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CONTACTS

Phone: **+998 50 737 87 88**

Website: <https://ist-journal.uz>

Email: innovationist2025@gmail.com

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CONTENTS

WAYS TO EXPAND THE COMPANY'S POSITION IN THE FURNITURE MARKET	6
Musayeva Shoirazimovna	
DIRECTIONS FOR IMPROVING THE ORGANIZATIONAL AND ECONOMIC MECHANISM OF MEDICINAL PLANT PROCESSING	11
Usmonov Mirgulom Khoshim o'g'li	
POLITICAL RELATIONS BETWEEN AZERBAIJAN AND UZBEKISTAN: HISTORY, CHALLENGES, AND PROSPECTS	17
Naila Ramazanova	
ANALYZING THE SUSTAINABILITY OF REGIONAL ECONOMIES USING MULTI-CRITERIA INDICES AND MODEL OPTIMIZATION	23
Sattorov Sanjar Abdumurodovich	
ECONOMIC ADVANTAGES OF MODERNIZING THE EDUCATION SYSTEM THROUGH INNOVATIVE TECHNOLOGIES	28
Rakhmatkhodjayev Akhrorhodja Akmal ugli	
XORIJIY MAMLAKATLAR KORPORATIV BOSHQARUV VA INNOVATSION RIVOJLANISH MODELLARINING QIYOSIY TAHLILI	34
Ismailov Allayor Rashidovich	
DIGITALIZATION OF FOREIGN EXCHANGE DIFFERENCE ACCOUNTING: CHALLENGES AND PROSPECTS IN EMERGING ECONOMIES	41
Pulatov Sirojbek, Misirov Kamoldin	
ВЛИЯНИЕ СОЦИАЛЬНО-ДЕМОГРАФИЧЕСКИХ ФАКТОРОВ НА ОБЕСПЕЧЕНИЕ ЭКОНОМИЧЕСКОЙ БЕЗОПАСНОСТИ СТРАНЫ	47
Ташмухамедова Яйра Атхамовна	
MAIN MEASURES TO STRENGTHEN EMPLOYMENT STABILITY AND IMPROVE EMPLOYMENT MANAGEMENT IN UZBEKISTAN	52
Abdullayeva Nigora Shamsiddinovna	
ECONOMETRIC ANALYSIS OF THE IMPACT OF INVESTMENTS ON THE CREATION OF NEW JOBS	57
Shayzak R. Kholmuminov, Shukhrat Sh. Kholmuminov	
RAQAMLASHTIRISH VA YASHIL TURIZM KONSEPSIYASI ASOSIDA TURIZM SOHASINING BARQAROR RIVOJLANISHI	68
Xaitov Oxunjon Nomoz o'g'li	
IQTISODIYOTDA DAVLAT ISHTIROKINI QISQARTIRISH ORQALI XUSUSIY SEKTOR ROLINI OSHIRISHNING IJTIMOY MUHITGA TA'SIRI	73
Musurmonqulov Muhammad	
DIAGNOSIS OF EMOTIONAL INTELLIGENCE DEVELOPMENT IN PRESCHOOL CHILDREN: METHODS AND RESULTS	77
Abduxamidova Dilorom Abdumuminovna	
MULTIMADANIY MUHITDA PEDAGOGLARNING TANQIDIY FIKRLASH KO'NIKALARINI SHAKLLANTIRISH MEKANIZMLARI	81
Gulyamova Nafisa Burikulovna	
WAYS TO IMPROVE MARKETING SERVICES IN A FURNITURE MANUFACTURING ENTERPRISE	85
Mukhtarov Samadjon Abdusattor ugli	
THE ROLE OF SMALL AND MEDIUM-SIZED ENTERPRISES (SMES) IN ENHANCING UZBEKISTAN'S EXPORT PERFORMANCE	90
Abduvoitov Bekzod Khikmatullaevich, Dr. Navik Istikomah, S.E., M.Si	
OPPORTUNITIES FOR FURTHER DEVELOPMENT OF THE TOURISM SECTOR WITH THE HELP OF AN INNOVATIVE IT PLATFORM	99
Nasrullaev Hikmatullo Habibulloevich	

