Examining the Literature from 1990 to 2020 on Off-line Handwritten Document Analysis

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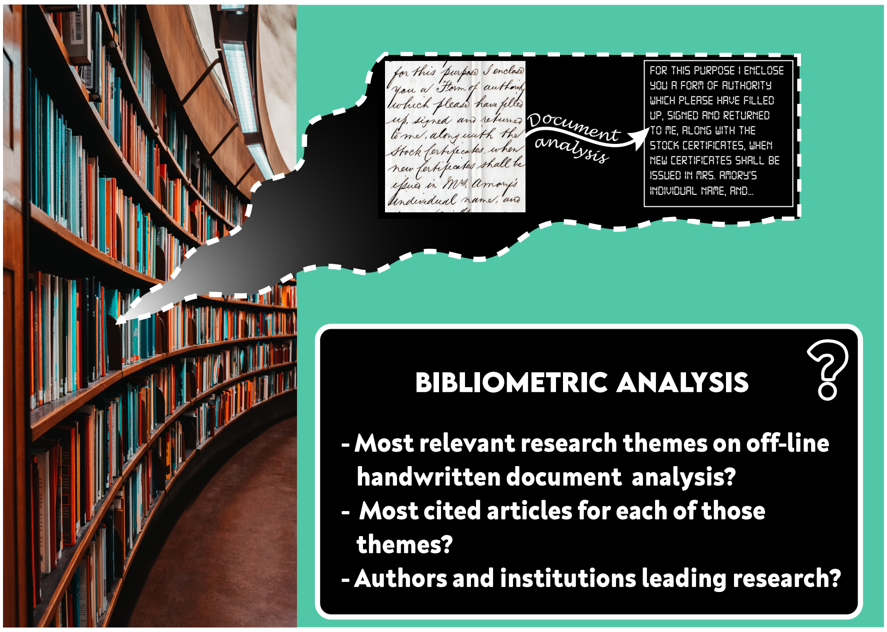
Appendix: Most Influential Papers



Abstract

This document is an appendix to the paper "Examining the Literature from 1990 to 2020 on Off-line Handwritten Document Analysis", whose abstract is the following one:

Computers with the ability to process handwriting is both important and challenging since many difficulties (e.g., different writing styles, alphabets, languages, etc.) need to be overcome for addressing a variety of problems (text recognition, signature verification, writer identification, word spotting, etc.). This paper reviews the growing literature on off-line handwritten document analysis over the last thirty years. A sample of 5,389 articles is examined using bibliometric techniques. This paper identifies (i) the most influential articles in the area, (ii) the most productive authors and their collaboration networks, (iii) the countries and institutions that have led research on the topic, (iv) the journals that have published most papers, and (v) the most relevant research topics and their evolution over the years.

This appendix summarizes the most influential papers identified in our bibliometric analysis.

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Most Influential Papers of the Whole Area

This chapter identifies the most relevant papers on the *Off-line Handwritten Document Analysis* research area considered as a whole. To do so, we use the concepts of citation classics. Garfield [71] coined the term *citation classics* to refer to the most impacting papers of a research area according to their number of citations. Later, Martinez et al. [157] provided the following formal definition, which will be used in this paper: "the citation classics, also called the *h-core*, of a research area whose h-index is h are the top h cited papers".

Table 1.1 summarizes the identified citation classics, whose h-index is 93. Table 1.2 includes the 5 most cited papers from 2018, 2019 and 2020.

Table 1.1: Citation classics (the h-index is 93).

Paper	**Year**	**Publisher**	**#Cit**
Plamondon and Srihari [176]. On-line and off-line handwriting recognition: A comprehensive survey	2000	IEEE T Pattern Anal	1,749
Xu et al. [244]. Methods of combining multiple classifiers and their applications to handwriting recognition	1992	IEEE T syst Man Cyb	1,655

