

Analyzing the Scientific Evolution of Face Recognition Research and Its Prominent Subfields

YAHYA ZENNAYI^{1,2}, FRANÇOIS BOURZEIX², AND ZOUHAIR GUENNOUN¹, (Senior Member, IEEE)

¹Smart Communications—ERSC Team, E3S Research Center, Mohammadia Engineering School, Mohammed V University, 10090 Rabat, Morocco

²Embedded System and AI Department, Moroccan Foundation for Advanced Science, Innovation and Research, 10010 Rabat, Morocco

Corresponding author: Yahya Zennayi (zennayi.yahya@gmail.com)

ABSTRACT This paper presents a science mapping approach to analyze thematic evolution of face recognition research. For this reason, different bibliometric tools are combined (performance analysis, science mapping and Co-word analysis) in order to identify the most important, productive and the highest-impact subfields. Moreover, different visualization tools are used to display a graphical vision of face recognition field to determine the thematic domains and their evolutionary behavior. Finally, this study proposes the most relevant lines of research for the face recognition field. Findings indicate a huge increase in face recognition research since 2014. Mixed approaches revealed a great interest compared to local and global approaches. In terms of algorithms, the use of deep learning methods is the new trend. On the other hand, the illumination variation impact on face recognition algorithms performances is nowadays, the most important and impacting challenge for the face recognition field.

INDEX TERMS Bibliometric studies, co-word analysis, face recognition, performance analysis, science mapping, thematic evolution.

I. INTRODUCTION

Face recognition (FR) and its applications have become part of our daily lives. When using a biometric passport to cross a border, when using social networks (especially those based on the use of photos), when shopping in certain stores in China, automatic FR is used.

FR is one of the most active research themes in the computer vision field, as shown by the numerous scientific articles published each year in this domain (For example in Web of science data base: 316 documents published in 2010 versus 862 documents in 2019). This interest is due to the high number of applications using this technology and the wide availability of cameras and photos containing faces. FR can be applied in several areas:

- 1) Access control: the human face can be considered as a biometric signature, hence FR can be used to validate a person's identity. This technology has an advantage over other access control techniques, since it doesn't require any physical contact with the device, unlike, for example, access control with fingerprint. [1]–[3].

- 2) Criminal investigations: FR can be used to find and validate a suspect's identity at the crime scene, using images from surveillance cameras or sketches as described by witnesses [4]–[6].
- 3) Wanted persons identification support: real-time FR using surveillance cameras increases the security level in public spaces. It can be used to detect wanted persons and it has proved to be a very practical tool for law enforcement to neutralize suspects [7]–[9].

This increase in scientific research activity has led to an overall improvement in algorithm performance, in recent years. Indeed, recognition accuracy exceeds 95% in certain cases [10]–[13]. However, the number of published papers in this research area keeps increasing each year, because of unresolved challenges.

Various FR algorithms have been proposed to achieve high accuracy rates and to solve known problems in this research area. Most of these algorithms are composed of a series of sub-algorithms which offer the researchers several possibilities to improve them. Due to this diversification of choices and challenges, FR domain is fragmented, which makes it difficult to obtain single access to this research topic.

Furthermore, it is difficult to have a global vision of this field. Recommendations and analyses for future researchers

The associate editor coordinating the review of this manuscript and approving it for publication was Zahid Akhtar¹.

are not complete. For this reason, exhaustive reviews are needed to integrate contributions and provide a critical perspective in this area. In fact, several works [14]–[16] have been published in this direction to analyze this research field, by addressing the major challenges, classifying the approaches, providing comparisons between these methods, and giving some recommendations for future work in the field of FR. However, no quantitative analysis was used in any of these studies. For example, these studies do not allow to fragment a research field in an exhaustive way, nor to find links between challenges, methods and techniques used. Also, they do not allow to evaluate the efforts made by the researchers on each of the axes of this field, nor the impact of these studies on future works.

Accordingly, science mapping,¹ Co-word analysis² and performance analysis (quantitative analysis) are necessary to examine the sets of terms shared by the documents, mapping the literature from the interaction of key terms, and showing the evolution of the FR field. In this regard, the science mapping approach presents the structural and dynamic aspect of scientific research [19] and is a spatial representation of how disciplines, fields, specialties and individual papers or authors are related to one another. These methods focus on domain monitoring and research area delimitation to establish the research cognitive structure and evolution. Indeed, this is done by determining the continuity of these fields over consecutive subperiod of time and by analyzing the evolution of their performances [20]. This longitudinal study based on co-words [21] allows to analyze the evolution of research subjects, and a longitudinal study based on co-citations allows to analyze the continuity of the intellectual base. Additionally, it detects the most important productive and impactful sub-areas.

Consequently, this article presents a general approach to analyze quantitatively the FR research field, by combining performance analysis and science mapping to detect and visualize conceptual subdomains [19], [20], in order to examine the concept's evolution and the impact of the research themes in the FR domain.

The rest of the paper is organized as follows: Section 2 provides a general overview of the latest reviews covering the RF theme. Section 3 presents the methodology and data collection. Then a presentation of the analysis and the results is discussed in Section 4. Finally, a conclusion is made in section 5.

II. FACE RECOGNITION: A LITERATURE REVIEW

Several studies have been performed to compare FR approaches and methods to solve major challenges or improve the performances of these systems. These studies can

¹Scientific mapping is a methodology that combines quantitative analysis, clustering, and visualization in order to identify the composition and interrelationships between bibliographic objects [17].

²A technique to analyze the co-occurrences of keywords characterizing scientific articles, as well as to identify the relationships and interactions between these articles [18].

be divided into several categories according to the authors' concern.

A. GENERAL CONTEXT

Some works have focused on FR on a general standpoint. [14] Zahid *et al.* provides a state-of-the-art analysis of FR algorithms, focusing on their performance on public databases. The work highlights the impact of image database conditions on the recognition rate of each approach. Finally, it gives researchers the ability to choose more easily the algorithm for a specific FR application. [22] Chihaoui *et al.* divided the 2D FR methods into three categories: Global approaches, Local approaches, and Hybrid approaches. The authors present an overview of some well-known methods in each of these categories. A comparison between FR techniques is provided. In addition, the databases used in FR are listed, and some results of the application of these methods on FR databases are presented. [23] Hassabalah and Aly reviewed current FR achievements and examined many challenges and key factors that can significantly affect the performance of FR systems. The use of FR technology in other scientific applications and daily life was proposed. Several research directions to improve the performance of advanced FR systems are also recommended for future work.

B. SPECIFIC FR CHALLENGE

Other works have focused on a specific FR challenge to give it more attention. [24] Ochoa-Villegas *et al.* deal with the FR uncontrolled illumination challenge. For that they classify the algorithms into two categories: relighting and unlighting. Relighting methods attempt to match the probe's illumination conditions using a subset of representative gallery images, while unlighting methods try to eliminate variations. The author's present the best methods for both categories that can be useful to determine research directions. [25] Abdurrahim *et al.* present an extensive and focused survey that covers recent research on demographic covariates (i.e., race, age, and gender) on FR performance. The authors examine and summarize the effect of age, gender, and racial covariates on FR. In addition, suggestions on the future direction of the field are made to fully understand these effects individually and their interactions with each other.

[16] Dagnes *et al.* provide a review of the methods of 3D FR to handle the problem of partial occlusions. The datasets used to evaluate a various techniques are presented. Moreover, the comparison of recent approaches is presented, and some conclusions and recommendations are suggested. The most studied and tested occlusions are those caused by free hands in front of the face and eyeglasses. The occlusions caused by scarves, caps and other accessories remain the major challenges to be solved for this category. [26] Wang *et al.* provide a comprehensive overview of the methods used to recognize faces from low resolution images with varying pose expression and illumination. In their work the authors classify the methods in two categories, super-resolution for LR FR and resolution-robust

feature representation for LR FR. The concept descriptions for each approach is presented. Their strategies advantages and disadvantages are also highlighted. [15] Ouyang *et al.* provide an exhaustive review of techniques to solve Heterogeneous Face Recognition (HFR) problems. The authors present the state of art, methodology and datasets in HFR across multiple modalities including Photo- Sketch, Visible-NIR, 2D- 3D and High-Low Resolution. Different methods are listed and analyzed to give the best approaches of each modality. An identification of common themes is also carried out to establish links between the different research communities on HFR, and to identify challenges in this area and orientations for future research.

Some other studies related to FR have focused on age and gender estimation. [27] Panis *et al.* present an overview of the research works on facial ageing impact on FR using the FG-NET database. An analysis of published articles using the FG-NET database is performed and the benchmark results are presented. The authors summarize the obtained results to provide roadmaps for future trends and an orientation for future research in facial ageing. [28] Choon-Boon *et al.* present a review of facial gender recognition, focusing on 2D computer vision approaches. The challenges involved are highlighted, which can be divided into human factors, image conditions and qualities. The authors examine the approaches and the dataset used for evaluation of gender classification performance.

C. REVIEWS INTERESTED IN TECHNIQUES OR APPROACHES

Other works have focused more on techniques or approaches to improve the performance of FR systems. [29] Kasar *et al.* present a review of the studies published in the literature on FR using Neural Network approaches. For that, the authors explore various architectures, algorithms and databases for training or testing images. In addition, they measured the performance of FR systems used in each study. [30] Sharma and Patterh provide an extensive survey of feature extraction and recognition methods for FR applications. They evaluate feature extraction techniques for various FR methods to draw a summary diagram, and to select the technique with the best accuracy. [31] Hongjun Wang *et al.* present a review of feature extraction framework for robust FR. More than 300 papers regarding face feature extraction are collected, analyzed and categorized into four components: filtering, local features, feature encoding, spatial pooling and holistic feature processing. Each component is analyzed and applied in a task with multiple levels. Also, they provide a brief review of methods using deep learning networks. Finally, a detailed performance comparison of various features on LFW and FERET face database are provided. [32] Tian and Wu present a review of compressive sensing (CS) methods employed for FR. These methods are grouped into four categories: Sparse representation classification (SRC), the method using the sparsity idea in CS theory, the combination of kernel trick and SRC, and the method based on

sparse preserving techniques. The results are summarized and analyzed to obtain the advantages and inconveniences of each approach. [33] Plichoski *et al.* bring a survey of Swarm Intelligence and Evolutionary Computation applied in 2D FR systems. The authors analyze the key techniques and approaches used and summarize the obtained results to suggest an orientation for future research.

D. SPECIFIC SUBJECTS

Finally, various works cover more specific subjects. [34] Blanco-Gonzalo *et al.* analyze the usability and the accessibility of FR systems used by visually impaired people. A comparison between the FR algorithms is provided in terms of performance and time spent in the process, which are critical aspects for this case. [35] Phillips and O'Toole provide a comparison between human and computer performance across FR. The cross-modal performance analysis (CMPA) framework is used to analyze performance across methods. The results of the analysis can be divided into two categories: 1) Frontal faces on still images; 2) Video and difficult still face pairs. For the first category the algorithms are always more efficient than humans. However, for the second, humans are better. [36] Sepas-Moghaddam *et al.* address the issue of the vulnerability of FR systems to presentation attacks. For that a review of methods are presented in the literature on light field based face presentation attack detection solutions. Finally, the approaches are assessed in terms of accuracy and complexity.

III. METHODOLOGY

In this work, we mainly employed the software SciMAT (Science Mapping Analysis software Tool) [37]. It is an open source software used to perform science mapping analysis on a research topic, based on a longitudinal approach. This tool has a graphical user interface and integrates algorithms, methods and measurements for all stages of the science mapping process, from the pre-processing to the results visualization [19]. This software combines performance analysis and scientific mapping tools, to analyze a research domain, to detect and to visualize its conceptual sub-domains (specific themes / themes or general thematic domains), as well as their evolution through the different subperiods studied [20]. SciMAT combines modules needed to achieve the scientific mapping workflow. From downloaded files, this software allows to load article information to build a database and automatically detect duplicate elements. Furthermore, this tool proposes several techniques for data normalization such as Jaccard's index, inclusion index, equivalence index, association strength and Salton's cosine. Different bibliometric measures based on citations are employed to build science maps enriched, such as: h-index, g-index, hg-index and q2-index. Finally, the tool allows to visualize the results in the form of strategic diagram, cluster network, overlapping map and evolution map.

Figure 1 shows the workflow used in this work. The first step is to recover the data. The raw data is collected from the

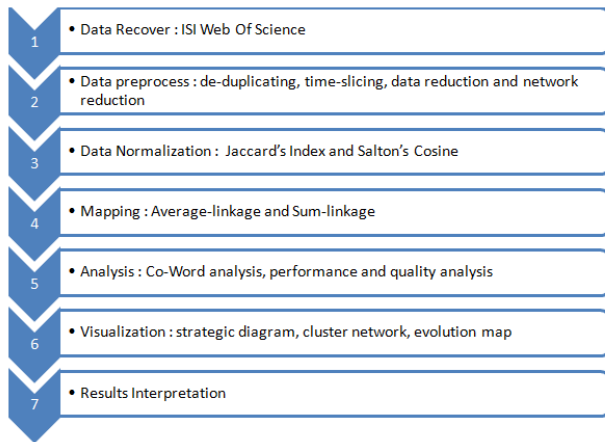


FIGURE 1. Workflow of science mapping.

published documents on the FR topic. An advanced search is carried out on the ISI Web Of Science bibliographic source, using keywords relating to FR and selecting the Research areas (WoS categorizes) of interest, to be limited to the face recognition articles by image processing. The search request is the following:

(TS=“Face recognition”) AND DOCUMENT TYPES: (Article OR Review) Refined by: RESEARCH AREAS: (COMPUTER SCIENCE OR ENGINEERING OR IMAGING SCIENCE PHOTOGRAPHIC TECHNOLOGY) AND WEB OF SCIENCE CATEGORIES: (COMPUTER SCIENCE ARTIFICIAL INTELLIGENCE OR ENGINEERING ELECTRICAL ELECTRONIC OR COMPUTER SCIENCE THEORY METHODS OR COMPUTER SCIENCE INFORMATION SYSTEMS OR COMPUTER SCIENCE SOFTWARE ENGINEERING OR IMAGING SCIENCE PHOTOGRAPHIC TECHNOLOGY OR COMPUTER SCIENCE CYBERNETICS OR COMPUTER SCIENCE HARDWARE ARCHITECTURE OR AUTOMATION CONTROL SYSTEMS OR ENGINEERING MULTIDISCIPLINARY).