DIGITALIZATION OF AGRICULTURAL PRODUCTS FOR EXPORT	105
Azimov R.B.	
IQTISODIYOTDA TO'G'RIDAN-TO'G'RI XORIJIY INVESTITSİYALARNI ROLINI OSHIRISH	109
Ruzibayeva Nargiza Xakimovna, Ro'ziqulov Abduqahhor Ixtiyor o'g'li	
SUSTAINABLE DIGITAL TRANSFORMATION STRATEGIES FOR INTERNATIONAL TRADE	114
Kurolov Maksud Obitovich	
THE DEVELOPMENT OF THE METAL MARKET AND THE ROLE OF SMALL BUSINESSES IN IT	129
Musinov Dilshod Sultanovich	
ANALYSIS OF EXISTING TECHNOLOGICAL SOLUTIONS TO THE PROBLEM OF WATERING GAS WELLS	134
Abdirazakov Akmal Ibrahimovich, Boymurodov Boynazar Muradillayevich	
РЕФОРМЫ РЕЛИГИОЗНО-ОБРАЗОВАТЕЛЬНОЙ СФЕРЫ УЗБЕКИСТАНА.....	140
Тиллябаева Гульсунхон Бахрамовна	
MODELS FOR ENHANCING THE COMPETITIVENESS OF SMALL BUSINESS ENTERPRISES.....	144
Melibayeva Gulxon Nazrullayevna	
TEXTILES AND SEWING-KNITTING INDUSTRY DEVELOPMENT STATUS AND PRODUCTION VOLUME FORECAST	152
Ikromova Takhmina Latifovna	
BIG DATA VA PREDICTIVE ANALYTICS YORDAMIDA KORXONA MOLIVAVIY RISKLARNI BASHORAT QILISH VA BOSHQARISH	159
Karimov Xondamir Jamshid o'g'li	
WAYS TO IMPROVE ALTERNATIVE FINANCING OF INVESTMENT ACTIVITIES	166
Boboqulov Akmal Muborakbekovich	
VENTURE CAPITAL IN UZBEKISTAN: ECOSYSTEM ASSESSMENT, KEY CHALLENGES, POLICY IMPLICATIONS.....	173
Umidjon Khoshimov	
STUDY OF ELECTRONIC WASTE RECYCLING IN UZBEKISTAN BASED ON THE EXPERIENCE OF UZVTORTSVETMET AND THE ALMALYK MINING AND METALLURGICAL COMPLEX.....	183
Musayev Marufjan Nabievich, Ergashev Sardor Bakhtiyor ogli	
ADVANCED INTERNATIONAL PRACTICES OF EFFECTIVE CREDIT PORTFOLIO MANAGEMENT AND THEIR IMPLEMENTATION OPPORTUNITIES.....	191
Yusupov Shaxzod Maxmatmurodovich	
ECONOMIC ADVANTAGES OF MODERNIZING THE EDUCATION SYSTEM THROUGH INNOVATIVE TECHNOLOGIES.....	197
Rakhmatkhajayev Axrorkhoja Akmal ogli	
DISTRICT PLANNING AND HOUSING INFRASTRUCTURE SYSTEM AS A FRAMEWORK FOR SUSTAINABLE REGIONAL ECONOMIC DEVELOPMENT	203
Daliev Akhtam Sharafutdinovich	
JAHONDA KREATIV IQTISODIYOTNI RIVOJLANTIRISHNING MODELLARI VA ULARNING O'ZIGA XOS XUSUSIYATLARI	211
Dusmuxamedov Oybek Suratbekovich	
INCREASING THE PROFITABILITY OF COMMERCIAL BANKS AS A WAY TO ENSURE FINANCIAL STABILITY	217
Umarov Davron Shavkatovich	
CONVERSATIONAL AND ACADEMIC ENGLISH: KEY DIFFERENCES AND PRACTICAL USES.....	224
Dr. Mamatkulova Shohista Jalolovna	
TIJORAT BANKLARI KORPORATIV BOSHQARUV TIZIMINING SAMARADORLIGINI BAHOLASHGA OID YANGICHA YONDASHUVLAR	228
Temirov Abdulaziz Alimjanovich	
AN INTELLECTUAL MODEL FOR ASSESSING THE EFFECTIVENESS OF USING INFORMATION TECHNOLOGIES IN THE MEDICAL FIELD.....	234
Vaxidov Inomjon Ixamovich, Maxsudov Moxirbek Tolibjonovich	

HOW EMOTIONAL INTELLIGENCE ENHANCES ETHICAL DECISION-MAKING IN FINANCE AND AUDIT 239
Rustamova Iroda Bahtiyorova

TEXT-LINE SEGMENTATION METHODS AND ALGORITHMS IN HANDWRITTEN DOCUMENT IMAGES..... 244
Mardiyev Azamat Shakar ogli, Allayorov Jasur A'zamjon ogli, Alisherova Sarvinoz Alisher qizi