Paper	**Year**	**Publisher**	**#Cit**
Hull [99]. A database for handwritten text recognition research	1994	IEEE T Pattern Anal	1,029
Graves et al. [75]. A novel connectionist system for unconstrained handwriting recognition	2009	IEEE T Pattern Anal	982
Marti and Bunke [156]. The IAM-database: An English sentence database for offline handwriting recognition	2003	Int J Doc Anal Recog	588
Graves and Schmidhuber [76]. Offline handwriting recognition with multidimensional recurrent neural networks	2009	NeurIPS	522
Huang and Suen [98]. A method of combining multiple experts for the recognition of unconstrained handwritten numerals	1995	IEEE T Pattern Anal	418
Liu et al. [137]. Handwritten digit recognition: Benchmarking of state-of-the-art techniques	2003	Pattern Recogn	401
Lorigo and Govindaraju [147]. Offline Arabic handwriting recognition: A survey	2006	IEEE T Pattern Anal	342
Marti and Bunke [155]. Using a statistical language model to improve the performance of an HMM-based cursive handwriting recognition system	2001	Int J Pattern Recogn	314
Suen et al. [217]. Computer recognition of unconstrained handwritten numerals	1992	P IEEE	300
Arica and Yarman-Vural [15]. An overview of character recognition focused on off-line handwriting	2001	IEEE T Syst Man Cy C	291
Said et al. [192]. Personal identification based on handwriting	2000	Pattern Recogn	246
Pham et al. [175]. Dropout Improves Recurrent Neural Networks for Handwriting Recognition	2014	ICFHR	239
Liu et al. [138]. Handwritten digit recognition: Investigation of normalization and feature extraction techniques	2004	Pattern Recogn	226
Bhattacharya and Chaudhuri [20]. Handwritten numeral databases of Indian scripts and multistage recognition of mixed numerals	2009	IEEE T Pattern Anal	210
Kimura et al. [111]. Handwritten numerical recognition based on multiple algorithms	1991	Pattern Recogn	203
Vinciarelli et al. [232]. Offline recognition of unconstrained handwritten texts using HMMs and statistical language models	2004	IEEE T Pattern Anal	201

Paper	Year	Publisher	#Cit
Lauer et al. [124]. A trainable feature extractor for handwritten digit recognition	2007	Pattern Recogn	194
Kirn and Govindaraju [113]. A lexicon driven approach to handwritten word recognition for real-time applications	1997	IEEE T Pattern Anal	189
Fischer et al. [63]. Lexicon-free handwritten word spotting using character HMMs	2012	Pattern Recogn Lett	186
Madhvanath and Govindaraju [151]. The role of holistic paradigms in handwritten word recognition	2001	IEEE T Pattern Anal	177
Kato [106]. A handwritten character recognition system using directional element feature and asymmetric mahalanobis distance	1999	IEEE T Pattern Anal	177
Manmatha et al. [153]. Word spotting: a new approach to indexing handwriting	1996	CVPR	176
El-Yacoubi et al. [58]. An HMM-based approach for off-line unconstrained handwritten word modeling and recognition	1999	IEEE T Pattern Anal	173
Chen et al. [33]. OffLine handwritten word recognition using a hidden Markov model type stochastic network	1994	IEEE T Pattern Anal	173
Senior and Robinson [198]. An off-line cursive handwriting recognition system	1998	IEEE T Pattern Anal	172
Liu et al. [142]. Online and offline handwritten Chinese character recognition: Benchmarking on new databases	2013	Pattern Recogn	169
España-Boquera et al. [60]. Improving offline handwritten text recognition with hybrid HMM/ANN models	2011	IEEE T Pattern Anal	168
Oliveira et al. [166]. Automatic recognition of handwritten numerical strings: A Recognition and Verification strategy	2002	IEEE T Pattern Anal	165
Zhong et al. [258]. High performance offline handwritten Chinese character recognition using GoogLeNet and directional feature maps	2015	ICDAR	158
Lavrenko et al. [125]. Holistic Word Recognition for Handwritten Historical Documents	2004	DIAL	155
Marti and Bunke [154]. A full English sentence database for off-line handwriting recognition	1999	ICDAR	154

