the graph. Indeed, some keywords are less readable on the graph due to their low number of occurrences, making their size very small. However, the most important information to extract from the graph concerns the evident and considerable keywords, which are also the most relevant ones, such as computer vision, machine vision, image processing, object detection, deep learning, thermal imaging, and image fusion.

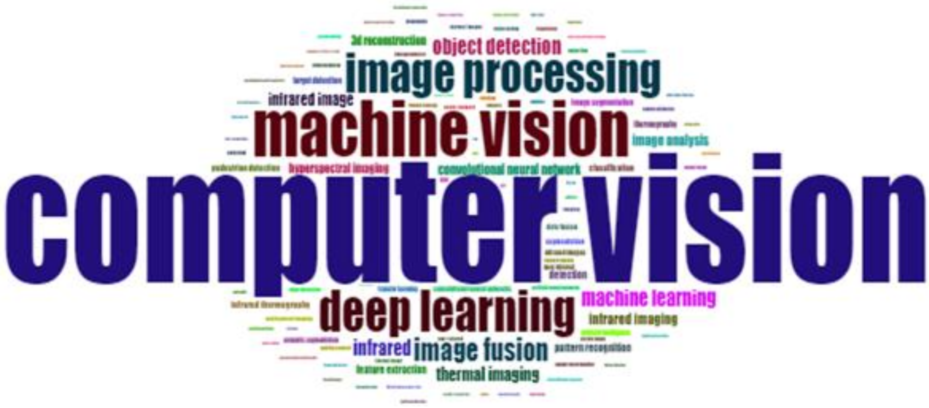

Figure 3. The most relevant keywords in the studied database

The bibliometric analysis also allows establishing the "CoWordNet," a map that presents the linked keywords in most articles and suggests their clustering into separate groups. Five keyword clusters are identified in the studied articles, as shown in Figure 4. The clusters' main keywords are as follows:

- Cluster 1: Computer vision and image processing, Machine Learning and Deep Learning, infrared, multispectral and hyperspectral imaging, cameras, and sensors.
- Cluster 2: Thermal images segmentation, edge detection, and pedestrian detection.
- Cluster 3: Infrared and visible images fusion.
- Cluster 4: Transfer learning and target detection.
- Cluster 5: Photogrammetry, infrared thermography, and 3D reconstruction.

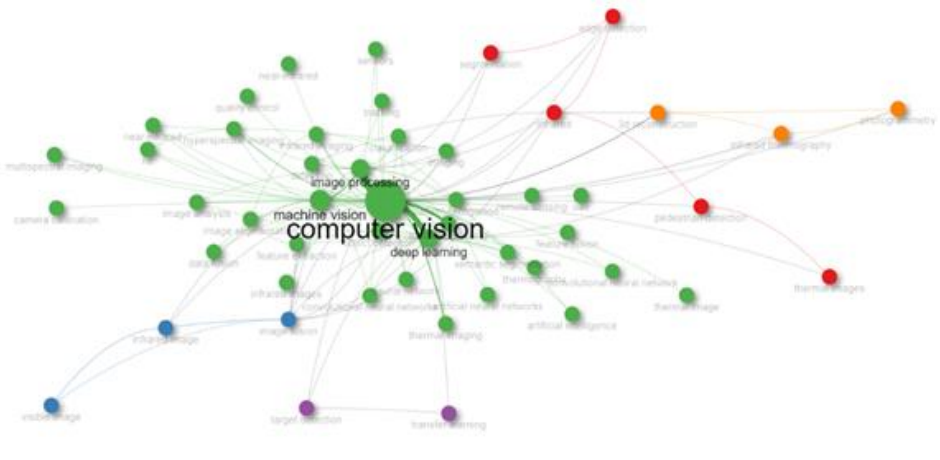

Figure 4. CoWordNet of the main keywords in the articles and their clustering into five groups

Trend topics are the most relevant topics discussed by the articles published in specific temporal periods. These topics can also be identified through bibliometric analysis. Figure 5 shows the temporal graph of the trend topics' evolution over time and their respective frequencies. Even if the first articles in the database start from 1986, the trend topic graph starts approximately in 2010. This can be explained by the fact that the topics in the articles published before 2010 are diverse, not recurrent, and thus, presenting a frequency less than the minimum required in the graphical representation. Therefore, evaluating the trend topics focuses on the period between 2010 and 2022.