TEXT-LINE SEGMENTATION METHODS AND ALGORITHMS IN HANDWRITTEN DOCUMENT IMAGES

Mardiyev Azamat Shakar ogli

PhD Candidate, Faculty of Automation and Information Technologies,
TIIAME National Research University
Email: mardievazamat7@gmail.com
ORCID: 0009-0002-5262-6809

Allayorov Jasur A'zamjon ogli

PhD Candidate, Faculty of Automation and Information Technologies,
TIIAME National Research University
Email: jasur_allayorov@outlook.com

Alisherova Sarvinov Alisher qizi

PhD Candidate, Faculty of Automation and Information Technologies,
TIIAME National Research University
Email: bilolbek02062019@gmail.com

Abstract: Automatic line segmentation plays a crucial role in the digitization and automatic recognition of handwritten and historical documents. The variability of handwriting styles, curved baselines, touching characters, ink diffusion, and uneven backgrounds make this task particularly challenging. Traditional methods based on projection profiles or morphological operations are effective for printed and well-structured texts but often fail when applied to degraded or historical documents. In recent years, advanced approaches based on probabilistic modeling, energy minimization, graph theory, and deep neural networks have emerged. This study presents a detailed review and comparative analysis of twenty-five leading line segmentation methods. The analysis encompasses language-independent probabilistic approaches, morphological hybrid models, the Mumford–Shah variational framework, and state-of-the-art deep learning architectures such as ARU-Net, Adaptive U-Net, Mask R-CNN, and GAN-based models. For each method, working principles, preprocessing requirements, evaluation datasets, and accuracy metrics are systematically examined. The results reveal a clear evolution from rule-based and geometry-driven algorithms toward data-centric, binarization-free methods capable of processing multilingual and noisy manuscripts. Furthermore, the analysis consolidates existing research achievements and identifies open research directions, including the integration of multimodal cues, self-supervised learning, and adaptive segmentation strategies. Overall, this comprehensive review contributes to a systematic understanding of progress and remaining challenges in the field of handwritten text line segmentation.

Key words: handwritten text image, text line segmentation, projection profile, handwritten document, parchment.

Annotatsiya: Qo'lyozma va tarixiy hujjatlarni raqamlashtirish hamda avtomatik tanib olish jarayonlarida matn qatorlarini avtomatik segmentatsiyalash muhim o'rin tutadi. Qo'lyozma yozuv uslublarining xilma-xilligi, egri asosiy chiziq, bir-biriga tegishgan belgilar, siyohning tarqalishi hamda notekis fon kabi omillar bu jarayonni ancha murakkablashtiradi. Proyeksiya profiliga yoki morfologik amallarga asoslangan an'anaviy usullar bosma va tuzilmasi aniq matnlarda samarali bo'lsa-da, eskirgan yoki buzilgan hujjatlarda ko'pincha natija bermaydi. Shu sababli, so'nggi yillarda ehtimollik modellashtirish, energiyani minimallashtirish, graf nazariyasi va chuqur neyron tarmoqlarga asoslangan ilg'or yondashuvlar paydo bo'lgan. Ushbu tadqiqotda matn qatorlarini segmentatsiyalashning yigirma beshta yetakchi usuli chuqur tahlil qilinadi va o'zaro solishtiriladi. Tahlil doirasida tilga bog'liq bo'lmagan ehtimollik yondashuvlari, morfologik gibridd modellar, Mumford–Shah variatsion yondashuvi, shuningdek, ARU-Net, Adaptive U-Net, Mask R-CNN va GAN asosidagi ilg'or chuqur o'rganish arxitekturalari qamrab olingan. Har bir yondashuvning ishlash prinsipi, oldindan ishlov berish talablari, sinov ma'lumotlar to'plamlari va aniqlik ko'rsatkichlari tizimli ravishda tahlil qilinadi. Tadqiqot natijalari qoidaga asoslangan va geometrik algoritmlardan ma'lumotga yo'naltirilgan, binarizatsiyasiz hamda ko'p tilli hujjatlar bilan ishlay oladigan usullarga o'tish evolyutsiyasini ko'rsatadi. Shuningdek, tahlil mavjud ilmiy yutuqlarni umumlashtirib, ko'p modal belgilarni birlashtirish,

o'z-o'zini o'qituvchi hamda adaptiv segmentatsiya strategiyalari kabi ochiq tadqiqot yo'nalishlarini aniqlaydi. Umuman olganda, ushbu keng qamrovli tahlil qo'lyozma matn qatorlarini segmentatsiyalash sohasidagi yutuqlar va mavjud muammolarni tizimli tushunishga hissa qo'shadi.

