vector angle was considered as a feature, for each subimage. A Euclidean-distance-based functional approach was proposed by Mizukami *et al.* [199] for offline signature verification. A questioned signature was compared with a corresponding authentic one by evaluating the minimum of the functional. The signature was then accepted only if the measured dissimilarity was below a well-defined threshold. In the approach of Murshed *et al.* [215], the signature was first centered and successively divided into m regions, through the use of an *identity grid.* In the verification stage, the grid-based information was fed to m fuzzy ARTMAP networks, each of which was responsible for one region in the signature. A majority voting rule was used to provide a verification response for the whole signature. Ramesh and Narasimha Murty [274] used four different types of pattern representation schemes based on geometric features, moment-based representations, envelope characteristics, and wavelet features. The final decision on signature authenticity was achieved by combining the outputs of the four subsystems, according to a genetic approach. A k-nearest neighbor classifier and a minimum distance classifier were used by Sabourin *et al.* [281] for offline signature verification based on extended-shadow coding. Sabourin *et al.* used a feedforward NN classifier and the directional pdf, for random forgery detection [282]; whereas they used a similarity measure with shape matrices as a mixed shape factor for offline signature verification [283]. Santos *et al.* used MLP to verify offline signatures described by graphometric-based features. Pattern matching was investigated by Ueda [318] for offline signature verification. For this purpose, signature strokes were first thinned and then blurred by a fixed point-spread function. An MLP classifier was used by Xiao and Leedham [350] with both direction-based and grid features. A selective attention mechanism was proposed to deal with the intraclass variability between genuine signatures and the difficulty of collecting forgeries. For this purpose, the MLP classifier was forced to pay special attention to local stable parts of the signature by weighting their corresponding node responses through a feedback mechanism.

In Table VI, a stroke-oriented description of signatures well suited for an ME approach was discussed by Bovino *et al.* [18]. Each stroke was analyzed in the domain of position, velocity, and acceleration. Successively, a two-level scheme for decision combination was used. For each stroke, at the first level soft- and hard-combination rules were used to combine decisions from different representation domains. At the second level, simple and weighted averaging was used to combine decisions from different parts of the signature. Di Lecce *et al.* [50] performed signature verification by combining three experts. The first expert uses shape-based features and performed signature verification by a global analysis. The second and third expert used speed-based features and adopted a regional analysis. The combination of expert decisions was performed by a majority voting strategy. Igarza *et al.* [130] used a left-to-right HMM for online signature verification and verified its superiority with respect to ergodic HMMs. The superiority of PCA and MCA for online signature verification with respect to DTW and Euclidean-based verification was also investigated by Igarza *et al.* [131]. Jain *et al.* [138] used a set of local parameters—describing both spatial and temporal information. In the verification process, the test signature was compared to all signatures in the reference set. Three methods to combine the individual dissimilarity values into one value were investigated: the minimum of all dissimilarity values, the average of all dissimilarity values, and the maximum of all dissimilarity values. Furthermore, common and personalized (signer dependent) thresholds were also considered. The best results were achieved by considering the minimum of all dissimilarity values and the personalized threshold values. The online signature verification system proposed by Kashi *et al.* [146] used a Fourier-transform-based normalization technique and both global and local features for signature modeling. The global features captured spatial and temporal information of the signature whereas local features, extracted by a left-to-right HMM, captured the dynamics of the signature production process. The verification result was achieved by the combination of the information derived by global and local features. Lee *et al.* [166] performed signature segmentation by a DP technique based on geometric extrema. Segment matching was performed by global features and a DP approach. BPN integrating the global features approach and the DP matching results was used for signature verification. The scheme proposed by Morita *et al.* [205] used position, pressure, and inclination functions, whereas DTW was considered to compute a distance between the template and input signature, in the verification phase. Templates were generated from several authentic signatures of individuals, in order to improve verification performances. Maramatsu and Matsumoto [213] used HMM-LR incorporating signature trajectories for online signature verification. In the approach proposed by Nakanishi *et al.* [220], position signals of the online signature were decomposed into subband signals by using the discrete wavelet transform (DWT). Individual features were extracted as high-frequency signals in subbands. The total decision for verification was carried out by averaging the verification results achieved at each subband. Ortega-Garcia *et al.* [238] presented an investigation of HMM-LR modeling capabilities of the signing process, based on a set of 24 function features (eight basic function features and their first and second derivatives). In the system of Shafiei and Rabiee [299], each signature was segmented using its perceptually important points. For each segment, four dynamic and three static parameters were extracted, which are scale and displacement invariant. HMM was used for signature verification. Wessels and Omlin [333] combined a Kohonen self-organizing feature map and a HMM. Both left-to-right and ergodic models were considered. Wijesoma *et al.* [335] considered two feature sets. The first set consisted of ten shape-related features while the second set consisted of 14 dynamics-related features. GAs were used to determine the optimal personalized features for each subject whereas verification decision was achieved by fuzzy logic. Fourier analysis was used by Wu *et al.* [347] for online signature verification. In particular, cepstrum coefficients were extracted and used for verification, according to a dynamic similarity measure. Geometric- and curvature-based features were used for the online signature verification discussed by Xuhua *et al.* [354]. Successively, a GA was used to select discriminative features and a fuzzy logic approach was applied for signature verification. Yang *et al.* [357] used directional features along with several HMM topologies for signature modeling. The results demonstrated that HMM-LR is superior to other topologies in capturing the individual features of the signatures and at the