The second step consists in preprocessing the data using the tool “SciMAT”. The goal of this operation is to detect duplicate documents, to regroup similar keywords, and to define time-slicing periods (1991-2003, 2004-2006, 2007-2009, 2010-2012, 2013-2015, 2016-2018 and 2019-2021), in this study periods of 3 years have been chosen in a perspective, to use a few years not too long to have variability, and not too short to have stability. In general, in literature studies, the last 3 or 5 years are often used. In this study we used the keywords (Authors keywords, journals keywords) presented in the documents as the basic elements of analysis. These keywords are used to extract a direct link between documents and references, this relationship is illustrated in a strategy diagram and an evolution graph. The third step consists to conduct a normalization process to build relationships network. Similarities between the items are calculated, using the frequency of keywords’ co-occurrences. Different measures can be used, in our case the Salton’s

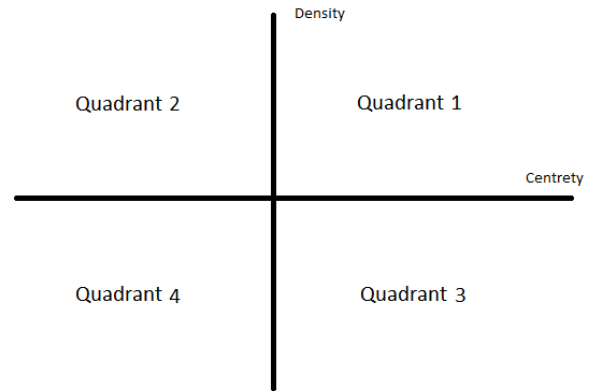


FIGURE 2. Strategic diagram.

Cosine and the Jaccard indexes are applied. The fourth consists in identifying research issues or areas of interest for the research community using clustering algorithms on keywords data resulting from previous step. For that, many clustering algorithms can be used to build the science map. In this work the principal component analysis is used. The fifth step is dedicated to extrating useful knowledge and measuring the relationship among the detected clusters of keywords, by carrying out a network analysis. The sixth step is the visualization of results. Each detected cluster (considered as research themes) is characterized by two parameters: centrality and density (Eq.1,2). These measures are used to have two different visualization instruments: strategic diagram and thematic network.

A strategic diagram as shown in fig.2 is a 2D graph built by plotting research themes based on their centrality and density values, the x-axis represents centrality and the y-axis the density.

Centrality (Given in Eq.1) measures the strength of external links with other themes. It gives an indication of the importance of the theme in the development of the entire research field analyzed. k is a keyword belonging to the cluster and h is a keyword belonging to other clusters.

$$Centrality = 10 \times \sum e_{kh} \tag{1}$$

Density (Given in Eq.2) measures the strength of internal links between all keywords defining the research theme. It can be considered as a measure of the evolution of the theme. i and j are the keywords belonging to the cluster, and n is the number of keywords in the cluster.

$$Density = 10 \times \sum \frac{e_{ij}}{n} \tag{2}$$

Once the visualization is performed, it is necessary to interpret the graphs and the generated results. The themes presented in the strategic diagram [19] are classified into four groups:

- 1) Themes in the quadrant 1 (Fig. 2) are the well-developed and also the most important for research field structuring. They are known as the motor-themes of the specialty, given that they present strong centrality and high density.

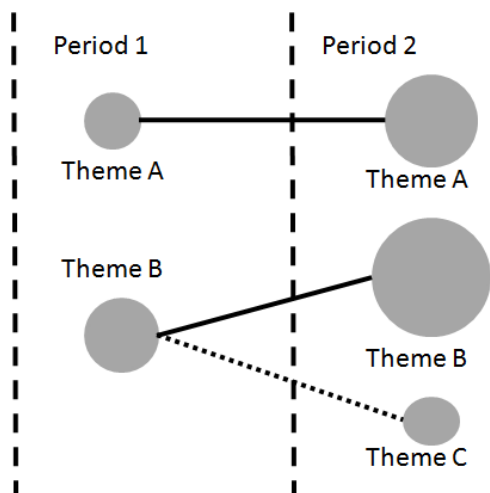


FIGURE 3. Thematic evolution.

- 2) Themes in the quadrant 2 (Fig.2) have well developed internal links, but unimportant external links and are therefore marginally important to the field. These themes are highly specialized and peripheral in nature.
- 3) Themes in the quadrant 3 (Fig. 2) are important for a research field, although they are not developed. Thus, this quadrant contains transversal and general basic themes.
- 4) Themes in the quadrant 4 (Fig. 2) are both underdeveloped and marginal. They have low density and low centrality representing mainly emerging or disappearing themes.

As shown in fig.3 thematic evolution can be considered as a bipartite graph, it allows visualizing the evolution of the themes through subperiods. The periods are presented by column, and the different thematic areas are linked from one column to the next column. Thus, a thematic area is defined as a group of themes evolving across different subperiods. Each theme is plotted as a sphere and labeled with the name of the most significant keyword in the cluster. These themes are linked together through subperiods by lines.

In thematic evolution (Fig. 3) the interconnection between two themes “conceptual nexus” indicates the relationship between them. The solid lines mean that the linked themes share elements other than the name of the themes. A dotted line means that the themes share elements that are not the name of the themes. The depth of the edges is proportional to the inclusion index [19] and the volume of the spheres is proportional to the number of published documents of the themes.

IV. RESULTS ANALYSIS

In this section, the results obtained from this bibliometric study are analyzed.³ The research activities in the field of FR experienced a growth in the early 2000s to reach a peak

³It should be noted that the extraction of the information was done at the end of 2021, therefore all the bibliometric informations (number of citations, Hidex) are updated until that date (end of 2021).

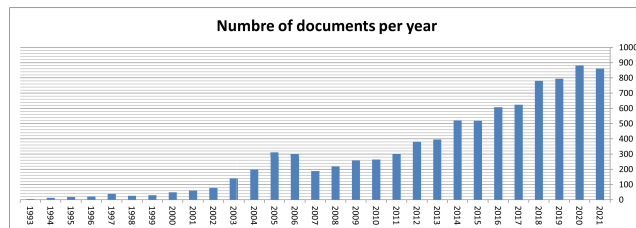


FIGURE 4. Number of documents published in the field of FR per year.

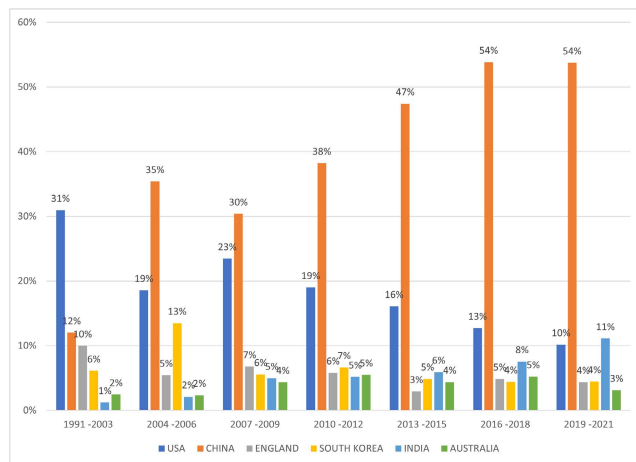


FIGURE 5. Contribution rate evolution in the FR domain by country.

of publication in 2005 (318 articles published), a decrease during 2006 and 2007. Since 2008, this field experienced a continuous growth period, the level of publication reached in 2005 being only outperformed in 2011. Although the number of papers per year exceeded the 500 papers limit only from 2014 onwards (see Fig. 4) - 8898 papers published. This growth in interest for this field is due to the high number of applications of this technology, the increasing availability of images containing faces and the challenges that have remained unsolved until now. The first growth period, until 2005, is explained by the availability of the largest face databases during this period (for example: FERET, ORL, AT&T, Yale Face, UMIST, AR, PIE, MIT-CBCL, CMU (for more details refer to [38])). At the start of 2010 many countries decided to boost the security of their cities by installing surveillance cameras. In China, this vision can be illustrated clearly by the Skynet project launched in 2011 to equip cities with video surveillance systems (1.1 million cameras were installed in 2012, to reach 200 million cameras installed in 2018), which explains the second growth. Also, the emergence of smartphones and social networks at this same period has pushed the scientific community to make more effort to meet this huge need.

This global growth tendency in research activity in the field of FR, is not uniform on a geographic standpoint, as can be seen in Figure5. China has become within 15 years an overwhelming actor in this technological field generating more than 50% of all articles since 2015 while it only produced

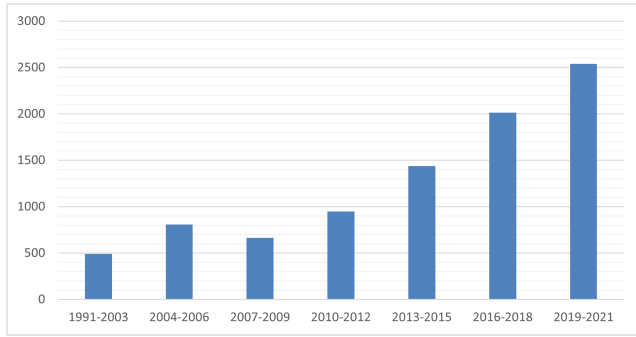


FIGURE 6. Number of documents published in the field of FR per period.

12% before 2003. China alone has been the essential driver of the scientific activity growth in this field since 2008. On the periode 2007-2009 the total publications number was 665, with 156 from USA (23%) and 202 from China (30%). It increased by 282%, to reach 2538 on the period 2019-2021 with 258 articles from USA (10%), 1364 from china (54%) and 282 from India (11%). China’s activity in terms of publications has grown by 575% on this periode of time, while the USA activity only increased by 65%. On the same periode, england and South Korea have experienced a growth of research activity, of the same order: +147% for england (from 45 to 111 articles) and +205% for Korea (from 37 to 113 articles). Another key fact is the emergence of India as a leading actor in the FR field. In the 1990s India was responsible for only 1% of the total research publications, while it generated between 2019-2021 11%, it became the second most active country in this field of research. It experienced an increase by +755% between the 2008-2010 and 2019-2021 periods. Research in the FR field is now an asian led activity, since this continent generated more than 69% of total publication in the 2019-2021 period. Across all periods, the countries most involved in scientific research in this field are: China, the United States and India (see figure 7). These participations represent 75% of the articles published worldwide.

A. FR THEMES VISUALIZATION

In the following, the results of the subperiods analysis are presented as a strategy diagram and tables containing quantitative and impact measures for each subperiod.

In the subperiod 1991-2003, a total of 491 documents (Fig. 6) in the FR theme are considered.

Looking at both the strategic diagrams (Fig. 8) and the quantitative measures (Table 1), we can observe that (i) the motor themes, PCA and CLASSIFICATION received a high citations and had the highest impact (high h-index scores); (ii) the basic and transversal theme, FEATURES received many citations and had a great impact later; (iii) a specific topics, TRACKING received a few citations and had the lowest impact; (iv)The emerging themes, 3D received a few citations and didn’t have a big impact;



FIGURE 7. Number of documents published in the field of FR per country.

TABLE 1. Performance measures for the themes of the subperiod 1991-2003.

Name	Documents	H-Index	Citations
CLASSIFICATION	115	47	23064
PCA	108	53	25196
TRACKING	32	21	6857
3D	27	18	5498
FEATURES	72	37	22491

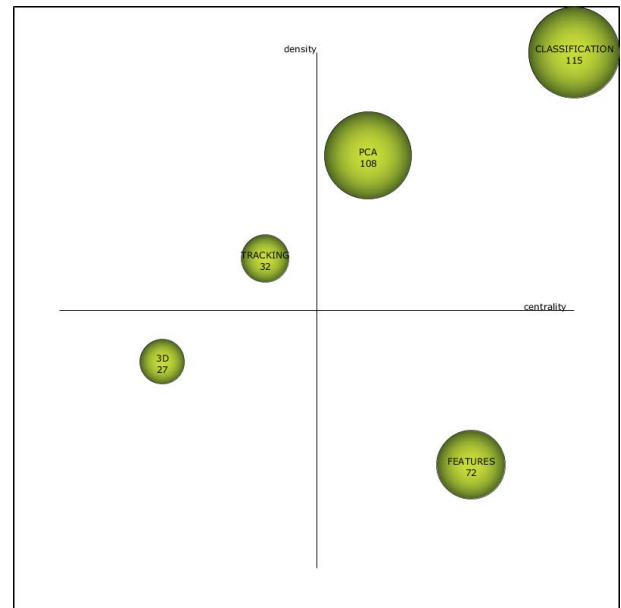


FIGURE 8. Strategic diagram for subperiod 1991-2003.