Paper	Year	Publisher	#Cit
Zheng and Doermann [257]. Machine printed text and handwriting identification in noisy document images	2004	IEEE T Pattern Anal	142
Plötz and Fink [177]. Markov models for offline handwriting recognition: A survey	2009	Int J Doc Anal Recog	141
Adankon and Cheriet [4]. Model selection for the LS-SVM. Application to handwriting recognition	2009	Pattern Recogn	140
Fukushima and Wake [66]. Handwritten Alphanumeric Character Recognition by the Neocognitron	1991	IEEE T Neural Netwo	140
Louloudis et al. [148]. Text line and word segmentation of handwritten documents	2009	Pattern Recogn	138
Rodríghez-Serrano and Perronnin [188].Handwritten word-spotting using hidden Markov models and universal vocabularies	2009	Pattern Recogn	136
C.L Liu et al. [134]. Lexicon-driven segmentation and recognition of handwritten character strings for Japanese address reading	2002	IEEE T Pattern Anal	134
Ha and Bunke [81]. Off-line, handwritten numeral recognition by perturbation method	1997	IEEE T Pattern Anal	133
Zhang et al. [254]. Online and offline handwritten Chinese character recognition: A comprehensive study and new benchmark	2017	Pattern Recogn	132
Li et al. [130]. Script-independent text line segmentation in freestyle handwritten documents	2008	IEEE T Pattern Anal	132
Jain and Zongker [101]. Representation and recognition of handwritten digits using deformable templates	1997	IEEE T Pattern Ana	132
Shi et al. [203]. Handwritten numeral recognition using gradient and curvature of gray scale image	2002	Pattern Recogn	130
Chacko et al. [29]. Handwritten character recognition using wavelet energy and extreme learning machine	2012	Int J Mach Learn Cyb	126
Kimura et al. [112]. Improvement of handwritten Japanese character recognition using weighted direction code histogram	1997	Pattern Recogn	126
Hildebrant and Liu [94]. Optical recognition of handwritten Chinese characters: Advances since 1980	1993	Pattern Recogn	126
Lu and Shridhar [150]. Character segmentation in handwritten words - An overview	1996	Pattern Recogn	124
Wunsch and Laine [242]. Wavelet descriptors for multiresolution recognition of handprinted characters	1995	Pattern Recogn	123

Paper	**Year**	**Publisher**	**#Cit**
El-Hajj et al. [56]. Arabic handwriting recognition using baseline dependant features and hidden Markov modeling	2005	ICDAR	122
Lee [128]. Off-line recognition of totally unconstrained handwritten numerals using multilayer cluster neural network	1996	IEEE T Pattern Anal	122
Yamada et al. [245]. A nonlinear normalization method for handprinted kanji character recognition-line density equalization	1990	Pattern Recogn	121
Koerich et al. [115]. Large vocabulary off-line handwriting recognition: A survey	2003	Pattern Anal Appl	119
Pal et al. [170]. Handwritten numeral recognition of six popular Indian scripts	2007	ICDAR	118
Bunke et al. [27]. Recognition of cursive roman handwriting - past, present and future	2003	ICDAR	118
Chen and Wang [34]. Segmentation of single- or multiple-touching handwritten numeral string using background and foreground analysis	2000	IEEE T Pattern Anal	118
Guerbai et al. [77]. The effective use of the one-class SVM classifier for handwritten signature verification based on writer-independent parameters	2015	Pattern Recogn	117
Mohamed and Gader [162]. Handwritten word recognition using segmentation-free hidden Markov modeling and segmentation-based dynamic programming techniques	1996	IEEE T Pattern Anal	117
Liu et al. [143]. ICDAR 2011 Chinese handwriting recognition competition	2011	ICDAR	113
Al-HajjMohamad et al. [7]. Combining slanted-frame classifiers for improved HMM-based Arabic handwriting recognition	2009	IEEE T Pattern Anal	113
Liu and Nakagawa [136]. Evaluation of prototype learning algorithms for nearest-neighbor classifier in application to handwritten character recognition	2001	Pattern Recogn	112
Arica and Yarman-Vural [16]. Optical character recognition for cursive handwriting	2002	IEEE T Pattern Anal	111
Knerr et al. [114]. Handwritten Digit Recognition by Neural Networks with Single-Layer Training	1992	IEEE T Neural Networ	111
Pal and Datta [169]. Segmentation of Bangla unconstrained handwritten text	2003	ICDAR	109