The results show that between 2010 and 2022, the year presents different trend topics with different term frequencies. For example, the trend topics for 2019 are computer vision, target detection and image segmentation, presenting frequencies 248 and 13, respectively. The most recent trend topics related to 2022 are feature extraction, semantic segmentation, and artificial intelligence. We notice that in our studied database, the more recent articles are, the more they focus on artificial intelligence applications for processing infrared thermal images.

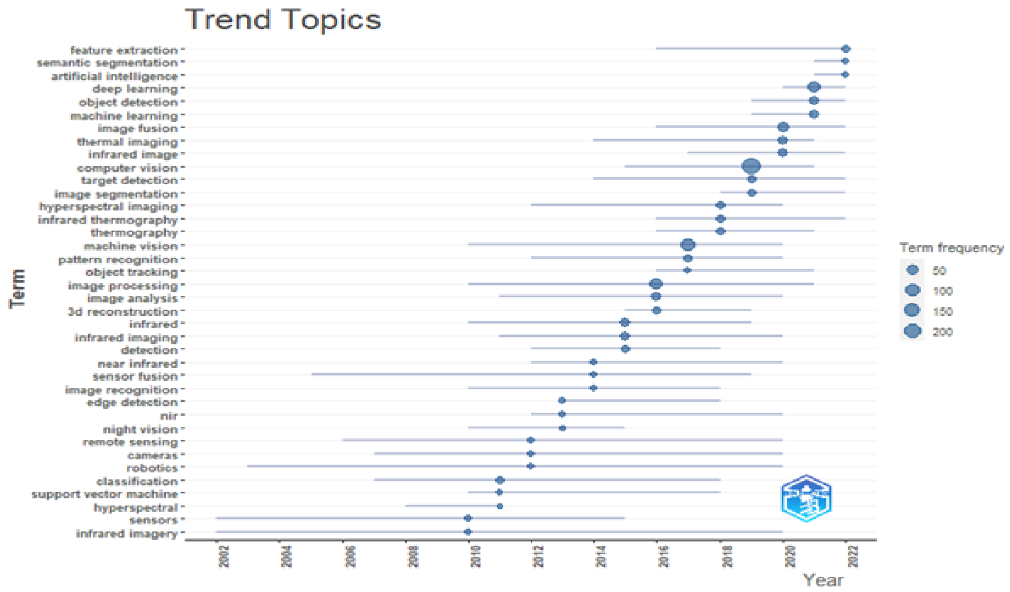

Figure 5. Evolution of the trend topics related to the studied articles over the years

To sum up, bibliometric analysis allows quantifying many aspects of the research topic and extracting meaningful information from the related articles. However, it does not allow a detailed analysis of the article's contents. Therefore, the following part of this section is focused on a detailed analysis of selected articles focusing on defect detection using infrared thermal imaging and computer vision, setting as an objective to present the articles' main topics and to classify them into their main application fields.

4.2. Focus on the Defects' Detection Issue Using infrared Thermal Imaging and Computer Vision

As mentioned in section 3, in addition to the research criteria used for the previous bibliometric analysis, we add the extra-keyword "defects" as a supplementary criterion for our qualitative analysis. The main objective of this specific part of the study is to focus on the research articles dealing with the issue of defect detection using infrared thermal imaging and computer vision. As a result, 22 articles belong to different application fields [41-62].

The articles [41-46] discuss using infrared thermal imaging and computer vision to detect defects in the agrifood industry, especially for fruit quality monitoring. Applying computer vision advanced techniques to infrared images of fruits allows the detection of defective ones and thus eliminating them to guarantee better quality. Thus, different case studies of fruit monitoring are presented in these articles.