The (Table2) lists the 3 most important documents of this subperiod by theme.

In the subperiod 2004-2006, the number of documents published in the FR theme has seen a marginal increase, be a total of 808 documents (Fig. 6). According to (Fig. 9) and (Table 3) it can be observed that (i) the motor themes, PCA and FEATURES are the most cited and they present the highest impact; (ii) the basic and transversal themes, CLASSIFICATION had many citations and a great impact; (iii) a specific topics, TRACKING and POSE present the lowest impact; (iv)The emerging themes, SVM received few citations and had limited impact.

TABLE 2. Three most important documents of the subperiod 1991-2003.

Theme	Document title	Publication year	Times cited	Reference
CLASSIFICATION (CLASSIFICATION ; ANN ; PATTERN-RECOGNITION)	Face recognition: a literature survey	2003	3285	[39]
	Face recognition with radial basis function (rbf) neural networks	2002	389	[40]
	Integrating faces and fingerprints for personal identification	1998	325	[41]
PCA (PCA ; EIGENFACES ; ICA)	Gabor feature based classification using the enhanced fisher linear discriminant model for face recognition	2002	1283	[42]
	Pca versus lda	2001	2050	[43]
	Face recognition by independent component analysis	2002	1188	[44]
TRACKING (TRACKING ; SEGMENTATION ; EXTRACTION)	Fast, reliable head tracking under varying illumination: an approach based on registration of texture-mapped 3d models	2000	220	[45]
	Probabilistic recognition of human faces from video	2003	169	[46]
	Comparing face images using the modified hausdorff distance	1998	117	[47]
FEATURES (FEATURES; PERFORMANCE; LDA)	Human and machine recognition of faces - a survey	1995	1410	[48]
	Face recognition - features versus templates	1993	1298	[49]
	Face recognition: the problem of compensating for changes in illumination direction	1997	625	[50]
3D (3D ; POSE)	Face recognition by elastic bunch graph matching	1997	1834	[51]
	Face recognition based on fitting a 3d morphable model	2003	1180	[52]
	From few to many: illumination cone models for face recognition under variable lighting and pose	2001	3150	[53]

TABLE 3. Performance measures for the themes of the subperiod 2004-2006.

Name	Documents	H-Index	Citations
PCA	202	55	17697
FEATURES	88	36	7869
POSE	60	27	5886
TRACKING	13	8	841
SVM	27	11	996
CLASSIFICATION	77	33	8659
FLD	37	21	2541

TABLE 4. Performance measures for the themes of the subperiod 2007-2009.

Name	Documents	H-Index	Citations
LDA	189	51	16666
PCA	169	42	7891
POSE	103	35	5338
MANIFOLD-LEARNING	58	28	6058
RECONSTRUCTION	9	8	346
PATTERN-RECOGNITION	74	28	3109
FUSION	36	17	1154
GABOR	115	42	7416
EXPRESSION	70	28	4576

The (Table 9) lists the 3 most important documents of this subperiod by theme.

In the subperiod 2007-2009, the FR theme has seen a slight decrease in terms of published documents. A total of 665 papers were published, either an decrease of 17% compared to the previous subperiod (Fig. 6). In this subperiod, according to (Fig. 10) and (Table 4), as with the previous subperiod, the motor-themes are the most cited and have the greatest impact. Also the emerging and specific topics have

TABLE 5. Performance measures for the themes of the subperiod 2010-2012.

Name	Documents	H-Index	Citations
DIMENSIONAL-REDUCTION	186	42	7632
LDA	256	45	9003
ILLUMINATION	117	37	7926
LBP	199	50	10844
PCA	255	43	9454
LOW-RESOLUTION	8	6	605
EXTRACTION	46	19	3762
PATTERN-RECOGNITION	60	26	8098
EXPRESSION	118	33	4903
SVM	111	32	3479
PROJECTION	68	38	801

TABLE 6. Performance measures for the themes of the subperiod 2013-2015.

Name	Documents	H-Index	Citations
SPARSE-REPRESENTATION	492	73	21078
DIMENSIONAL-REDUCTION	385	55	12481
ILLUMINATION	163	34	4023
LDA	352	51	882
PATTERNS	93	30	4308
EXPRESSION	205	45	7188
TRACKING	61	23	2578
LOW-RESOLUTION	27	15	885
HETEROGENEOUS	18	15	1378
FLD	73	24	2813
ANN	99	25	379
PATTERN-RECOGNITION	110	29	2727
SEGMENTATION	96	30	545
HYPERSPECTRAL	82	31	3483
REGRESSION	160	43	6807
DISCRIMINANT-ANALYSIS	159	37	5277

the lowest impact. The table 10lists the 3 most important documents of this subperiod by theme.

TABLE 7. Performance measures for the themes of the subperiod 2016-2018.

Name	Documents	H-Index	Citations
SPARSE-REPRESENTATION	817	59	16038
DIMENSIONAL-REDUCTION	554	48	10045
ILLUMINATION	192	32	3328
GABOR	223	29	3387
EIGENFACES	345	35	5172
3D	246	33	417
SEGMENTATION	153	32	3619
SUPERRESOLUTION	82	25	2203
DEEP-LEARNING	166	33	3958
TRACKING	107	22	1742
AGE	91	24	2209
FUSION	142	27	2564
PROJECTION	63	17	854
PATTERN-RECOGNITION	138	29	2574
PCA	319	39	5808
HYPERSPETRAL	235	35	4861
REGULARIZATION	158	28	324

TABLE 8. Performance measures for the themes of the subperiod 2019-2021.

Name	Documents	H-Index	Citations
SPARSE-REPRESENTATION	686	26	4157
FEATURES	890	30	5340
LDA	254	18	1321
CLUSTERING	175	16	1051
ANN	567	23	3169
ILLUMINATION	190	14	838
HETEROGENEOUS	100	15	796
LOW-RESOLUTION	102	14	565
GABOR	171	12	759
FUSION	213	17	1561
TRACKING	173	15	833
SUBSPACE	56	11	454
3D	129	14	640
REGRESSION	321	22	1982
EIGENFACES	153	13	750

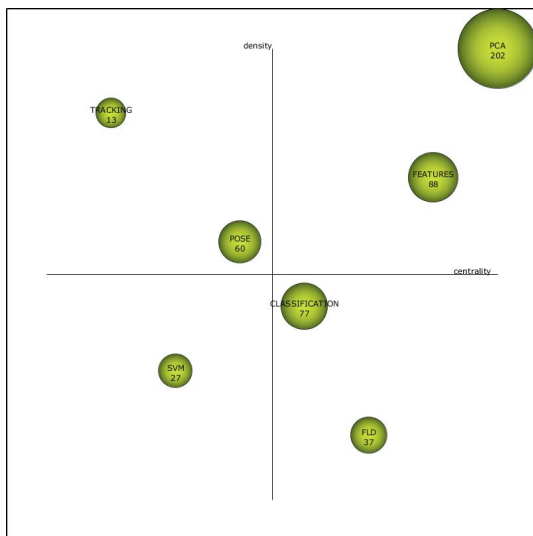


FIGURE 9. Strategic diagram for subperiod 2004-2006.

In the subperiod 2010-2012, FR was a theme of strong interest to researchers. A total of 947 documents are published, either an increase of 42% compared to the previous

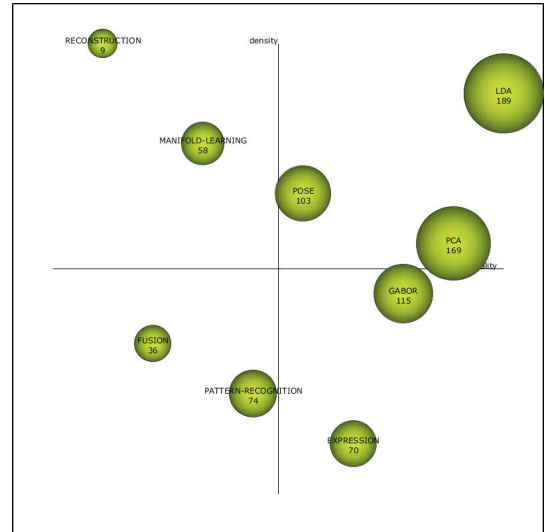


FIGURE 10. Strategic diagram for subperiod 2007-2009.

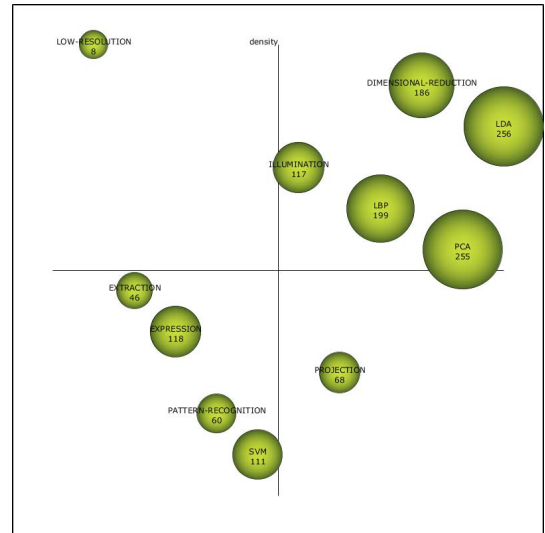


FIGURE 11. Strategic diagram for subperiod 2010-2012.

subperiod (Fig. 7). In this subperiod, according to (Fig. 11) and (Table 5), the themes of the FR field were increasingly developing and motor themes were becoming more and more numerous. Same as previous subperiod, the motor-themes are the most cited and had the greatest impact, especially LDA and PCA themes, while the specific topics have the lowest impact (LOW-RESOLUTION).

The (Table 11) lists the 3 most important documents of this subperiod by theme.

In the subperiod 2013-2015, the FR theme received even more attention from the scientific community. A total of 1436 documents are published, either an increase of 51% compared to the previous subperiod (Fig. 6). In this subperiod, according to (Fig. 12) and (Table 6), as with the previous subperiod, the motor-themes were the most cited and had the

TABLE 9. Three most important documents of the subperiod 2004-2006.

Theme	Document title	Publication year	Times cited	Reference
PCA (PCA ; LDA ; EIGENFACES)	Face description with local binary patterns: application to face recognition	2006	3368	[54]
	Face recognition using laplacian faces	2005	2350	[55]
	Two-dimensional PCA: a new approach to appearance-based face representation and recognition	2004	2211	[56]
FEATURES (FEATURES ; DISCRIMINANT-ANALYSIS ; PROJECTION)	Orthogonal laplacianfaces for face recognition	2006	585	[57]
	(2d)(2)pca: two-directional two-dimensional pca for efficient face representation and recognition	2005	347	[58]
	Gabor-based kernel PCA with fractional power polynomial models for face recognition	2005	366	[59]
POSE (POSE; ILLUMINATION; 3D)	Acquiring linear subspaces for face recognition under variable lighting	2005	1598	[60]
	Illumination compensation and normalization for robust face recognition using discrete cosine transform in logarithm domain	2006	363	[61]
	A survey of approaches and challenges in 3D and multi-modal 3D+2D face recognition	2006	600	[62]
CLASSIFICATION (CLASSIFICATION ; DISTANCE ; FUSION)	Kpca plus lda: a complete kernel fisher discriminant for feature extraction and recognition	2005	560	[63]
	Face Recognition With Local Binary Patterns	2004	1323	[64]
	Recent advances in visual and infrared face recognition - a review	2005	307	[65]
TRACKING (TRACKING ; VIDEO)	Preserving Privacy By De-identifying Face Images	2005	233	[66]
	Visual Tracking And Recognition Using Probabilistic Appearance Manifolds	2005	144	[67]
	A weighted probabilistic approach to face recognition from multiple images and video sequences	2006	38	[68]
SVM (SVM; DIMENSIONAL-REDUCTION)	Locally linear discriminant analysis for multimodally distributed classes for face recognition with a single model image	2005	193	[69]
	Support Vector Machine Based Multi-view Face Detection And Recognition	2004	92	[70]
	Solving The Small Sample Size Problem In Face Recognition Using Generalized Discriminant Analysis	2006	82	[71]
FLD (FLD ; PATTERN-RECOGNITION)	Two-dimensional Discriminant Transform For Face Recognition	2005	215	[72]
	Recognizing partially occluded, expression variant faces from single training image per person with som and soft k-nn ensemble	2005	164	[73]
	High-speed Face Recognition Based On Discrete Cosine Transform And Rbf Neural Networks	2005	144	[74]

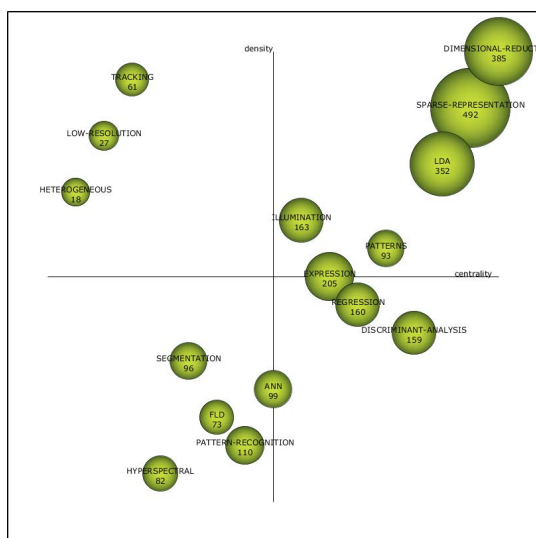


FIGURE 12. Strategic diagram for subperiod 2013-2015.

biggest impact, whereas, the emerging and specific topics have the lowest.