TABLE VI
PERFORMANCES: ONLINE SYSTEMS

Authors	Main features	Database	Approach	Results
L. Bovino et al. [18]	Position, Velocity, Acceleration	**Training)** 45(G) (3(G) x 15(A)) **Test)** 750(G) (50(G)x15(A)), 750 (F) (50(F)x15(A))	DTW (ME by simple averaging)	**EER**: 0,4%
V. Di Lecce et al. [50]	Shape-based features (segmentation dependent), Velocity	**Training)** 45(G) (3(G) x 15(A)) **Test)** 750 (G) (50(G)x15(A)), 750 (F) (50(F)x15(A))	DTW (ME by majority voting)	**FRR**: 3,2%, **FAR**: 0.55%
K. Huang and H. Yan [129]	Velocity, Pressure	**FD)** 4600 (S)	DTW	**EER**: 4%
J. J. Igarza et al. [130]	Direction of pen movement, …	**FD)** 3750 (G) (25(G)x150(A)), 3750 (F)	HMM	**EER**: 9,253%
A. K. Jain et al. [138]	Velocity, Curvature based.	**FD)** 1232 (S) (from 102 (A))	String matching	**FRR**: 3,3%, **FAR**: 2,7% (common threshoold) **FRR**: 2,8%, **FAR**: 1,6% (writer dependent threshold)
R. S. Kashi et al. [146]	Total signature time duration, X-Y (speed) correlation, RMS speed, Moment-based, direction-based, etc.	**Test)** 542 (G), 325 (F)	HMM	**EER**: 2,5%
J. Lee et al. [166]	Position (geometric extrema), AVE velocity, number of pen-ups, time duration of neg. /pos. velocity, total signing time, direction-based, …	**FD)** 6790 (S) (from 271(A))	NN + DP	**EER**: 0.98%
B. Li et al. [180]	Position, Velocity	**Training)** 405 (G) (5(G) x 81(A)) **Test)** 405 (G) (5(G) x 81(A)), 405(F) (5(F) x 81(A))	PCA, MCA	**EER**: 5,00%
H. Morita et al. [205]	Position, Pressure, Pen Inclination	**Training)** 205 (S) **Test)** 861 (G), 1921 (F)	DTW	**EER**: 3%
D. Muramatsu and T. Matsumoto [213]	Direction of pen movements	**Training)** 165 (G) **Test)** 1683 (G), 3170 (SK)	HMM	**EER**: 2,78%
I. Nakanishi et al. [220]	Wavelet Transform.	**Training)** 20(G) from(4(A)) **Test)** 98 (G) (from 4(A)), 200(F) (from 5(A))	Dynamic Programming	**EER**: 4%
J. Ortega-Garcia et al. [238]	Position, Velocity, Pressure, Pen Inclination (Azimuth), Direction of Pen Movement, …	**Training)** 300(G) (from 50(A)) **Test)** (450 (G) (from 50(A)), 750 (SK) (from 50(A))	HMM	**EER**: 1,21% (global threshold) **EER**: 0,35% (user-specific threshold)
T. Qu et al. [266]	Total signature time, AVE/RMS speed, pressure, direction-based, number of pen-ups/pen downs, …	**Test)** 60 (G), 60 (F)	Membership function	**FRR**: 6,67%, **FAR**: 1,67%
M. M. Shafiei and H. R. Rabiee [299]	AVE Speed, acceleration, pressure, Direction of Pen movement,…	**FD)** 622 (G) (from 69(A)), 1010 (SK)	HMM	**FRR**: 12%, **FAR**: 4%
T. Wessels and C.W. Omlin [333]	Position, Pressure, Direction of pen movements, Pen inclination.	**Training)** 750 (G) (15(G) x 50(A)) **Test)** 750 (G) (15(G) x 50(A))	HMM	**FAR**: 13%
W. S. Wijesoma et al. [335]	RMS / MAX speed, acceleration, Time duration of Positive /Negative Velocity, Pen-down time ratio, Direction-based, …	**Training)** 410(G) (10(G) x 41(A)) **Test)** 820(G) (20(G) x 41(A)), 410 (F) (from 6 (A))	Fuzzy Logic	**EER**: 4,82%
Q. Z. Wu et al. [347]	Fourier transform (cepstrum coefficients)	**Training)** 270(G) (from 27(A)) **Test)** 560 (G) (from 27(A)), 650 (F)	Dynamic similarity measure	**FRR**: 1,4%, **FAR**: 2,8%