In the articles [47-49], the topic of buildings' auscultation using infrared thermal imaging and computer vision to detect defects is discussed. The structural condition of buildings can be assessed using these technologies. For example, buildings' subsurface defects causing heat loss are monitored, their severity is quantified, and their contours are enhanced using thermal image segmentation techniques [47]. Similar techniques based on infrared image processing are used to detect rust defects on steel bridges. Thus, rusted regions are identified, and the percentage of rust is evaluated [48]. Besides, the issue of façade falling objects from tall buildings is highlighted. Periodic monitoring of the façade's condition using infrared thermography and image-based sensing allows the prediction of façades defects and the prevention of falls generated by these anomalies [49].

Defect detection in the electrical field using thermal imaging and computer vision techniques is also investigated [50-51]. In fact, in the study established in [50], Machine Learning models are applied to infrared images to predict defects in electrical power substations and to prevent damages that can occur to this kind of equipment due to the increase in the internal temperature. In the same scope, the study in [51] discusses applying computer vision methods to thermal images to visualize defects in high-voltage insulators. Thus, a real-time monitoring system of these insulators can be developed based on the infrared image segmentation approaches used in the article.

Thermal imaging and computer vision are also useful to detect defects in electronic components [52-54]. Printed circuit boards' solder joints are inspected using machine vision and infrared imagery [52-53]. In the same scope, the quality of printed circuit board assemblies is assessed using thermal images and deep learning models [54].

Several materials are also studied to detect defects using infrared thermal imaging and computer vision. For instance, using these technologies, knots in wood are detected [55], micro-cracks and defects are identified on solar wafers and PV panels [56-57], and steel materials are diagnosed [58-59]. This diagnosis concerns mainly the rail industry, where sliding railway wheels and hot bearings are detected [58], and the alloy industry, where defects are detected in heat-resistant alloy coating structures using the same technologies [59]. Besides, inclusion defects in composite materials are detected through thermal imagery and segmentation techniques [60]. Moreover, the fiber placement defects' detection, location, and classification using the fusion of infrared and visible images are also studied [61]. Furthermore, defects in nonel tubes used for the blasting operation in mining are detected using a system based on machine vision and infrared imaging [62]. The system's architecture was developed within the related study and presented in the article.

The diagram presented in Figure 6 summarizes the results presented above based on the adopted research criteria.

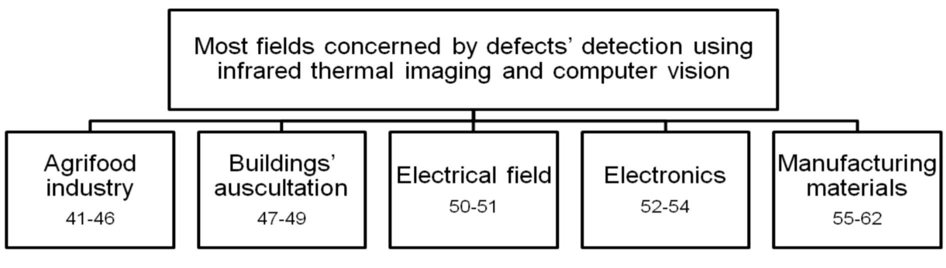

Figure 6. Classification of the articles focusing on defect detection using infrared thermal imaging and computer vision based on the adopted research criteria

5. CONCLUSION AND DISCUSSION

Thermal imaging and computer vision have proven their efficiency in many fields recently. This study aimed to investigate research articles discussing the combination of thermal imaging and computer vision. For this purpose, after presenting an overview of different scientific questions studied using these technologies, both bibliometric and qualitative analysis were established, which allowed extracting information regarding the publications' evolution, their most relevant sources, authors, affiliations, and publishing countries, in addition to their essential keywords and trend topics. Besides, a particular focus of the paper concerns defect detection using infrared thermal imaging and computer vision.