Paper	Year	Publisher	#Cit
Cao et al. [28]. Recognition of handwritten numerals with multiple feature and multistage classifier	1995	Pattern Recogn	108
Papavassiliou et al. [171]. Handwritten document image segmentation into text lines and words	2010	Pattern Recogn	106
Sudholt and Fink [214]. PHOCNet: A deep convolutional neural network for word spotting in handwritten documents	2016	ICFHR	106
Yin and Liu [248]. Handwritten Chinese text line segmentation by clustering with distance metric learning	2009	Pattern Recogn	106
Liu [132]. Normalization-cooperated gradient feature extraction for handwritten character recognition	2007	IEEE T Pattern Anal	105
Revow et al. [187]. Using generative models for handwritten digit recognition	1996	IEEE T Pattern Anal	105
Pechwitz and Maergner [174]. HMM based approach for handwritten Arabic word recognition using the IFN/ENIT-database	2003	ICDAR	104
Heutte et al. [93]. HMM based approach for handwritten Arabic word recognition using the IFN/ENIT - database	1998	ICDAR	104
Salah et al. [193]. A selective attention-based method for visual pattern recognition with application to handwritten digit recognition and face recognition	2002	IEEE T Pattern Anal	102
Wang et al. [236]. Handwritten Chinese text recognition by integrating multiple contexts	2012	IEEE T Pattern Anal	101
Stamatopoulos et al. [211]. ICDAR 2013 handwriting segmentation contest	2013	ICDAR	100
Yin et al.. [249]. ICDAR 2013 Chinese handwriting recognition competition	2013	ICDAR	100
Su et al. [213]. Off-line recognition of realistic Chinese handwriting using segmentation-free strategy	2009	Pattern Recogn	100
He et al. [91]. Writer identification of Chinese handwriting documents using hidden Markov tree model	2008	Pattern Recogn	100
Su et al. [212]. Corpus-based HIT-MW database for offline recognition of general-purpose Chinese handwritten text	2007	Int J Doc Anal Recog	100

Paper	Year	Publisher	#Cit
Seni and Cohen [197]. External word segmentation of off-line handwritten text lines	1994	Pattern Recogn	99
Si Wei Lu et al. [149]. Hierarchical attributed graph representation and recognition of handwritten chinese characters	1991	Pattern Recogn	99
Hafemann et al. [82]. Learning features for offline handwritten signature verification using deep convolutional neural networks	2017	Pattern Recogn	98
Toselli et al. [225]. Integrated handwriting recognition and interpretation using finite-state models	2003	Int J Pattern Recogn	98
Oliveira et al. [167]. A methodology for feature selection using multiobjective genetic algorithms for handwritten digit string recognition	2003	Int J Pattern Recogn	98
Dehghan et al. [48]. Handwritten Farsi(Arabic) word recognition: A holistic approach using discrete HMM	2001	Pattern Recogn	98
Gader et al. [69]. Handwritten word recognition with character and inter-character neural networks	1997	IEEE T syst Man Cyb B	98
Van Breukelen et al. [230]. Handwritten digit recognition by combined classifier	1998	Kybernetika	96
Favata and Srikantan [61]. A multiple feature/resolution approach to handprinted digit and character recognition	1996	Int J Imag syst Tech	96
Chi et al. [39]. Handwritten numeral recognition using self-organizing maps and fuzzy rules	1995	Pattern Recogn	95
H. Liu and Ding. [144]. Handwritten numeral recognition using self-organizing maps and fuzzy rules	2005	Pattern Recogn	94
Sako et al. [139]. Discriminative learning quadratic discriminant function for handwriting recognition	2004	IEEE T Neural Networ	93
Al-Ohali et al. [8]. Databases for recognition of handwritten Arabic cheques	2003	Pattern Recogn	93

Table 1.2: Hot papers: top 5 cited articles in 2020, 2019 and 2018.