Калит so'zlar: qo'lyozma matn tasviri, matn qatorlari segmentatsiyasi, proyeksiya profili, qo'lyozma hujjat, pergament.

Аннотация: В процессе оцифровки и автоматического распознавания рукописных и исторических документов важную роль играет автоматическая сегментация строк текста. Разнообразие стилей письма, кривые базовые линии, соприкасающиеся символы, растекание чернил и неравномерный фон значительно усложняют этот процесс. Традиционные методы, основанные на проекционных профилях или морфологических операциях, эффективны для печатных и хорошо структурированных текстов, но часто оказываются неработоспособными для повреждённых или деградированных документов. В связи с этим в последние годы появились передовые подходы, основанные на вероятностном моделировании, минимизации энергии, теории графов и глубоких нейронных сетях. В данном исследовании проведён детальный анализ и сравнительное исследование двадцати пяти ведущих методов сегментации строк текста. Анализ охватывает вероятностные модели, не зависящие от языка, морфологические гибридные подходы, вариационный метод Мамфорда–Ша, а также современные архитектуры глубокого обучения – ARU-Net, Adaptive U-Net, Mask R-CNN и модели на основе GAN. Для каждого подхода системно рассмотрены принципы работы, требования к предварительной обработке, наборы тестовых данных и показатели точности. Результаты показывают эволюцию от правил-ориентированных и геометрических алгоритмов к методам, основанным на данных, не требующим бинаризации и способным работать с многоязычными документами. Кроме того, исследование обобщает существующие научные достижения и определяет открытые направления исследований, такие как интеграция мультимодальных признаков, самообучающиеся и адаптивные стратегии сегментации. В целом проведённый обзор способствует системному пониманию достижений и нерешённых проблем в области сегментации строк рукописного текста.

Ключевые слова: рукописный текст, сегментация строк текста, проекционный профиль, рукописный документ, пергамент.

INTRODUCTION

Segmentation of Handwritten Text Lines is one of the most crucial stages in document image analysis, as it determines the accuracy of subsequent processes such as character detection, recognition, and text reconstruction. For historical manuscripts in particular, this task is challenging due to factors like line curvature, overlapping lines, diacritical marks, noise, and uneven background illumination — all of which directly affect segmentation quality. Therefore, in recent years, numerous studies have explored geometric, morphological, probabilistic, energy-minimization, graph-based, and deep-learning approaches to improve performance. While classical methods (such as projection profiles, Hough transform, morphological operations, and energy-based functions) produced effective results at early stages, most of them remained dependent on the type of script, language, or document conditions. Modern research, on the other hand, aims to overcome these limitations through binarization-free, language-independent, and neural network-based segmentation techniques.

REVIEW OF LITERATURE ON THE SUBJECT

This study analyzes both traditional and modern approaches to text-line segmentation in handwritten and historical documents, highlighting their evolutionary development. Li, Zheng, Doermann, and Jaeger proposed a language-independent segmentation model based on probabilistic density functions, which identified line boundaries through level sets and laid the theoretical foundation for later deep-learning models. Louloudis, Gatos, and Pratikakis achieved over 95% accuracy on skewed, dense, and diacritic-rich manuscripts using Hough transform and skeleton-based methods. Dos Santos et al. developed a fast and robust morphological projection approach that reached 99% accuracy on the IAM dataset. Du, Pan, and Bui introduced a script-independent segmentation method using the Mumford–Shah variational model, providing a parameter-free solution.

Papavassiliou and colleagues presented a probabilistic approach based on the Viterbi algorithm and hidden Markov models, while for word segmentation they used an SVM-based “soft-boundary” metric. Alaei and Nagabhushan proposed a “piecewise painting” technique, applying morphological dilation to accurately separate handwritten lines. Ryu and Cho designed an energy-minimizing algorithm based on connected components, and Saabni and El-Sana introduced a binarization-free, language-independent energy-map approach achieving 98% accuracy.

Later, Kavitha, Shivakumara, and Lu developed a novel method for degraded Indus manuscripts by combining Sobel and Laplacian filters. Khare and collaborators achieved 97–98% accuracy using a “Weighted-

Gradient Features” approach, while Grüning and Labahn proposed the ARU-Net model, demonstrating high performance on curved baselines. Kurar Barakat and El-Sana introduced an unsupervised graph-cut method, and Hu and Wang presented a hybrid approach integrating baseline and component analysis for Tibetan Uchen manuscripts.