The (Table 12) lists the 3 most important documents of this subperiod by theme.

In the subperiod 2016-2018, the FR topic kept attracting the scientists' focus. A total of 2013 documents were published (Fig. 6).

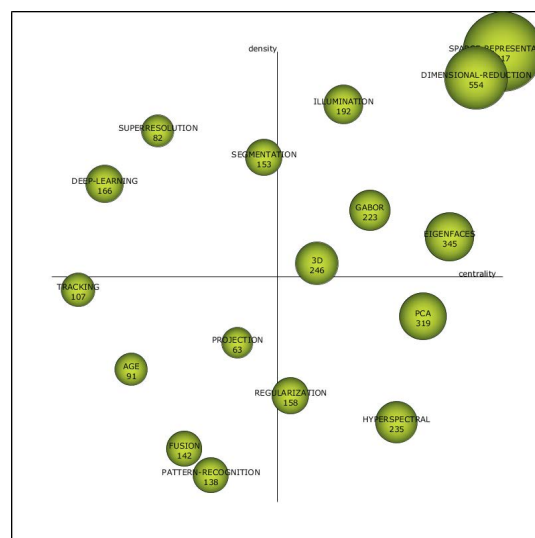


FIGURE 13. Strategic diagram for subperiod 2016-2018.

In this subperiod, according to (Fig. 13) and (Table 7), we can observe that (i) the motor themes, SPARSE-REPRESENTATION, DIMENSIONAL-REDUCTION, EIGENFACES ILLUMINATION, PCA, 3D and GABOR received a high citations and had the highest impact; (ii) the basic and transversal themes, PCA, HYPERSPERICAL and REGULARIZATION received a lot of citations and had a powerful impact. Thus, the emerging and specific themes had the least impact.

TABLE 10. Three most important documents of the subperiod 2007-2009.

Theme	Document title	Publication year	Times cited	Reference
LDA [LDA ; FEATURES ; DISCRIMINANT-ANALYSIS]	General tensor discriminant analysis and gabor features for gait recognition	2007	877	[75]
	MPCA: multilinear principal component analysis of tensor objects	2008	515	[76]
	Eigenfeature regularization and extraction in face recognition	2008	219	[77]
MANIFOLD-LEARNING [MANIFOLD-LEARNING; SUBSPACE-LEARNING; DIMENSIONAL-REDUCTION]	Robust face recognition via sparse representation	2009	6728	[78]
	Graph embedding and extensions: a general framework for dimensionality reduction	2007	2132	[79]
	Globally maximizing, locally minimizing: unsupervised discriminant projection with applications to face and palm biometrics	2007	381	[80]
POSE [POSE ; ILLUMINATION ; 3D]	The cas-peal large-scale chinese face database and baseline evaluations	2008	615	[81]
	Face recognition across pose: a review	2009	286	[82]
	Multiscale facial structure representation for face recognition under varying illumination	2009	140	[83]
EXPRESSION [EXPRESSION ; ROBUST ; SVM]	Gesture recognition: a survey	2007	1012	[84]
	2D and 3D face recognition: a survey	2007	505	[85]
	A region ensemble for 3-D face recognition	2008	172	[86]
GABOR [GABOR ; CLASSIFICATION; LBP]	Dominant local binary patterns for texture classification	2009	539	[87]
	Histogram of gabor phase patterns (HGPP): a novel object representation approach for face recognition	2007	405	[88]
	Hierarchical ensemble of global and local classifiers for face recognition	2009	191	[89]
PATTERN-RECOGNITION [PATTERN-RECOGNITION ; ANN ; FLD]	Tied factor analysis for face recognition across large pose differences	2008	127	[90]
	Incremental linear discriminant analysis for face recognition	2008	117	[91]
	Kernel grassmannian distances and discriminant analysis for face recognition from image sets	2009	71	[92]
PCA [PCA ; ICA ; EIGENFACES]	Uncorrelated multilinear discriminant analysis with regularization and aggregation for tensor object recognition	2009	88	[93]
	Learning the uncorrelated, independent, and discriminating color spaces for face recognition	2008	74	[94]
	Feature extraction using radon and wavelet transforms with application to face recognition	2009	55	[95]
RECONSTRUCTION [RECONSTRUCTION ; SUPERRESOLUTION]	An example-based face hallucination method for single-frame, low-resolution facial images	2008	95	[96]
	Uncorrelated multilinear discriminant analysis with regularization and aggregation for tensor object recognition	2009	88	[93]
	Image reconstruction for face recognition based on fast ICA	2008	21	[97]
FUSION [FUSION ; SEGMENTATION]	Application of nonlinear feature extraction and support vector machines for fault diagnosis of induction motors	2007	184	[98]
	An example-based face hallucination method for single-frame, low-resolution facial images	2008	95	[96]
	Color image discriminant models and algorithms for face recognition	2008	74	[99]

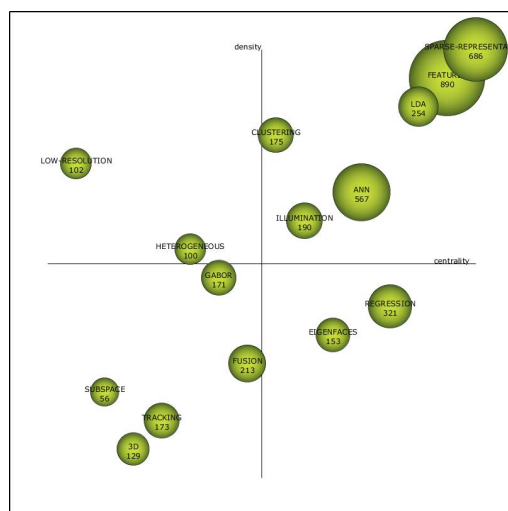


FIGURE 14. Strategic diagram for subperiod 2019-2021.

The (Table 13) lists the 3 most important documents of this subperiod by theme.

In the subperiod 2019-2021, the scientific community’s interest in the FR theme continued to grow. A total of 2538 documents were published, either an increase of 26% compared to the previous subperiod (Fig. 6). In this subperiod, according to (Fig. 14) and (Table 8), as with the previous subperiod, the motor-themes were the most cited and had the biggest impact, especially FEATURES, SPARSE-REPRESENTATION and ANN themes. Also the emerging and specific themes had the least impact.

The (Table 14) lists the 3 most important documents of this subperiod by theme.

In general, it can be remarked that in all the subperiods studied, the motor-themes achieved the highest number of documents, citation scores and impacts. It is logical to find CLASSIFICATION, EIGENFACES, LDA, FEATURES and PCA as the motor themes, they receive more attention and citations because they present the basic of the FR algorithms. In contrast to TRACKING, HETEROGENEOUS, FUSION and 3D, which represent very specific challenges or new techniques.

TABLE 11. Three most important documents of the subperiod 2010-2012.

Theme	Document title	publication year	Times cited	Reference
LDA [LDA ; FEATURES; REDUCTION]	Face recognition using histograms of oriented gradients	2011	327	[100]
	describable visual attributes for face verification and image search	2011	248	[101]
	effective unconstrained face recognition by combining multiple descriptors and learned background statistics	2011	216	[102]
DIMENSIONAL-REDUCTION [DIMENSIONAL-REDUCTION; DISCRIMINANT-ANALYSIS; MANIFOLD-LEARNING]	Linear regression for face recognition	2010	715	[103]
	discriminant sparse neighborhood preserving embedding for face recognition	2012	202	[104]
	a multi-manifold discriminant analysis method for image feature extraction	2011	149	[105]
ILLUMINATION [POSE ; ILLUMINATION ; NORMALIZATION]	Enhanced local texture feature sets for face recognition under difficult lighting conditions	2010	1567	[106]
	toward a practical face recognition system: robust alignment and illumination by sparse representation	2012	418	[107]
	statistical computations on grassmann and stiefel manifolds for image and video-based recognition	2011	228	[108]
PCA [PCA ; EIGENFACES ; ICA]	maximum correntropy criterion for robust face recognition	2011	463	[109]
	human face recognition based on multidimensional pca and extreme learning machine	2011	235	[110]
	enhanced patterns of oriented edge magnitudes for face recognition and image matching	2012	149	[111]
SPARSE-REPRESENTATION [PROJECTION ; SPARSE-REPRESENTATION ; PERFORMANCE]	Sparse representation for computer vision and pattern recognition	2010	1275	[112]
	visual classification with multitask joint sparse representation	2012	275	[113]
	Detecting skin in face recognition systems: a colour spaces study	2010	105	[114]
PATTERN-RECOGNITION [PATTERN-RECOGNITION ; VIDEO ; MACHINE-LEARNING]	a two-phase test sample sparse representation method for use with face recognition	2011	394	[115]
	coupled bias-variance tradeoff for cross-pose face recognition	2012	108	[116]
	Supervised sparse representation method with a heuristic strategy and face recognition experiments	2012	57	[117]
EXTRACTION [EXTRACTION ; REGULARIZATION ; ROBUST]	Age-invariant face recognition	2010	228	[118]
	face recognition based on extreme learning machine	2011	149	[119]
	Soft biometric traits for continuous user authentication	2010	105	[120]
EXPRESSION [EXPRESSION ; TRACKING ; 3D]	local binary patterns and its application to facial image analysis: a survey	2011	480	[121]
	static and dynamic 3d facial expression recognition: a comprehensive survey	2012	240	[122]
	facial expression recognition using radial encoding of local gabor features and classifier synthesis	2012	188	[123]
LBP [LBP; CLASSIFICATION; GABOR]	Local derivative pattern versus local binary pattern: face recognition with high-order local pattern descriptor	2010	643	[124]
	Sparsity preserving projections with applications to face recognition	2010	600	[125]
	Generalized discriminant analysis: a matrix exponential approach	2010	121	[126]
PROJECTION [PROJECTION ; SUBSPACE-LEARNING ; PERFORMANCE]	extended src: undersampled face recognition via intraclass variant dictionary	2012	446	[127]
	kernel sparse representation-based classifier	2012	233	[128]
	Regularized kernel discriminant analysis with a robust kernel for face recognition and verification	2012	47	[129]
SVM [SVM ; ANN ; FUSION]	Fusing local patterns of Gabor magnitude and phase for face recognition	2010	256	[130]
	matching forensic sketches to mug shot photos	2011	217	[131]
	face recognition with an improved interval type-2 fuzzy logic sugeno integral and modular neural networks	2011	87	[132]
LOW-RESOLUTION [LOW-RESOLUTION ; SUPERRESOLUTION]	very low resolution face recognition problem	2012	265	[133]
	Low-resolution face recognition via coupled locality preserving mappings	2010	120	[134]
	multidimensional scaling for matching low-resolution face images	2012	72	[135]

B. EVOLUTION OF THE FR THEMES

In this sub-section, the thematic evolution of the FR research field is analyzed, using the components of each thematic and their evolution through the subperiods. According to the table of themes for each subperiods (Tables: 1, 3, 4, 5, 6, 7, 8), the keywords are not the same. Their number and composition change. There is an increase in the number of themes with

time. We go from 5 themes up to 15 between 1991-2003 and 2019-2021 periods. That is the FR research field evolves through the time. So, there are some themes that appear from one subperiod to the next, others that disappear and others that remain in all the subperiods. For example, the keyword CLASSIFICATION and ILLUMINATION appear in all the subperiods. However the keyword HYPERSPECTRAL,

TABLE 12. Three most important documents of the subperiod 2013-2015.