Paper	Year	Publisher	#Cit
Ghosh et al. [73]. Graphology based handwritten character analysis for human behaviour identification	2020	CAAI T Intell Technol	35
Ahlawat et al. [5]. Improved handwritten digit recognition using convolutional neural networks (CNN)	2020	Sensors	19

Paper	Year	Publisher	#Cit
Zhao and Liu [255]. Multiple classifiers fusion and CNN feature extraction for handwritten digits recognition	2020	Granul Comput	18
Jiang and Zhang [102]. Edge-SiamNet and Edge-TripleNet: New deep learning models for handwritten numeral recognition	2020	IEICE T Inf Syst	18
Malakar et al. [152]. A GA based hierarchical feature selection approach for handwritten word recognition	2020	Neural Comput Appl	16
Diaz-Cabrera et al. [49]. A perspective analysis of handwritten signature technology	2019	ACM Comput Surv	64
Cilia et al. [41]. A ranking-based feature selection approach for handwritten character recognition	2019	Pattern Recogn Lett	44
De Stefano et al. [47] Handwriting analysis to support neurodegenerative diseases diagnosis: A review	2019	Pattern Recogn Lett	31
Baldominos et al. [19]. A survey of handwritten character recognition with MNIST and EMNIST	2019	Appl Sci	27
He and Schomaker [89]. Deep adaptive learning for writer identification based on single handwritten word images	2019	Patter Recogn	24
Hafemann et al. [83]. Offline handwritten signature verification - Literature review	2018	IPTA	65
Baldominos et al. [18]. Evolutionary convolutional neural networks: An application to handwriting recognition	2018	Neurocomputing	57
Pramanik and Bag [181]. Shape decomposition-based handwritten compound character recognition for Bangla OCR	2018	J Vis Commun Image R	53
Kulkarni and Rajendran [119]. Spiking neural networks for handwritten digit recognition—Supervised learning and network optimization	2018	Neural Networks	49
Sueiras et al. [215]. Offline continuous handwriting recognition using sequence to sequence neural networks	2018	Neurocomputing	46

2

Most Influential Papers per Period and Thematic Network

To analyze the temporal evolution of the area, our bibliometric analysis divides the document sample into six periods of five years. In each period, the most relevant research themes are identified.

2.1 Period 1: 1990-1994

Table 2.1 summarizes the top ten cited papers for the most relevant research themes from 1990 to 1994. The last column follows the notation $[\text{reference}]_{\#\text{citations}}$, e.g., $[217]_{300}$ means that [217] has been cited 300 times since its publication.

Table 2.1: Thematic networks' performance (Period 1: 1990-1994).

Thematic network	Network's keywords	#Papers	h-index	Top 10 papers
Character Recognition	Character Recognition, Statistical Model, Graph, Decision Tree, MLP, NN, Numeral Recognition, Preprocessing, Arabic Text Recognition, Template Matching, Japanese Text Recognition, Ensemble Classification	43	22	[217]$_{300}$ [111]$_{203}$ [33]$_{173}$ [94]$_{126}$ [245]$_{121}$ [149]$_{99}$ [210]$_{80}$ [127]$_{78}$ [3]$_{71}$ [67]$_{51}$
Text Recognition	Text Recognition, Segmentation, Feature Extraction	14	11	[99]$_{1029}$ [197]$_{99}$ [210]$_{80}$ [216]$_{72}$ [234]$_{49}$ [57]$_{42}$ [200]$_{38}$ [239]$_{34}$ [172]$_{19}$ [14]$_{18}$

2.2 Period 2: 1995-1999

Table 2.2 summarizes the top ten cited papers for the most relevant research themes from 1995 to 1999.

Table 2.2: Thematic networks' performance (Period 2: 1995-1999).

Thematic network	Network's keywords	#Papers	h-index	Top 10 papers
Character Recognition	Character Recognition, Structural Features, Statistical Model, MLP, Character Segmentation, Feature Extraction, NN, Classification, HMM, Word Recognition, Template Matching, Japanese Text Recognition	162	37	[113]$_{189}$ [153]$_{176}$ [58]$_{173}$ [198]$_{172}$ [81]$_{133}$ [101]$_{132}$ [112]$_{126}$ [150]$_{124}$ [242]$_{123}$ [128]$_{122}$
Numeral Recognition	Numeral Recognition, Ensemble Classification, Structural Classification, Segmentation, GA, Clustering, Fuzzy Logic	75	29	[98]$_{418}$ [113]$_{189}$ [58]$_{173}$ [81]$_{133}$ [101]$_{132}$ [128]$_{122}$ [28]$_{108}$ [39]$_{95}$ [247]$_{78}$ [222]$_{77}$