The overview presented at the beginning of the study shows the wide use of infrared thermal imaging and computer vision in many fields, which emphasizes the importance of the studied topic and its efficiency in handling various research questions. This fact enhances the motivation to establish the bibliometric and qualitative analysis presented in this study.

Concerning the bibliometric analysis, the principal results show that the annual scientific production concerning infrared thermal imaging and computer vision increased sharply in recent years, especially since 2018. Besides, China is the country that publishes the most in the studied field through both single-country publications and multiple-country publications. Bibliometric analysis also shows that computer vision is the most frequent keyword in the studied articles. However, the trend topics within the studied research question differ depending on the studied period. As a particular focus, the trend topics in recent years are more focused on using Artificial Intelligence in the field of infrared thermal image processing.

The qualitative analysis focuses on the articles studying the issue of defect detection using infrared thermal imaging and computer vision. The results show that on the studied database, five fields are concerned with this topic: the agrifood industry, the auscultation of buildings, the electrical field, the electronics, and the manufacturing materials.

Starting from both results of the bibliometric and the qualitative analysis that we established about the combination of infrared thermal imaging and computer vision, some of the aspects that could be improved in the future are:

- Contributing to the topic by more countries worldwide to analyze various case studies: In fact, the country scientific production map in Figure 7 shows that some dominant countries publish many articles related to the studied topic, which are presented through the blue color on the map, while other countries do almost not have any contributions in the field. They are presented through the grey color on the same map. Contributing to the topic by many research institutions in various countries can present a real potential for discovering new innovative case studies, especially those related to these countries geographic location.

- Concerning defect detection using infrared thermal imaging and computer vision, the case studies belong to a few dominating fields. Many applications are not frequently or not at all studied using these technologies. Thus, there is a real need for further research on various research questions that can be studied using thermal imaging and computer vision to detect defects in other materials or within other processes. For example, we work on a research project to detect geological and geotechnical defects, mainly rock mass discontinuities. We use infrared thermal imaging and computer vision to identify unstable rock blocks and prevent rock fall accidents in deep underground mines. This is just one example of innovative applications.

However, there are many other ones belonging to several fields that can enrich the research concerning defect detection using infrared thermal imaging and computer vision.

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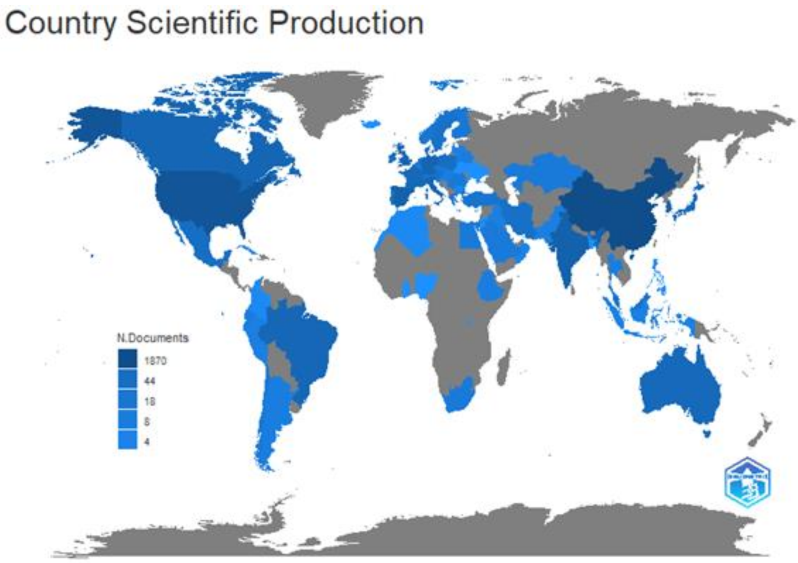

Figure 7. Country scientific production map

All in all, the presented bibliometric findings and the established qualitative analysis will not only guide future contributions in each application field identified within the analysis but will also hopefully encourage novel contributions in new fields that require more investigations to adopt innovative approaches and methods based on thermal images and computer vision techniques.

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