Theme	Document title	Publication year	Times cited	Reference
SPARSE-REPRESENTATION [SPARSE-REPRESENTATION; CLASSIFICATION; COLLABORATIVE-REPRESENTATION]	Pcanet: a simple deep learning baseline for image classification?	2015	793	[136]
	Face spoof detection with image distortion analysis	2015	297	[137]
	Half-quadratic-based iterative minimization for robust sparse representation	2014	171	[138]
DIMENSIONAL-REDUCTION [DIMENSIONAL-REDUCTION; FEATURES; MANIFOLD-LEARNING]	Learning compact binary face descriptor for face recognition	2015	257	[139]
	Neighborhood repulsed metric learning for kinship verification	2014	249	[140]
	Learning discriminant face descriptor	2014	238	[141]
ILLUMINATION [POSE ; ILLUMINATION ; NORMALIZATION]	Robust face recognition via adaptive sparse representation	2014	146	[142]
	A novel local pattern descriptor-local vector pattern in high-order derivative space for face recognition	2014	93	[143]
	Extracting sparse error of robust pca for face recognition in the presence of varying illumination and occlusion	2014	65	[144]
TRACKING [TRACKING ; VIDEO ; AAM]	A survey of approaches and trends in person re-identification	2014	260	[145]
	A benchmark and comparative study of video-based face recognition on cox face database	2015	87	[146]
	robust face recognition for uncontrolled pose and illumination changes	2013	69	[147]
LDA [LDA ; PCA; EIGENFACES]	sparse coding based visual tracking: review and experimental comparison	2013	241	[148]
	Prototype-based discriminative feature learning for kinship verification	2015	82	[149]
	Integrate the original face image and its mirror image for face recognition	2014	63	[150]
DISCRIMINANT-ANALYSIS [DISCRIMINANT-ANALYSIS ; PERFORMANCE ; REGULARIZATION]	Discriminative multim manifold analysis for face recognition from a single training sample per person	2013	268	[151]
	Fast L(1)-minimization algorithms for robust face recognition	2013	234	[152]
	Cloudid: trustworthy cloud-based and cross-enterprise biometric identification	2015	170	[153]
REGRESSION [REGRESSION ; ROBUST ; EXTREME-LEARNING-MACHINE]	Joint sparse representation for robust multimodal biometrics recognition	2014	193	[154]
	Face recognition by sparse discriminant analysis via joint l-2,l-1-norm minimization	2014	64	[155]
	An efficient illumination invariant face recognition framework via illumination enhancement and dd-dtcwt filtering	2013	53	[156]
SUPERRESOLUTION [SUPERRESOLUTION ; LOW-RESOLUTION]	Robust face recognition via occlusion dictionary learning	2014	138	[157]
	Using the original and 'symmetrical face' training samples to perform representation based two-step face recognition	2013	132	[158]
	Pose-robust recognition of low-resolution face images	2013	69	[159]
EXPRESSION [EXPRESSION ; LBP ; 3D]	Biometric antispoofing methods: a survey in face recognition	2014	186	[160]
	Kinectfacedb: a kinect database for face recognition	2014	154	[161]
	Unconstrained face recognition: identifying a person of interest from a media collection	2014	115	[162]
PATTERNS [PATTERNS ; GABOR ; DEEP-LEARNING]	Face recognition and retrieval using cross-age reference coding with cross-age celebrity dataset	2015	147	[163]
	Detection of face spoofing using visual dynamics	2015	132	[164]
	Sparse and dense hybrid representation via dictionary decomposition for face recognition	2015	119	[165]
HETEROGENEOUS [HETEROGENEOUS ; FORENSIC-SKETCH]	Heterogeneous face recognition using kernel prototype similarities	2013	222	[166]
	Unconstrained face recognition: identifying a person of interest from a media collection	2014	115	[162]
	Matching composite sketches to face photos: a component-based approach	2013	114	[167]
ANN [ANN ; SVM; COMPONENT-ANALYSIS]	Integrating conventional and inverse representation for face recognition	2014	112	[168]
	Data uncertainty in face recognition	2014	105	[169]
	Face recognition with symmetric local graph structure (SLGS)	2014	67	[170]
SEGMENTATION [CLUSTERING ; SEGMENTATION ; LOW-RANK]	Coupled discriminative feature learning for heterogeneous face recognition	2015	63	[171]
	Mixed-norm sparse representation for multi view face recognition	2015	38	[172]
	A novel semi-supervised learning for face recognition	2015	24	[173]
FLD [FLD ; SVD ; SUBSPACE-LEARNING]	Discriminative graph regularized extreme learning machine and its application to face recognition	2015	80	[174]
	Extracting sparse error of robust pca for face recognition in the presence of varying illumination and occlusion	2014	65	[144]
	Subspace-based discrete transform encoded local binary patterns representations for robust periocular matching on nist's face recognition grand challenge	2014	50	[175]
PATTERN-RECOGNITION [PATTERN-RECOGNITION ; MACHINE-LEARNING ; SPACE]	Robust face recognition via multimodal deep face representation	2015	235	[176]
	Regularized robust coding for face recognition	2013	204	[177]
	Deep reconstruction models for image set classification	2015	111	[178]
HYPERSPSPECTRAL [HYPERSPSPECTRAL ; FUSION]	Class-dependent sparse representation classifier for robust hyperspectral image classification	2015	93	[179]
	Hyperspectral face recognition with spatio-spectral information fusion and pls regression	2015	92	[180]
	Infrared face recognition: a comprehensive review of methodologies and databases	2014	86	[181]

TABLE 13. Three most important documents of the subperiod 2016-2018.

Theme	Document title	Publication year	Times cited	Reference
SPARSE-REPRESENTATION [CLASSIFICATION; SPARSE-REPRESENTATION; COLLABORATIVE-REPRESENTATION]	Nuclear norm based matrix regression with applications to face recognition with occlusion and illumination changes	2017	162	[182]
	Semi-supervised sparse representation based classification for face recognition with insufficient labeled samples	2017	159	[183]
	Beyond trace ratio: weighted harmonic mean of trace ratios for multiclass discriminant analysis	2017	115	[184]
DIMENSIONAL-REDUCTION [DIMENSIONAL-REDUCTION; FEATURES; MANIFOLD-LEARNING]	Context-aware local binary feature learning for face recognition	2018	113	[185]
	Simultaneous local binary feature learning and encoding for homogeneous and heterogeneous face recognition	2018	105	[186]
	Fast and orthogonal locality preserving projections for dimensionality reduction	2017	101	[187]
ILLUMINATION [POSE ; ILLUMINATION ; NORMALIZATION]	Pose-invariant face recognition with homography-based normalization	2017	79	[188]
	A survey of dictionary learning algorithms for face recognition	2017	71	[189]
	Local directional gradient pattern: a local descriptor for face recognition	2017	48	[190]
GABOR [GABOR ; LBP ; PATTERNS]	Microexpression identification and categorization using a facial dynamics map	2017	100	[191]
	Age invariant face recognition and retrieval by coupled auto-encoder networks	2017	55	[192]
	VIPLFaceNet: an open source deep face recognition SDK	2017	48	[193]
SEGMENTATION [SEGMENTATION ; LOW-RANK ; ; CLUSTERING]	Sequential three-way decision and granulation for cost-sensitive face recognition	2016	177	[194]
	Learning robust and discriminative low-rank representations for face recognition with occlusion	2017	63	[195]
	Learning kernel extended dictionary for face recognition	2017	36	[196]
DEEP-LEARNING [DEEP-LEARNING ; CNN]	VGGFace2 A dataset for recognising faces across pose and age	2018	552	[197]
	CosFace Large Margin Cosine Loss for Deep Face Recognition	2018	516	[198]
	Approximate orthogonal sparse embedding for dimensionality reduction	2016	136	[199]
EINGENFACES [EINGENFACES ; LDA ; DISCRIMINANT-ANALYSIS]	Multi-task convolutional neural network for pose-invariant face recognition	2018	118	[200]
	A non-greedy algorithm for L1-norm LDA	2017	70	[201]
	Tensor rank preserving discriminant analysis for facial recognition	2018	48	[202]
REGULARIZATION [REGULARIZATION ; MACHINE-LEARNING ; EXTREME-LEARNING-MACHINE]	Evolutionary cost-sensitive extreme learning machine	2017	103	[203]
	Heterogeneous face recognition: a common encoding feature discriminant approach	2017	46	[204]
	Superimposed sparse parameter classifiers for face recognition	2017	31	[205]
HYPERSPETRAL [HYPERSPETRAL ; REGRESSION ; SVM]	PLTD: patch-based low-rank tensor decomposition for hyperspectral images	2017	109	[206]
	Face recognition via collaborative representation: its discriminant nature and superposed representation	2018	70	[207]
	Superimposed sparse parameter classifiers for face recognition	2017	31	[205]
3D [3D ; EXPRESSION ; DISTANCE]	A survey of local feature methods for 3D face recognition	2017	81	[208]
	Novel descriptors for geometrical 3D face analysis	2017	38	[209]
	3D-2D face recognition with pose and illumination normalization	2017	35	[210]
TRACKING [TRACKING ; AAM ; VIDEO]	Trunk-branch ensemble convolutional neural networks for video-based face recognition	2018	191	[211]
	Deep multi-view feature learning for person re-identification	2018	47	[212]
	Dynamic ensembles of exemplar-svms for still-to-video face recognition	2017	39	[213]
PCA [PCA ; ANN ; ROBUST]	A comprehensive survey on pose-invariant face recognition	2016	200	[214]
	Fully automatic face normalization and single sample face recognition in unconstrained environments	2016	94	[215]
	A novel adaptive cuckoo search algorithm for intrinsic discriminant analysis based face recognition	2016	82	[216]
LOW-RESOLUTION [LOW-RESOLUTION ; REGULARIZATION ; SUPERRESOLUTION]	SRLSP: a face image super-resolution algorithm using smooth regression with local structure prior	2017	112	[217]
	A new discriminative sparse representation method for robust face recognition via l(2) regularization	2017	106	[218]
	Discriminative block-diagonal representation learning for image recognition	2018	72	[219]
FUSION [FUSION ; SPACE ; FORENSIC-SKETCH]	Bayesian face sketch synthesis and recognition	2017	146	[220]
	Anchored neighborhood index for face sketch synthesis	2018	36	[221]
	Forensic face photo-sketch recognition using a deep learning-based architecture	2017	32	[222]
SVD [SVD ;PATTERN-RECOGNITION]	Sample diversity, representation effectiveness and robust dictionary learning for face recognition	2017	53	[223]
	Longitudinal study of automatic face recognition	2018	45	[224]
	Multi-feature kernel discriminant dictionary learning for face recognition	2017	30	[225]
PROJECTION [PROJECTION ; SUBSPACE-LEARNING]	The megaface benchmark 1 million faces for recognition at scale	2016	149	[226]
	Facial image hallucination through coupled-layer neighbor embedding	2016	64	[227]
	Facial image hallucination through coupled-layer neighbor embedding	2016	64	[227]
AGE [AGE ; APPEARANCE ;PERFORMANCE]	Large age-gap face verification by feature injection in deep networks	2017	33	[228]
	Age-related factor guided joint task modeling convolutional neural network for cross-age face recognition	2018	22	[229]
	Discriminative transfer learning with sparsity regularization for single-sample face recognition	2017	18	[230]

TABLE 14. Three most important documents of the subperiod 2019-2021.

Theme	Document title	Publication year	Times cited	Reference
SPARSE-REPRESENTATION [CLASSIFICATION; SPARSE-REPRESENTATION; COLLABORATIVE-REPRESENTATION]	Structured Optimal Graph Based Sparse Feature Extraction For Semi-supervised Learning	2020	74	[231]
	Discriminative Low-rank Preserving Projection For Dimensionality Reduction	2019	52	[232]
	Recent Advances In Open Set Recognition: A Survey	2021	45	[233]
FEATURES [FEATURES ; CNN ; EXPRESSION]	Intelligent Face Recognition And Navigation System Using Neural Learning For Smart Security In Internet Of Things	2019	79	[234]
	Wasserstein Cnn: Learning Invariant Features For Nir-vis Face Recognition	2019	75	[235]
	Low-resolution Face Recognition In The Wild Via Selective Knowledge Distillation	2019	57	[236]
ILLUMINATION [ILLUMINATION ; SVD NORMALIZATION]	Multi-view Frontal Face Image Generation: A Survey	2020	30	[237]
	Improving Shadow Suppression For Illumination Robust Face Recognition	2019	29	[238]
	Multi-resolution Dictionary Learning For Face Recognition	2019	26	[12]
LDA [LDA ; PCA ; PATTERNS]	Face Recognition Based On Genetic Algorithm	2019	31	[239]
	Secure And Efficient Outsourcing Of Pca-based Face Recognition	2020	22	[240]
	Feature Extraction For Incomplete Data Via Low-rank Tensor Decomposition With Feature Regularization	2019	21	[241]
CLUSTERING [CLUSTERING ; SEGMENTATION ; LOW-RANK ;]	R-1-2-dpca and face recognition	2019	11	[242]
	Deep Imbalanced Learning For Face Recognition And Attribute Prediction	2020	30	[243]
	Sparse Low-rank Component-based Representation For Face Recognition With Low-quality Images	2019	14	[244]
ANN [DEEP-LEARNING ; ANN ; MACHINE-LEARNING]	ArcFace: Additive Angular Margin Loss for Deep Face Recognition	2019	80	[245]
	A Survey On Deep Learning Based Face Recognition	2019	50	[246]
	Convergence Of Edge Computing And Deep Learning: A Comprehensive Survey	2020	161	[247]
HETEROGENEOUS [HETEROGENEOUS ; FORENSIC-SKETCH; DISCRIMINANT-ANALYSIS]	Robust Heterogeneous Discriminative Analysis For Face Recognition With Single Sample Per Person	2019	27	[13]
	Dual-transfer Face Sketch-photo Synthesis	2019	30	[6]
	Robust Heterogeneous Discriminative Analysis For Face Recognition With Single Sample Per Person	2019	27	[13]
LOW-RESOLUTION [LOW-RESOLUTION ; POSE ; SUPERRESOLUTION]	On Low-resolution Face Recognition In The Wild: Comparisons And New Techniques	2019	35	[248]
	Cross-resolution Face Recognition With Pose Variations Via Multilayer Locality-constrained Structural Orthogonal Procrustes Regression	2020	24	[249]
	Low Resolution Face Recognition Using A Two-branch Deep Convolutional Neural Network Architecture	2020	20	[250]
REGRESSION [REGRESSION ; SUBSPACE-LEARNING ; ROBUST]	Multi-resolution Dictionary Learning For Face Recognition	2019	26	[12]
	A Survey On Techniques To Handle Face Recognition Challenges: Occlusion, Single Sample Per Subject And Expression	2019	26	[251]
	Adversarial Cross-spectral Face Completion For Nir-vis Face Recognition	2020	22	[252]
GABOR [GABOR ; LBP ; PATTERNS]	Past, Present, And Future Of Face Recognition: A Review	2020	42	[253]
	Multi-fold Gabor, Pca, And Ica Filter Convolution Descriptor For Face Recognition	2019	17	[254]
	A Local Multiple Patterns Feature Descriptor For Face Recognition	2020	16	[255]
FUSION [FUSION ; SVM ; HYPERSPETRAL]	Face Recognition Systems: A Survey	2020	39	[256]
	Multibiometric Fusion Strategy And Its Applications: A Review	2019	26	[257]
	Multimodal Biometric Scheme For Human Authentication Technique Based On Voice And Face Recognition Fusion	2019	17	[258]
EINGENFACES [EINGENFACES ; MANIFOLD-LEARNING ; COMPONENT-ANALYSIS]	Recent Development In Face Recognition	2020	14	[259]
	Privacy Preserving Face Recognition Utilizing Differential Privacy	2020	12	[260]
	Local Polynomial Contrast Binary Patterns For Face Recognition	2019	10	[261]
TRACKING [TRACKING ; PERFORMANCE ; RECONSTRUCTION]	Face Recognition Systems Under Morphing Attacks: A Survey	2019	59	[262]
	On The Reconstruction Of Face Images From Deep Face Templates	2019	34	[263]
	A Discrete-time Projection Neural Network For Sparse Signal Reconstruction With Application To Face Recognition	2019	20	[264]
SUBSPACE [SUBSPACE ; REGULARIZATION]	Fast Kernel Sparse Representation Based Classification For Undersampling Problem In Face Recognition	2020	3	[265]
	Face Recognition Algorithm Based On Feature Descriptor And Weighted Linear Sparse Representation	2019	3	[266]
	Discriminant Maximum Margin Projections For Face Recognition	2019	2	[267]
3D [3D ; VIDEO]	Raspberry Pi Assisted Face Recognition Framework For Enhanced Law-enforcement Services In Smart Cities	2020	48	[268]
	On Low-resolution Face Recognition In The Wild: Comparisons And New Techniques	2019	35	[248]
	3d-aided Dual-agent Gans For Unconstrained Face Recognition	2019	26	[269]