Thematic network	**Network's keywords**	**#Papers**	**h-index**	**Top 10 papers**
Chinese Character Recognition	Chinese Character Recognition, Directional Feature, Preprocessing, Graph	41	15	[106]$_{177}$ [58]$_{173}$ [198]$_{172}$ [101]$_{132}$ [112]$_{126}$ [222]$_{77}$ [12]$_{66}$ [227]$_{63}$ [145]$_{49}$ [30]$_{48}$
Word Spotting	Word Spotting, Information Retrieval, Text Recognition	27	14	[98]$_{418}$ [153]$_{176}$ [154]$_{154}$ [165]$_{69}$ [109]$_{46}$ [36]$_{43}$ [2]$_{35}$ [108]$_{32}$ [85]$_{31}$ [40]$_{29}$
Digit Recognition	Digit Recognition, KNN, Feature Selection	16	8	[81]$_{133}$ [101]$_{132}$ [88]$_{69}$ [68]$_{45}$ [204]$_{38}$ [35]$_{22}$ [159]$_{17}$ [116]$_{14}$ [110]$_{7}$ [158]$_{5}$

2.3 Period 3: 2000-2004

Table 2.3 summarizes the top ten cited papers for the most relevant research themes from 2000 to 2004.

Table 2.3: Thematic networks' performance (Period 3: 2000-2004).

Thematic network	**Network's keywords**	**#Papers**	**h-index**	**Top 10 papers**
HMM	HMM, Sentence Recognition, Dictionary, Large Vocabulary, Text Recognition, Feature Selection, Preprocessing, Word Recognition, Arabic Text Recognition, Language Model, Ensemble Classification, Synthetic Data	122	29	[176]$_{1749}$ [156]$_{588}$ [155]$_{314}$ [15]$_{291}$ [138]$_{226}$ [232]$_{201}$ [151]$_{177}$ [257]$_{142}$ [134]$_{134}$ [115]$_{119}$

Thematic network	**Network's keywords**	**#Papers**	**h-index**	**Top 10 papers**
Character Recognition	Character Recognition, Statistical Model, Graph, SOM, Character Segmentation, Feature Extraction, Segmentation, NN, Classification, Template Matching, Fuzzy Logic, Structural Features	164	35	[137]$_{401}$ [15]$_{291}$ [166]$_{165}$ [134]$_{134}$ [203]$_{130}$ [34]$_{118}$ [136]$_{112}$ [16]$_{111}$ [48]$_{98}$ [139]$_{93}$
Chinese Character Recognition	Chinese Character Recognition, PCA, Active Shape Model, SVM, GA, Wavelet, Supervised Learning, Postprocessing	59	19	[137]$_{401}$ [257]$_{142}$ [203]$_{130}$ [136]$_{112}$ [133]$_{85}$ [140]$_{74}$ [209]$_{59}$ [256]$_{52}$ [202]$_{50}$ [31]$_{38}$
Writer Identification	Writer Identification, Signature Verification, Mathematical Transform, Texture Features	23	10	[176]$_{1749}$ [192]$_{246}$ [257]$_{142}$ [196]$_{56}$ [231]$_{45}$ [92]$_{29}$ [251]$_{29}$ [96]$_{16}$ [74]$_{15}$ [161]$_{11}$
Numeral Recognition	Digit Recognition, Structural Classification, Decision Tree, Clustering	63	22	[137]$_{401}$ [138]$_{226}$ [166]$_{165}$ [203]$_{130}$ [27]$_{118}$ [193]$_{102}$ [139]$_{93}$ [65]$_{89}$ [123]$_{78}$ [140]$_{74}$

2.4 Period 4: 2005-2009

Table 2.4 summarizes the top ten cited papers for the most relevant research themes from 2005 to 2009.

Table 2.4: Thematic networks' performance (Period 4: 2005-2009).