Y. Xuhua et al. [354]	Geometric-based, Curvature-based,,…	**Training)** 45(G) (45(G) x 1(A)), 45(F) (from 19 (A)) **Test)** 75(G) (75(G) x 1(A)), 90 (F) (from 19 (A))	Fuzzy Logic	**FRR**: 8,5%, **FAR**: 1,8%
L. Yang et al. [357]	Direction of Pen movements	**FD)** 496 (S) (from 31 (A)	HMM	**FRR**: 1,75%, **FAR**: 4,44%
D.-Y. Yeung et al. [360] (1st Int. Signature Verification Competition)	**Task 1:** Position; **Task 2:** Position, Pen Inclination (azimuth), Pressure,…	**Training)** 800(G)(20(G)x40(A)),800(SK)(20(SK)x40(A)) **Test 1)** 600(G)(10(G)x60(A)), 1200(SK)(20(SK)x60(A)) **Test 2)** 600(G)(10(G)x60(A)), 1200(RF)(20(RF)x60(A))		**(Test 1) EER:** 2,84% (Task 1), **EER:** 2,89% (Task 2) **(Test 2) EER:** 2,79% (Task 1), **EER:** 2,51% (Task 2)
H.S. Yoon et al. [362]	Position	**Training)** 1500 (S) ((15 (S) x 100 (A)) **Test)** 500(S) (5 (S) x 100 (A))	HMM	**EER**: 2,2%
K. Zhang et al. [371]	Geometric-based, Curvature–based	**FD)** 306 (G), 302 (F)	Mahalanobis distance, Euclidean Distance,DTW	**FRR**: 5,8%, **FAR**: 0%
M. Zou et al. [379]	Speed, Pressure, Direction-based, Fourier transform	**FD)** 1000 (G), 10000 (F)	Membership function	**FRR**: 11,30%, **FAR**: 2,00%

Full Database (FD), Signature (S), Genuine Signatures (G), Forgeries (F), Random Forgeries (RF), Simple Forgeries (SF), Skilled Forgeries (SK), Number of Authors (A)

same time accepting variability in signing. Yeung *et al.* [360] reported the results of the First International Signature Verification Competitions (SVC2004), to which teams from all over the world participated. In particular, SVC2004 considered two separate signature verification tasks using two different signature databases. The signature data for the first task contained position information only, which was well suited for online signature verification on small pan-based input devices such as PDA. The signature data for the second task contained position, pen inclination, and pressure information that were well suited for applications based on digitizing tablets. A polar coordinate system was considered for signature representation by Yoon *et al.* [362] in order to reduce normalization error and computing time. Signature modeling and verification was performed by HMMs that demonstrated their ability to capture the local characteristics in the time-sequence data and their flexibility to model signature variability. The system presented by Zhang *et al.* [371] used global, local, and function features. The first verification stage implemented a parameter-based method, in which the Mahalanobis distance was used as a dissimilarity measure between the signatures. The second verification stage involved corner extraction and corner matching. It also performed signature segmentation. The third verification stage used an elastic matching algorithm establishing a point-to-point correspondence between the compared signatures. By combining the three different types of verification, a high security level was reached. Zou *et al.* [379] used local shape analysis for online signature verification. More precisely, Fast Fourier Transform (FTT) was used to derive spectral and tremor features from well-defined segments of the signature. A weighted distance was finally considered to combine the similarity values derived from different feature sets.