HETERONEOUS, FLD and DEEP-LEARNING only appear in the last three subperiods.

The thematic evolution of FR research field is shown in Fig. 15. As previously mentioned the solid lines signify that

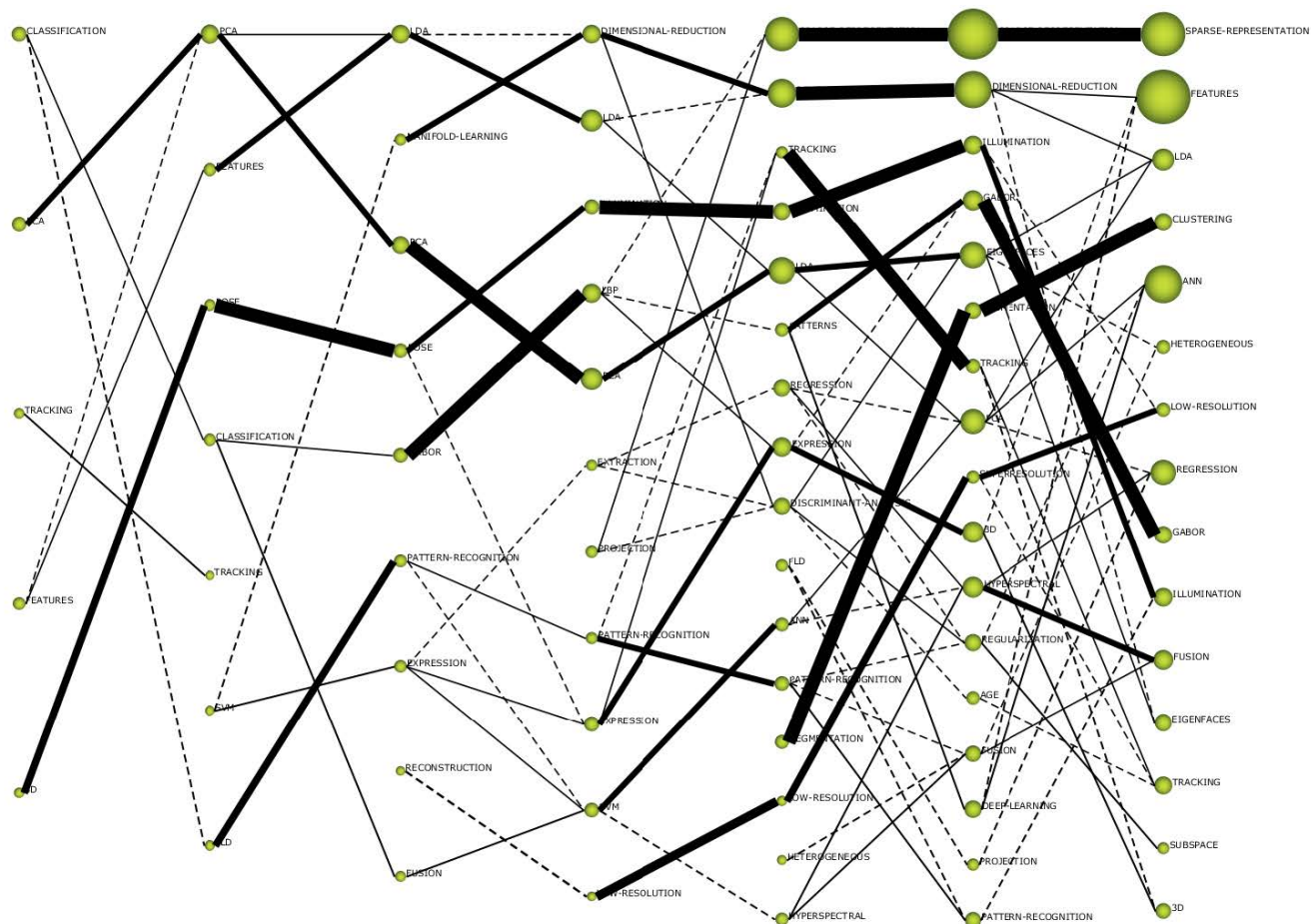


FIGURE 15. Thematic evolution of the FR research field (1991–2021).

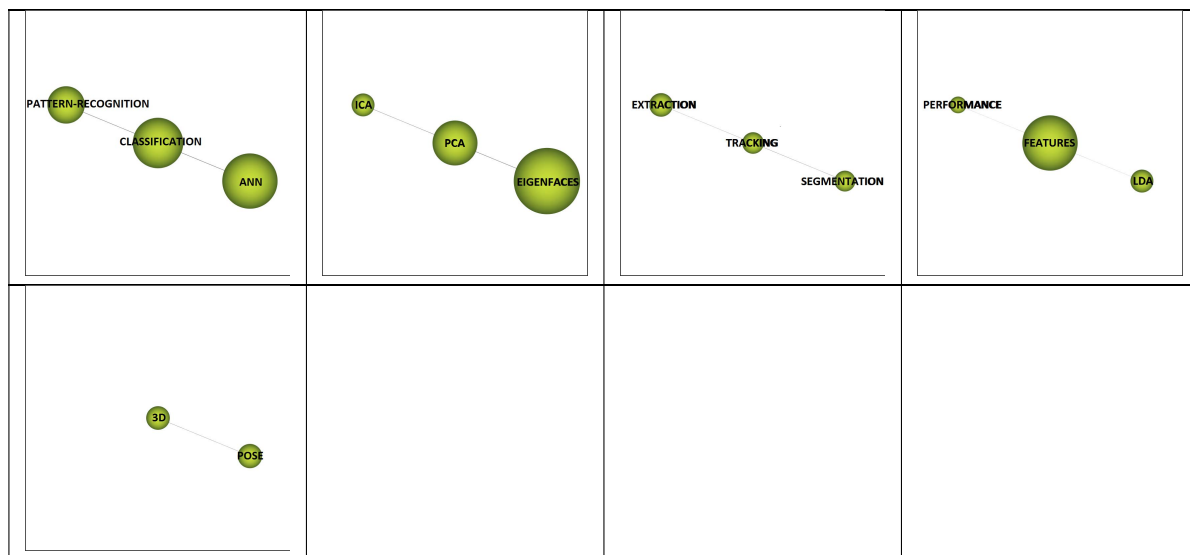


FIGURE 16. Composition themes of the subperiod(1991–2003).

the related themes share the same name. A dashed line signifies that the themes share elements other than the theme name.

The edge thickness is proportional to the inclusion index, and the spheres' volume is proportional to the number of

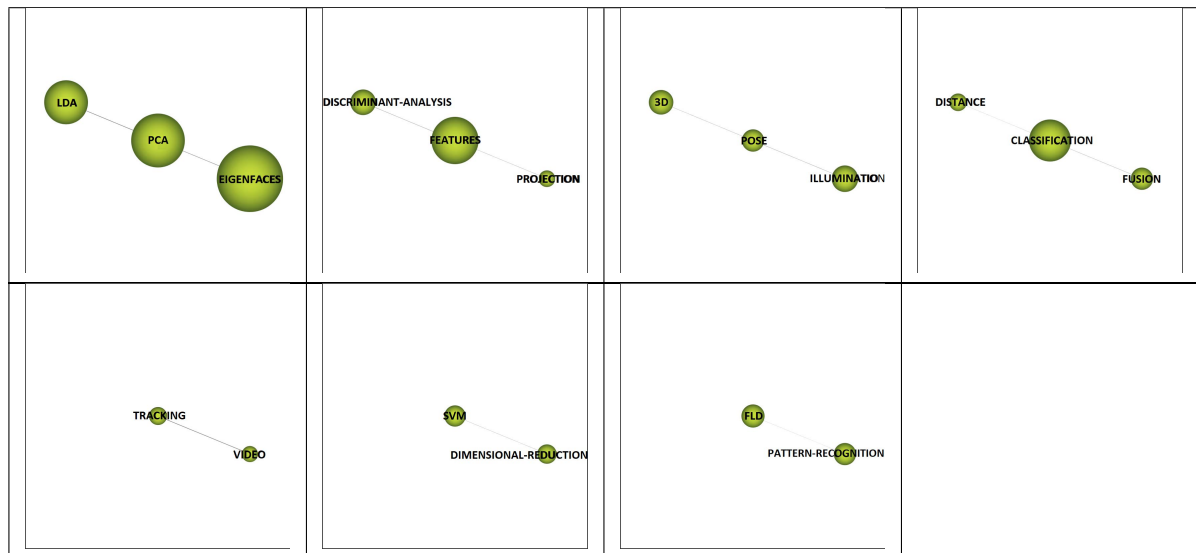


FIGURE 17. Composition themes of the subperiod(2004–2006).

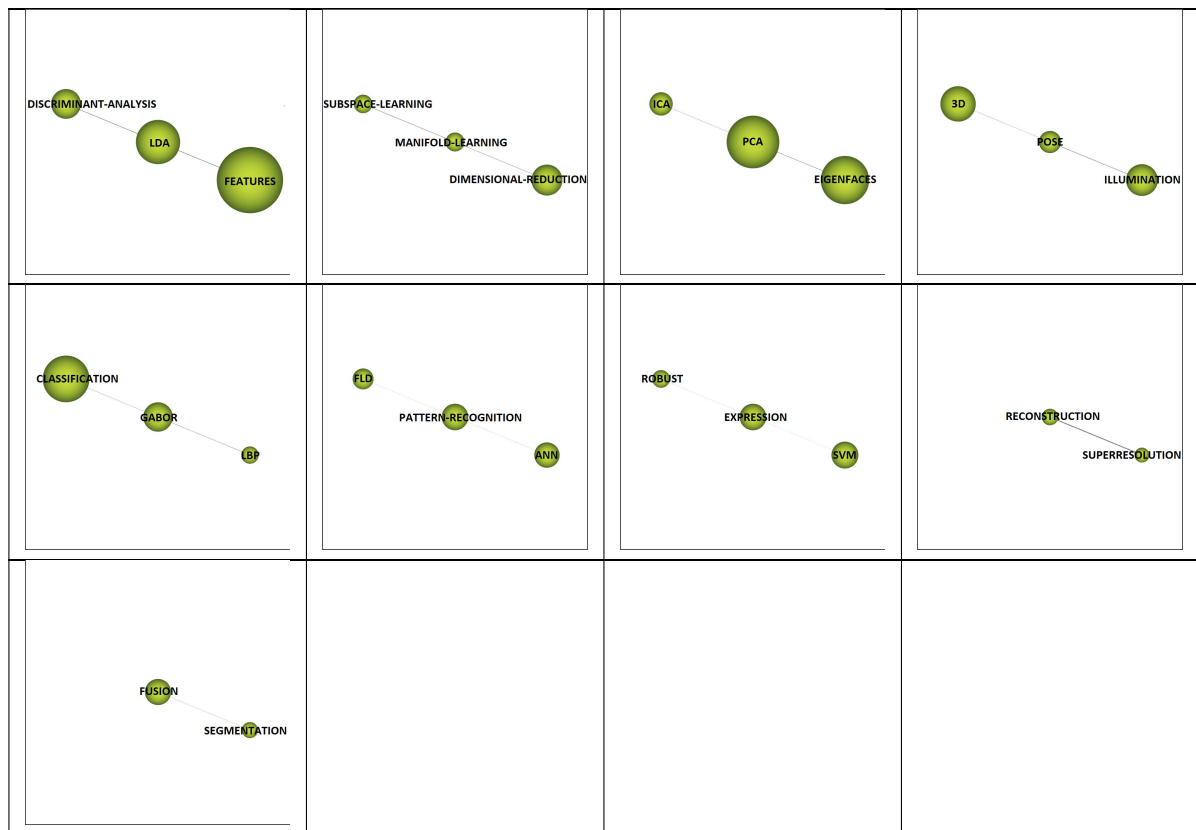


FIGURE 18. Composition themes of the subperiod(2007–2009).