Thematic network	**Network's keywords**	**#Papers**	**h-index**	**Top 10 papers**
SVM	SVM, Indian Text Recognition, Elastic Mesh, RBF, Feature Extraction, Character Recognition, Digit Recognition, Classification, Chinese Character Recognition, Feature Selection, Arabic Text Recognition, KNN	254	32	[147]$_{342}$ [20]$_{210}$ [124]$_{194}$ [4]$_{140}$ [7]$_{113}$ [132]$_{105}$ [213]$_{100}$ [91]$_{100}$ [212]$_{100}$ [238]$_{84}$
HMM	HMM, Sentence Recognition, Moments, Dictionary, Text Recognition, Chinese Text Recognition, Word Recognition, RNN, Language Model, Ensemble Classification, Statistical Model, Graph	198	27	[75]$_{982}$ [177]$_{141}$ [148]$_{138}$ [188]$_{136}$ [130]$_{132}$ [7]$_{113}$ [248]$_{106}$ [213]$_{100}$ [91]$_{100}$ [253]$_{79}$
Segmentation	Segmentation, Structural Features, Bank Check Recognition, Digit Segmentation, NN, Writer Identification, Numeral Recognition, Preprocessing, Historical Documents, Script Identification, Fuzzy Logic	206	28	[188]$_{136}$ [7]$_{113}$ [132]$_{105}$ [213]$_{100}$ [91]$_{100}$ [253]$_{79}$ [53]$_{70}$ [141]$_{66}$ [135]$_{65}$ [228]$_{64}$
Signature Verification	Signature Verification, Verification, Wavelet, DTW, Mathematical Transform	55	14	[91]$_{100}$ [26]$_{92}$ [78]$_{51}$ [180]$_{36}$ [25]$_{35}$ [80]$_{34}$ [179]$_{19}$ [185]$_{19}$ [223]$_{14}$ [70]$_{12}$

2.5 Period 5: 2010-2014

Table 2.5 summarizes the top ten cited papers for the most relevant research themes from 2010 to 2014.

Table 2.5: Thematic networks' performance (Period 5: 2010-2014).

Thematic network	**Network's keywords**	**#Papers**	**h-index**	**Top 10 papers**
Character Recognition	Character Recognition, Statistical Model, Mathematical Transform, Zonning, Feature Extraction, NN, SVM, Preprocessing, Arabic Text Recognition, KNN, Wavelet, Indian Text Recognition	632	35	[60]$_{168}$ [29]$_{126}$ [143]$_{113}$ [171]$_{106}$ [249]$_{100}$ [22]$_{86}$ [235]$_{85}$ [173]$_{84}$ [229]$_{80}$ [240]$_{79}$
Segmentation	Segmentation, SOM, Character Segmentation, Text Line Segmentation, Text Recognition, Chinese Text Recognition, GA, Math Recognition, Dymanic Programming, Structural Features, Postprocessing, Projection Features	386	33	[175]$_{239}$ [63]$_{186}$ [142]$_{169}$ [60]$_{168}$ [143]$_{113}$ [171]$_{106}$ [236]$_{101}$ [211]$_{100}$ [249]$_{100}$ [44]$_{86}$
HMM	HMM, Sentence Recognition, Bayesian Network, Viterbi Algorithm, DBNN, Word Spotting, Word Recognition, RNN, Clustering, Music Recognition, Roman Script, GMM	219	29	[175]$_{239}$ [63]$_{186}$ [60]$_{168}$ [171]$_{106}$ [22]$_{86}$ [62]$_{83}$ [52]$_{82}$ [10]$_{75}$
Classification	Classification, Feature Reduction, RBF, BKS, Chinese Character Recognition, Digit Recognition, Signature Verification, Script Identification, Fuzzy Logic, Ensemble Classification, HOG, Chain Code, Feature Reduction	292	22	[173]$_{84}$ [229]$_{80}$ [43]$_{75}$ [163]$_{56}$ [100]$_{49}$ [120]$_{41}$ [54]$_{38}$ [50]$_{36}$ [86]$_{30}$ [17]$_{29}$