The results in Tables V and VI are encouraging. Concerning offline systems, Table V shows that k-nearest neighbor classifier [281] and pattern matching techniques [283] provided good results when datasets of small to medium size were considered (for instance, datasets with a total number of signatures for training and testing less than 1000). When larger datasets were used, the best results were achieved with HMM, using both grid-based [71] and graphometric-based [144] features. Conversely, as Table VI shows, experimental results achieved with datasets of small to medium [146] and large [238] size demonstrated the superiority of HMM for online signature verification. Similar results were also achieved by means of DTW in combination with ME approaches [18], when several functions were used as features. Anyway, it should be pointed out that, although several results are very positive, system performances were generally overestimated since they were obtained from laboratory tests, which usually took into consideration very controlled writing conditions and poor forgeries produced by researchers [341].

Furthermore, the approaches proposed in the literature cannot be easily compared due to the lack of large, public signature databases and widely accepted protocols for experimental tests [65], [73], [89], [247], [341]. Indeed, there have been only a limited number of very large-size public experiments to date [107], [257]. Furthermore, it is worth noting that the development of a benchmark signature database is a time-consuming and expensive process. It involves not only scientific and technical issues, like those related to the statistical relevance of the population of individuals involved as well as the acquisition devices and protocols, but also legal aspects related to data privacy and intellectual property rights [89]. On the other hand, since the development of benchmark databases is rightly recognized as a key aspect for the success and diffusion of signature-based verification systems, specific efforts have recently been made to develop both unimodal benchmark databases (i.e., that contain only a single biometric trait) and multimodal ones (i.e., that contain two or more biometric traits from the same individuals). Some of the most important examples are the MCYT [239] and MYIDEA [69] signature databases, which contain both online and offline data; the BIOMET [106], Philips [63], and SVC2004 [360] databases of online signatures; the GPDS [91] database of offline signatures; and the Caltech [207]–[209], [211] database obtained by using cameras.

In this sense, the results obtained during the signature verification competition realized in 2004 (SVC2004) are a precise reference for advancements in the field, since they were obtained by using common benchmark databases and testing protocols [360]. Furthermore, the results demonstrate that signature verification systems can be considered as not particularly less accurate than other biometric systems, like those based on face and fingerprint [326]. Indeed, the objective of SVC2004 was to allow researchers and practitioners to evaluate the performance of different online signature verification systems systematically, not only for error rates of difficult tasks (based on pen tablet without visual feedback, synthetic signatures, dynamics of the signatures to imitate provided to forgers, etc.), but also for other parameters, like system cost, verification cost, processing speed, security of data, number of training samples required, and so on. In fact, the feasibility of a particular system in relation to a specific operating environment should also be determined by the analysis of all these parameters [78].

VI. Discussion and Conclusion

Automatic signature verification is a very attractive field of research from both scientific and commercial points of view. In recent years, along with the continuous growth of the Internet and the increasing security requirements for the development of the e-society, the field of automatic signature verification is being considered with renewed interest since it uses a customary personal authentication method that is accepted at both legal and social levels [78], [196], [258]. Furthermore, recent results achieved in international competitions using standard databases and test protocols have revealed that signature verification systems can have an accuracy level similar to those achieved by other biometric systems [326]. Finally, different from physiological biometrics, handwritten signature is an active method that requires the user to perform the explicit act of signing. Thus, automatic signature verification is particularly useful in all applications in which the authentication of both transaction and user is required [259], [326].