published documents in each theme. The Thematic Network as shown in (Fig. 16, 17, 18, 19, 20, 21,22) presents the composition and evolution of each of the themes across the subperiods. Each theme is formed by the assembly of several keywords with a strong link between them, and labeled

with the name of the most significant keyword in the group. The volume of the sphere is proportional to the number of documents published using the keyword, the thickness of the link between two spheres is proportional to the number of documents using both keywords. As according to

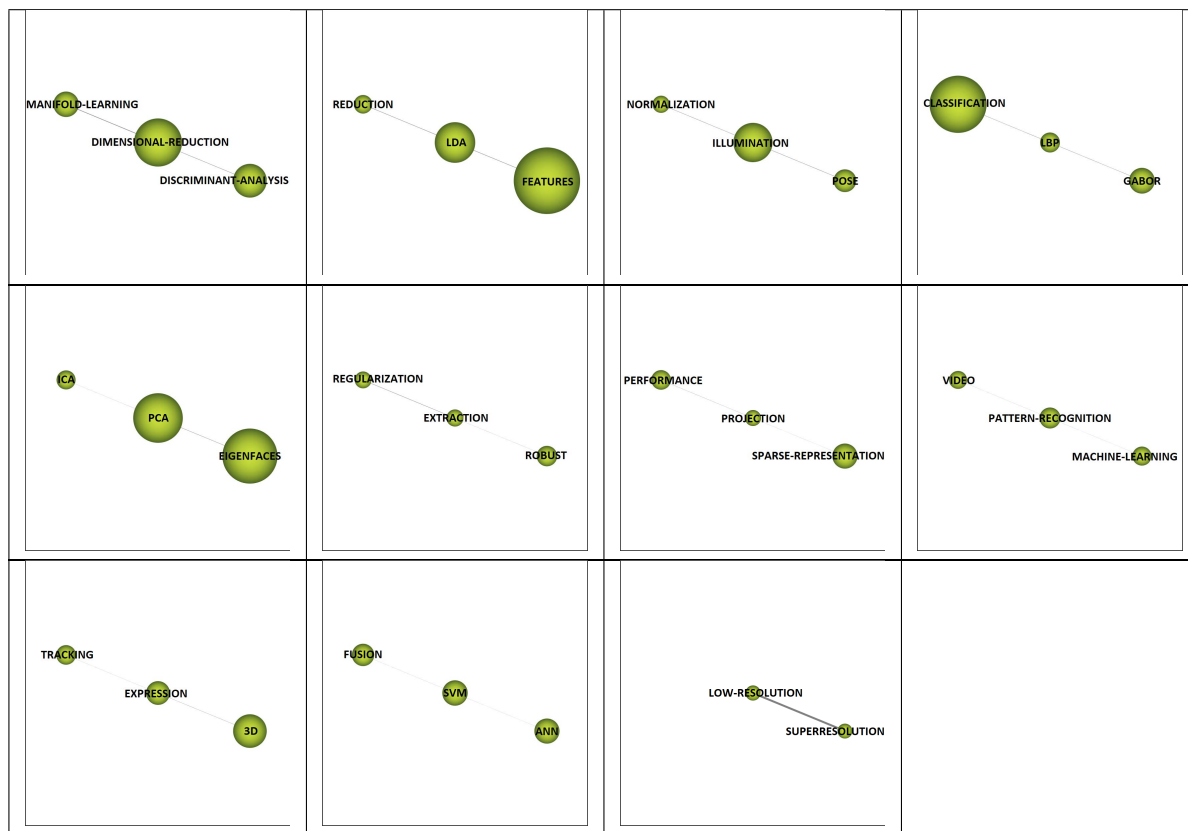


FIGURE 19. Composition themes of the subperiod(2010–2012).

Fig. 15 8, 9, 10, 11, 12,13,14 we should highlight the following points:

- In the first period, CLASSIFICATION is the most important theme. This theme is composed of CLASSIFICATION, ANN and PATERN-RECOGNITION. It reflects an interest of the scientific community by the FR essentially as a classification to identify people. The evolution of this theme throughout the periods is as following: in the period 2004-2006 it has kept the main element, but it has lost importance, which is reflected on the one hand by a decrease in the number of articles of this theme compared to the total number of articles of the whole FR research theme (from 32% to 15%), and on the other hand by the fact that it has changed from a motor theme to a basic and transversal theme. For the period 2007-2009 this theme switched its main element to GABAR and its composition became (GABOR, CLASSIFICATION, LBP) and it kept the same importance as the previous period. In the period 2010-2012, the main element has changed to LBP, keeping the same composition, but growing in importance regarding the research theme by moving to the category of motor themes. For the period 2013-2015, it changed again its main element to become SPARSE-REPRESENTATION with the composition (SPARSE-REPRESENTATION, CLASSIFICATION, COLABORATIVE-REPRESENTATION),

and it became the most important theme of the research theme (the theme with the most published articles and citations, as well as its rank as a motor theme of the research theme). For the two periods 2016-2018 and 2019-2021 it has kept the same main elements, the same composition, and the same importance despite the change of compositions. This reflects the concern of the scientific community by the main objective of this research theme.

- PCA and FEATURES are the most important and impacting themes in the first subperiod with CLASSIFICATION, they include respectively (PCA, EIGNFACES and ICA) and (FEATURES, LDA and PERFORMANCE). They represent the two main categories of the FR approaches “Features Based” and “Holistic based”, which reflects the focus of the scientific community on the development of these first basic technologies to overcome the general problem of facial recognition. During this period, researchers did not yet seek to manage the most complex facial recognition situations. Hence a reduced number of 5 themes. These two themes have maintained their positions and importance for the next 3 subperiods (2004-2006, 2007-2009 and 2010-2012), their composition has not changed much except for the FEATURES theme which has changed its main element from the 2010-2012 subperiod to become ICA. The composition of the PCA

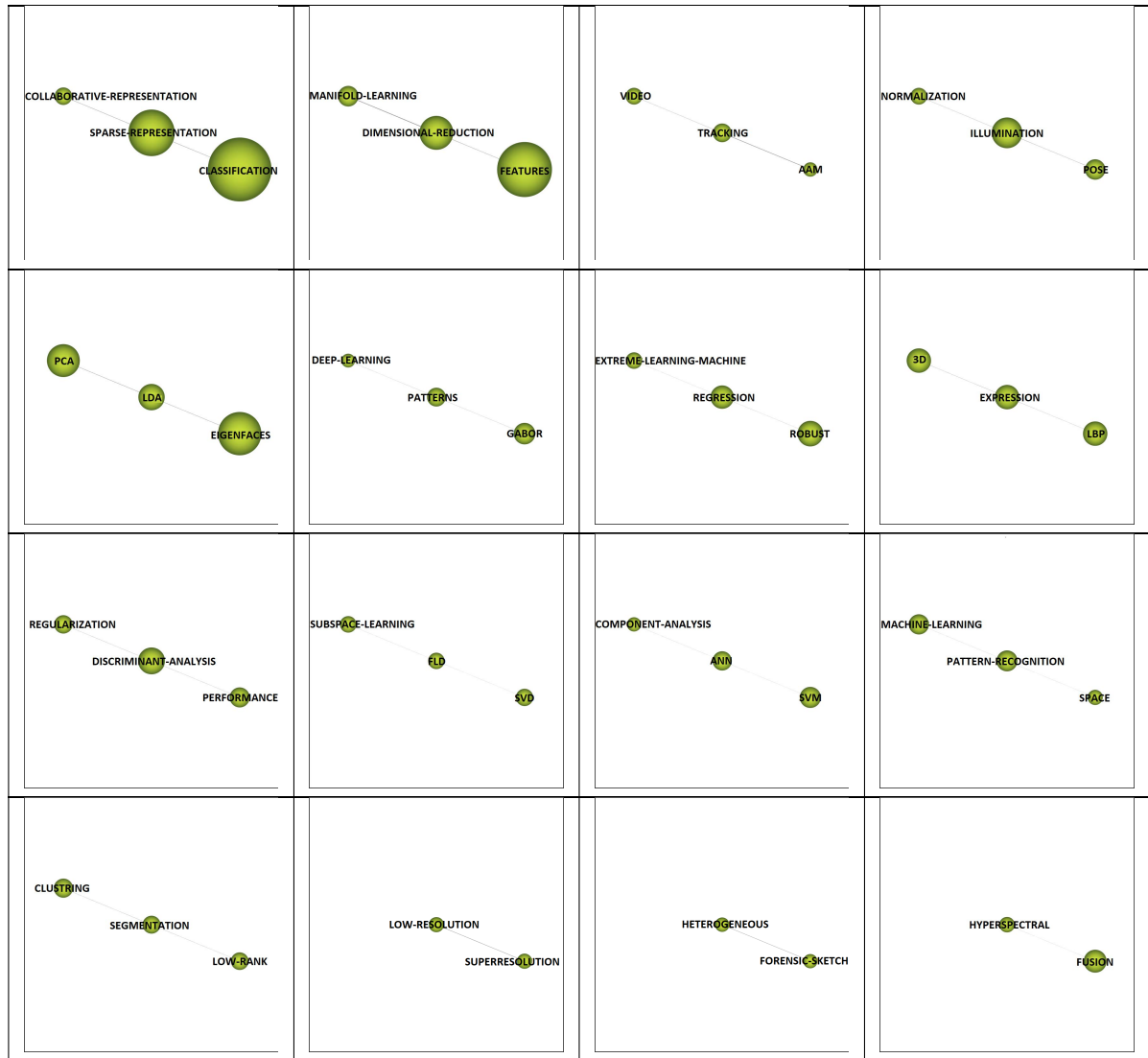


FIGURE 20. Composition themes of the subperiod(2013–2015).

theme over these sub-periods is respectively, (PCA, EIGENFACES and LDA), (PCA, EIGENFACES and ICA) and (PCA, EIGENFACES and ICA). Also the composition of the FEATURES theme on these sub-periods is respectively, (FEATURES, DISCRIMINANT-ANALYSIS and PROJECTION), (LDA, FEATURES and DISCRIMINANT-ANALYSIS) and (LDA, FEATURES and REDUCTION). From the 5th sub-period the theme PCA has been represented firstly by ENGENFACES and secondly by LDA, and it can be seen that the importance of this theme has deteriorated with time to reach a contribution of published articles that does not exceed 6% and a citation name that does not exceed 5% in the last sub-period. The FEATURES theme, has changed its main element from the 3rd sub-period (3rd sub-period: LDA; 4th, 5th and 6th sub-periods: DIMENSIONAL-REDUCTION;

7th sub-period: FEATURES), but it has kept its importance and its progression to have a contribution of 21% of published articles and 22% of the number of citations. This indicates an adoption of the “Features Based” approach by the scientific community.