Thematic network	Network's keywords	#Papers	h-index	Top 10 papers
Writer Identification	Writer Identification, Histogram, Texture Features, Feature Selection, Forensics	79	14	[44]$_{86}$ [46]$_{80}$ [51]$_{53}$ [64]$_{49}$ [32]$_{33}$ [95]$_{28}$ [121]$_{23}$ [129]$_{23}$ [1]$_{22}$ [183]$_{22}$
MLP	MLP, PFGA, Numeral Recognition, Moments	73	10	[60]$_{168}$ [13]$_{64}$ [237]$_{30}$ [160]$_{20}$ [122]$_{20}$ [208]$_{15}$ [104]$_{13}$ [182]$_{12}$ [201]$_{11}$ [189]$_{10}$
Historical Documents	Historical Documents, Language Model, Morphology Operator	57	12	[236]$_{101}$ [250]$_{44}$ [146]$_{39}$ [32]$_{33}$ [107]$_{24}$ [72]$_{22}$ [183]$_{22}$ [195]$_{21}$ [117]$_{19}$ [194]$_{14}$

2.6 Period 6: 2015-2020

Table 2.6 summarizes the top ten cited papers for the most relevant research themes from 2015 to 2020.

Table 2.6: Thematic networks' performance (Period 6: 2015-2020).

Thematic network	Network's keywords	#Papers	h-index	Top 10 papers
DNN	DNN, Text Recognition, Character Recognition,CNN, Digit Recognition, RNN, Transfer Learning, Indian Text Recognition, Data Augmentation, Dropout, DCNN, DBNN	1,1138	30	[258]$_{158}$ [254]$_{132}$ [214]$_{106}$ [82]$_{98}$ [59]$_{82}$ [246]$_{70}$ [243]$_{68}$ [233]$_{68}$ [241]$_{66}$ [97]$_{65}$

Thematic network	**Network's keywords**	**#Papers**	**h-index**	**Top 10 papers**
SVM	SVM, Texture Features, Decision Tree, PCA, Feature Extraction, NN, Classification, Signature Verification, Arabic Text Recognition, KNN, HOG, Statistical Model, Texture Features	902	23	[77] $_{117}$ [59] $_{82}$ [219] $_{54}$ [168] $_{53}$ [199] $_{48}$ [105] $_{29}$ [24] $_{25}$ [178] $_{23}$ [206] $_{20}$ [23] $_{16}$
Segmentation	Segmentation, Histogram, Character Segmentation, Text Line Segmentation, Word Spotting, Preprocessing, Word Recognition, Math Recognition, Historical Documents, Sliding Window, FCNN, Projection Features	455	18	[77] $_{117}$ [214] $_{106}$ [190] $_{52}$ [252] $_{46}$ [118] $_{45}$ [9] $_{35}$ [181] $_{34}$ [37] $_{27}$ [55] $_{26}$ [226] $_{25}$
Ensemble Classification	Ensemble Classification, Moments, ResNet,Chinese Character Recognition, Chinese Text Recognition, Feature Selection, GA, Script Identification, Fuzzy Logic, Structural Features, Mathematical Transform, Graph	379	20	[258] $_{158}$ [254] $_{132}$ [42] $_{73}$ [243] $_{68}$ [241] $_{66}$ [18] $_{44}$ [186] $_{42}$ [45] $_{35}$ [41] $_{34}$ [131] $_{33}$
HMM	HMM, Embedding,Tibetan Text Recognition, Language Model, Music Recognition, Roman Text Recognition, Multi-Script Recognition, N-Grams, Sentence Recognition, Bayesian Network	165	14	[241] $_{66}$ [190] $_{52}$ [90] $_{52}$ [118] $_{52}$ [37] $_{45}$ [220] $_{25}$ [84] $_{25}$ [224] $_{20}$ [21] $_{18}$ [38] $_{18}$
Writer Identification	Writer Identification, Siamese Network, Verification, Template Matching, Wavelet, Forensics, SIFT, Autoencoder	155	12	[87] $_{58}$ [90] $_{52}$ [184] $_{29}$ [205] $_{29}$ [103] $_{23}$ [126] $_{22}$ [89] $_{17}$ [11] $_{16}$ [38] $_{15}$ [164] $_{14}$

Thematic network	Network's keywords	#Papers	h-index	Top 10 papers
Numeral Recognition	Numeral Recognition, MLP, Attention Mechanism, Graphology, End-to-end, ELM	141	12	[252] $_{46}$ [181] $_{34}$ [131] $_{33}$ [126] $_{22}$ [6] $_{19}$ [207] $_{19}$ [79] $_{18}$ [221] $_{16}$ [191] $_{15}$ [218] $_{14}$

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