Therefore, the number of possible applications for online signature verification is continuously growing along with the development of more and more sophisticated and easy-to-use input devices for online handwriting acquisition. For instance, online signature verification can be a valuable contribution for controlling access security in computer networks, documents, and databases. An example of this application can be seen in health care applications—for medical record access and remote partner verification—in distributed working communities, as well as in the areas of passport and driving license applications. Online signature verification has important applications in online banking, monetary transactions, and retail POS. For instance, it can be used to replace the current practice of signing paper credit card receipts. In this case, the verification process can be performed by comparing the live online signature of a user with the biometric information of his/her handwritten signature that can be stored in a personal smart card to verify that the person using the card is the rightful owner. Furthermore, online signature verification can support switching paper-based documents to digital documents. For instance, it can enhance administrative procedures for insurance companies by reducing the amount of paper-based documents, generating a higher return on investment [103], [160], [259], [320], [324].

Notwithstanding efforts toward the dematerialization of documents, the need for fast and accurate paper-based document authentication is still growing in our society. Offline signature verification applications mainly concern the authentication of bank checks, contracts, ID personal cards, administrative forms, formal agreements, acknowledgement of services received, etc. [60], [171], [236], [259]. This type of verification is related to paper-based document authentication. Thus, offline signature verification systems can be more limited with respect to online systems.

The net result is that in the near future, along with a wide range of potential applications, a significant annual growth is expected in the worldwide signature verification market [133], [153], [320]. Of course, this trend has been further affected by research results in recent years, which have significantly advanced the state of the art in the field. Nevertheless, in order to strengthen the commercial and social benefits related to automatic signature verification, additional efforts are necessary.

In this paper, the state of the art in automatic signature verification has been presented and the main results have been addressed. Furthermore, some of the most promising directions for research in this field have been highlighted. In the near future, research need not be focused almost exclusively on accuracy improvements, as it has mostly been in the past. Instead, it should address a multitude of issues related to various scenarios of the application themselves.

For instance, as the number of input devices and techniques for handwriting acquisition increases, device interoperability will become an area of greater relevance and need specific investigation. The result of these developments is that signature capture will be feasible in many daily environments by means of fixed and mobile devices, and automatic signature verification will be used in even more applications [5].

Furthermore, in recent years, a number of benchmark databases have been developed in order to comparatively evaluate signature verification systems, and important results have been achieved for the standardization of signature data interchange formats, in order to facilitate system interoperability and integration. Advances in this direction can be expected on the well-suited integration of metadata in large-size databases and the design and implementation of standard frameworks for effective experimental construction and evaluation of signature verification systems under different forgery quality models [16], [113], [327], [377]. In the context of "soft biometrics," the deployment of metadata-based systems for large-scale applications, which can expect both multiethnic and multilingual users, is very important and needs specific consideration [325], [342].

The analysis of individual characteristics of handwriting still remains an interesting research area that encompasses not only those features produced by people with normal abilities but also those generated by people who suffer from disabilities and diseases that may lead to handwriting constraints [259]. For this purpose, investigation of the mechanisms underlying handwriting production and the ink-depository processes is worthy of additional attention, as well as studies on feature selection techniques and signature modeling methods for the adaptability and personalization of the verification processes. Similarly, techniques for the analysis of signature complexity and stability can offer insight into the selection of the most profitable biometric signature data for various kinds of applications, such as cryptography—for cryptographic key generation [103], [320], [319].

In addition, ME systems offer the potential of improving signature verification accuracy by combining different decisions. They can combine decisions obtained through multiple representations and matching algorithms at both local and global levels. Furthermore, ME systems can support a combination of decisions achieved on various biometric traits, also by using adaptive management strategies that are worthy of specific studies [322]. Indeed, to date, the characteristics of unimodal biometrics are not always adequate for large-scale deployment and for security critical applications, independent of which biometric trait is considered [65], [325]. Thus, an ME approach could also be an important area for further research to enable multimodal biometrics [93], [98], [108], [160], [240], which addresses the problem of nonuniversality and is expected to achieve higher performance than unimodal approaches [93], [105].

Finally, the relevance of the results in the legal and regulatory aspects of personal verification by handwritten signature should also be underlined. These findings are a sign of the awareness and attention that governments and institutions at national and international levels are giving to this important field of research. However, it is clear that several issues still remain to be addressed also in this field, such as those concerning privacy and the protection of personal data.

Thus, in the age of the e-society, automatic signature verification can no longer be considered exclusively restricted to academics and research laboratories since the possibility of applying automatic signature verification in a range of applications is becoming a reality. Definitely, further research is necessary to fully investigate and interpret the potential of handwritten signatures, which remain very distinct signs, unequivocally demonstrating the inspiration and complexity of human beings.

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