- From the 4th subperiod (2010-2012) there is a wide interaction between themes to form the new themes for the following subperiod, with the exception of some themes that remain stable during all the following sub-periods such as LOW-RESOLUTION and ILLUMINATION. From this period the scientific community has mixed the different techniques of FR, namely the appearance of “Hybrid Approaches”.
- ILLUMINATION is one of the most important themes of FR topic. In the second subperiod (2004-2006) ILLUMINATION was as a specific-theme, then it transforms into a motor-theme of the FR topic until

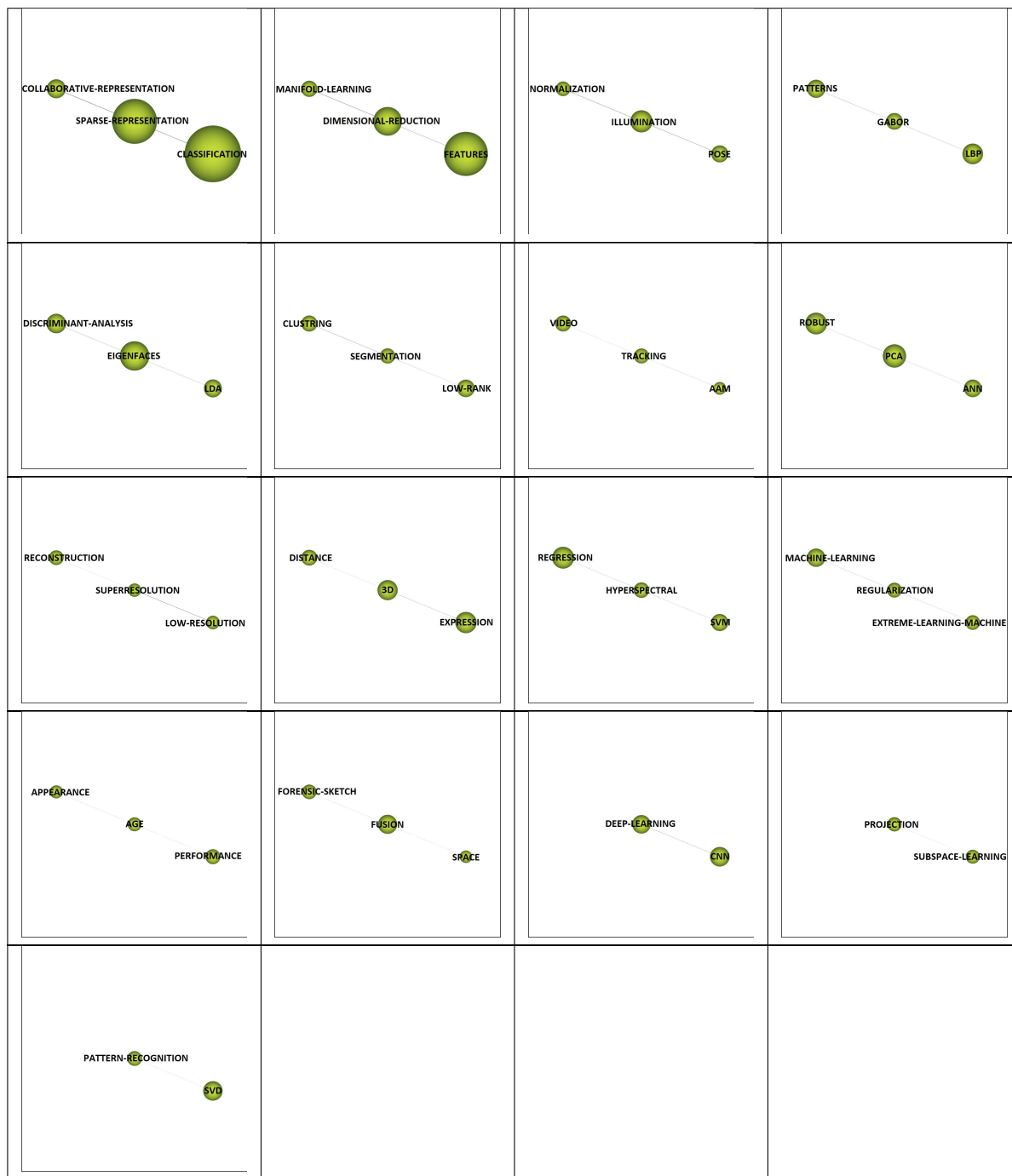


FIGURE 21. Composition themes of the subperiod(2016–2018).

the last subperiod. It can be seen that the number of documents published has not ceased to increase. This theme consists mainly of ILLUMINATION and POSE (except the last subperiod), including a third keyword that changes between subperiods (2004-2006: 3D; 2007-2009: 3D; 2010-2012: NORMALIZATION; 2013-2015: NORMALIZATION; 2016-2018: NORMALIZATION;). It can be noted that

the challenges ILLUMINATION and POSE are in general addressed at the same time. ILLUMINATION attracts greater attention from the scientific community than POSE, except the 3 first sub-period when POSE has the main element of the theme. The number of shared documents and the h-index of this theme has constantly increased, so the challenge is always a current one. In the last sub-period, the theme has

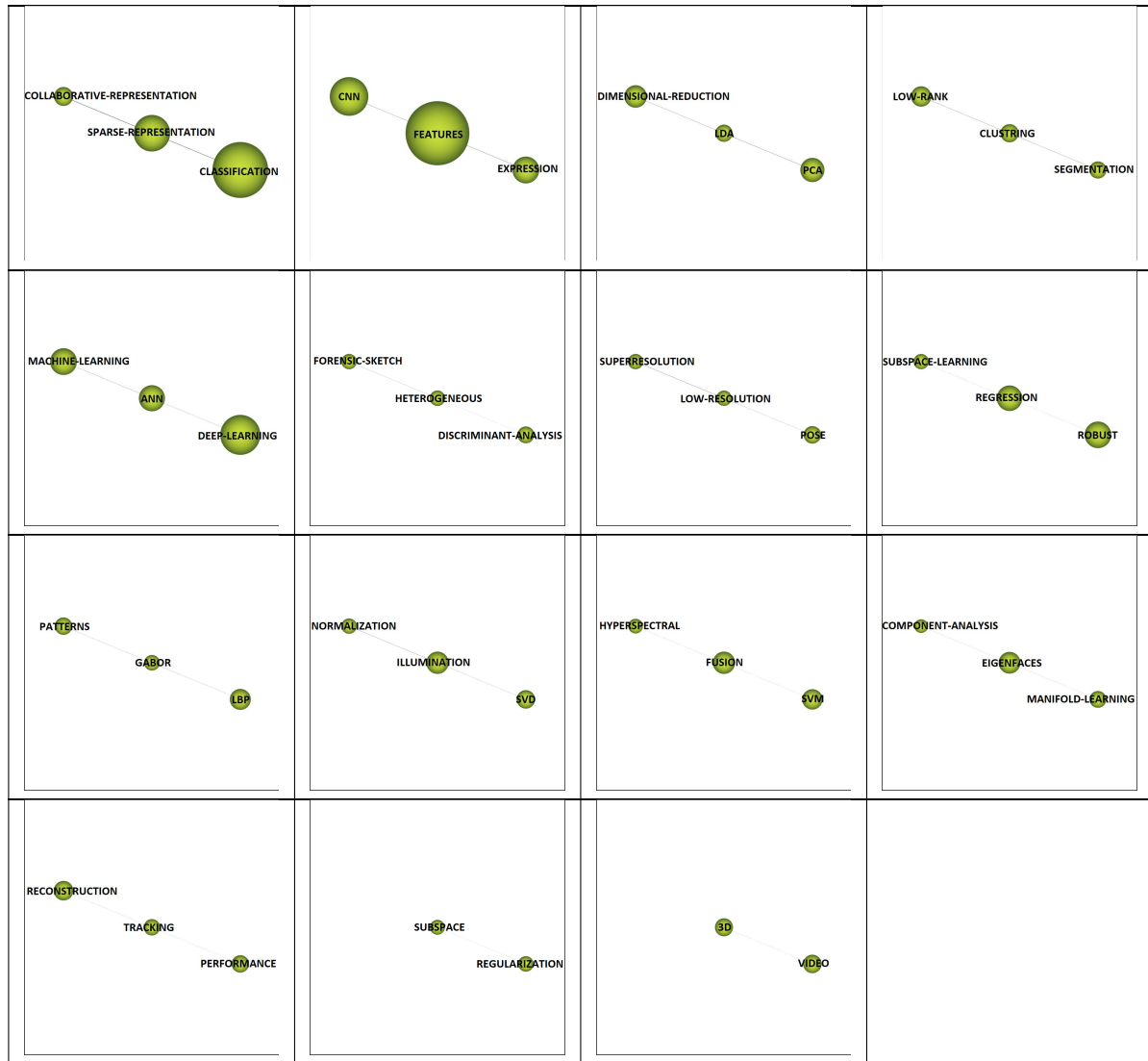


FIGURE 22. Composition themes of the subperiod(2019–2021).

known the first disassociation between ILLUMINATION and POSE, to have two themes ILLUMINATION formed by (ILLUMINATION; NORMALIZATION; SVD) and LOW-RESOLUTION formed by (LOW-RESOLUTION; POSE; SUPERRESOLUTION).

- The TRACKING theme was considered as a specific theme in the first two sub-periods. This theme has deteriorated in terms of the number of articles published, thus it disappeared as an FR theme in the two sub-periods 2007-2009 and 2010-2012. This theme appeared again in the sub-period 2013-2015 as a specific theme, and then it became as a disappearing-theme in the last two sub-periods. the h-index of this theme has slightly decreased in the last 3 sub-periods
- The EXPRESSION theme appeared in the subperiod “2007-2009”. The impact and interest in this theme changed over time, in the subperiod “2007-2009” it

was a basic and transversal theme, then it became an emerging theme, after that it became a motor-theme in “2013-2015”, it maintained its importance during the last two sub-periods by associating at the beginning with the 3D theme and after that with FEATURES.

- The themes LOW-RESOLUTION appeared during the subperiod “2010-2012” in the specific theme category, and composed of (LOW-RESOLUTION and SUPERRESOLUTION). They remained in the same category for the following subperiods with a slight increase of published documents. However, the H-index did not show any progress.
- The HYPERSPECTRAL theme appeared in the subperiod “2013-2015” after the democratization of hyperspectral cameras for large public in this period, but this use did not involve a large part of the scientific community. This theme was composed of (HYPERSPECTRAL

and FUSION), this theme was divided into two themes HYPERSPECTRAL and FUSION for the next sub-period to join again in the same theme for the last sub-period.

- The theme HETEROGENEOUS appeared in the sub-period “2013-2015”, it is composed of HETEROGENEOUS and FORENSIC-SKETCH, which shows a strong interest in using forensic sketch to identify persons in real image databases, compared to other heterogeneous modes of use such as the infrared or multispectral image fields. This theme appeared in the category of specific topics, with a very low number of published papers and citations. The interest of the scientific community for this theme is not consistent in time, the theme has disappeared from the active themes of the RF during the subperiod 2016-2018 to re-appear again in the subperiod 2019-2021 with the same status of subperiod 2013-2015.
- The DEEP-LEARNING theme formed by the keywords (DEEP-LEARNING, ANN and CNN) appeared in the subperiod “2014-2016”. The scientific community started to use and apply this technique in the field of FR, with the emergence of new framework in this subperiod to ease the development and deployment of this technology, like Caffe in 2013 [270], and Tensorflow [271] and Keras in 2015 [272]. This theme has seen a huge growth in terms of the number of documents published in the following subperiod, it is considered as a specific theme but it has a high potential in the following years.

V. CONCLUSION

In this paper, the topic of Face Recognition (FR) was analyzed using bibliometric tools, including science mapping analysis, Co-word analysis, and performance analysis techniques. In a first step we have retrieved all the documents published in the FR theme through Web of Science database. Then we used the Scimat tool to detect, quantify, and visualize the evolution of a Research Field. Finally, we analyzed and interpreted the results. A growth of interest in the FR field, reflecting a gradual increase in the number of studies published in international journals since 2010, particularly an increasing of 59% over the period 2014-2016 and of 31% over the last period 2017-2019. Therefore, it can be concluded that the theme is still relevant and attracts increasingly the attention of the scientific community. The researchers have used the local and global approaches equitably for the first periods of study, then the local approaches received more attention, and finally the mixed methods became the trend. The deep learning methods are applied on FR field from the 2014-2016 period, and they have an enormous potential, it represents the biggest evolution in terms of documents shared among all the FR theme over all the periods of our study, representing an increase of 938% between the last two periods (2014-2016 and 2017-2019). On the other hand, the Illumination challenge has preserved the same interest throughout the periods of study, and still has a great impact on the theme. It can be

considered that it represents the most interesting challenge to solve, in addition to the challenges Pose and Heterogeneous sources. At last we can also highlight a very big increase of china's activity in this field since 2008, which is responsible for more than 50% of all published articles since 2014.

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YAHYA ZENNAYI received the Engineering degree in electronics and telecommunications systems from the Faculty of Science and Technology (FST), Sidi Mohamed Ben Abdellah University, Fes, Morocco, in 2013. He is currently pursuing the Ph.D. degree with the Smart Communications Research Team—ERSC (as part of the research center in engineering sustainable and smart systems), Department of Electrical Engineering, IMI School of Engineering, Mohamed V University, Rabat, Morocco. In 2013, he joined the Morocco Foundation for Advanced Science, Innovation and Research (MAScIR). He is the Team Leader of the Image Processing Unit, MAScIR. His research interests include real-time image processing, artificial intelligence, and face recognition systems.



FRANÇOIS BOURZEIX received the D.E.A. degree in applied mathematics from University PARIS IX Dauphine, in 1995, and the Engineering degree in electronics and signal processing from the National School of Telecommunications of Paris, in 1996. He was an Engineer with the Polytechnic School of Paris, in 1994. He has worked in several high tech companies, including Motorola Semiconductor as a Software Development Engineer and a Hardware and Architectural Engineer of wireless products (2.5G, 3G, and Wi-Fi), ST Microelectronics as the Technical Leader in firmware development for HDMI, and Amesys Morocco applications as the Technical Director. In 2009, he joined the Moroccan Foundation for Advanced Science, Innovation and Research (MAScIR), where he is currently the Director of the Embedded Systems Department.



ZOUHAIR GUENNOUN (Senior Member, IEEE) was born in Fes, Morocco, in 1964. He received the Engineering degree in electronics and telecommunications from the Electronics and Electrical Montefiore Institute, ULG Liege, Belgium, in 1987, and the M.Sc. degree in communication systems and the Ph.D. degree from the EMI School of Engineering, Rabat, Morocco, in 1993 and 1996, respectively. He visited the Centre for Communication Research (CCR), University of Bristol, U.K., from 1990 to 1994, to prepare a split Ph.D. From 1988 to 1996, he worked as an Assistant Lecturer with the EMI School of Engineering, where he has been working as a Professor Lecturer, since 1996. Currently, he is in charge of the research team of Smart Communications—ERSC (formerly known as LEC) as part of the research center in engineering sustainable and smart systems at the EMI School of Engineering, University Mohammed V. His research interests include digital signal processing, error control coding, speech and image processing, telecommunication systems, networks architecture, and networks security. He is an Ex-Member of the Moroccan IEEE Section Executive Committee.

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