In the latest developments, Sahare proposed a graph-based shortest-path algorithm, and Kumar and Doermann applied graph clustering for Arabic manuscripts. Garz and Bunke used probabilistic clustering for binarization-free parchment texts, while Renton and Paquet, as well as Vo and Lee, achieved high accuracy with fully convolutional networks. Daldali and Souhar proposed an energy-map-based Arabic text segmentation method with resizing normalization. Gader and Echi developed the AR2U-Net model, Mechi and Amara designed a two-stage Adaptive U-Net approach, Barakat and Droby combined FCN with EM, Droby and El-Sana implemented Mask R-CNN, and Özşeker and Özkaya introduced an advanced GAN-based architecture.

Overall, recent research trends demonstrate a clear shift from rule-based and geometric methods toward deep-learning-driven, binarization-free, language-independent, and multi-scenario segmentation models.

RESEARCH METHODOLOGY

This paper systematically analyzes the main approaches proposed for handwritten text-line segmentation — including algorithms, methods, techniques, and systems — by examining their advantages, limitations, and evolutionary development paths.

ANALYSIS AND RESULTS

In the study by Li, Y., Zheng, Y., Doermann, D., and Jaeger, S., a language- and script-independent approach based on probability density functions was proposed for text-line segmentation in handwritten documents. The goal of the research was to automatically detect curved, adjacent, or touching text lines in a way that differs from traditional Docstrum or projection profile methods. The proposed approach relies on constructing a probabilistic density map that estimates text density, followed by segmentation through the level-set method. First, an anisotropic Gaussian kernel is applied to the binarized image to produce a smoothed probability density map. Then, line boundaries evolve over time according to the level-set equation, naturally separating the text lines. The resulting segments are merged during post-processing based on orientation and distance criteria. The scientific significance of this approach lies in its integration of bottom-up and top-down probabilistic reasoning, which later provided a theoretical foundation for deep-learning-based page layout analysis models such as DAS, U-Net, dhSegment, and DAN.

Louloudis, G., Gatos, B., Pratikakis, I., and Halatsis, C. developed a comprehensive algorithm for handwritten text-line detection that effectively handles arbitrary skew angles, overlapping or touching lines, and diacritical marks. The algorithm consists of three main stages: preprocessing, Hough transform-based mapping, and post-processing. During preprocessing, connected components are extracted and categorized into three spatial subsets based on their size characteristics: regular characters, large/touching components, and small diacritics. In the detection stage, a block-based Hough transform is applied, where each connected component contributes multiple voting points rather than a single one, thereby improving positional accuracy for non-uniformly slanted lines. In the post-processing stage, line merging, recovery of missed lines, and character-level vertical segmentation using skeleton-based techniques are performed. Evaluation on 152 multilingual documents (English, Greek, French, and German), comprising 3382 text lines, achieved a 95.8% detection rate and 93.8% recognition accuracy. These results outperformed projection-profile, uncertainty-based, run-length, and standard Hough-based methods. The proposed algorithm effectively integrates connected component analysis with parametric geometry, ensuring robustness for dense and multi-slanted handwritten texts, while maintaining computational efficiency.

Later, Louloudis, G., Gatos, B., Pratikakis, I., and Halatsis, C. extended their work by integrating skeleton-based segmentation and a Gaussian mixture model-based clustering stage to simultaneously handle text-line and word segmentation within a unified geometric-statistical framework. This approach operates with the same parameters across multiple languages, including Latin, French, Greek, and German scripts.

In the research by Dos Santos, R. P., Clemente, G. S., Ren, T. I., and Cavalcanti, G. D., a fast and morphology-based method was proposed for handwritten text-line segmentation, optimized for the IAM database. The method combines mathematical morphology with horizontal (Y-axis) and vertical (X-axis) projection histograms to accurately detect and refine line boundaries. The process begins with morphological binarization, applying closing, opening, and thresholding operations to enhance text clarity and suppress background noise. The Y-axis projection then identifies candidate line regions, while adaptive thresholding eliminates false lines. During the line reconstruction stage, interruptions caused by descending or ascending strokes are restored.

Finally, the X-axis projection determines word boundaries and filters out false word segments, preserving only genuine text regions. Experiments conducted on 150 IAM manuscript pages (1353 lines) yielded a 99% line-detection accuracy and a 1% false-line rate, confirming the method's high precision, low computational cost, and robustness to variations in illumination, skew, and noise.

Du, X., Pan, W., and Bui, T. D. proposed a script-independent text-line segmentation algorithm based on the Mumford–Shah variational model. The method focuses on processing overlapping or broken lines in free-style handwritten documents. The algorithm models the image as two homogeneous regions—text and background—and minimizes the Mumford–Shah energy functional under a piecewise-constant approximation using the level-set method, thus eliminating the need for explicit iteration control. The procedure consists of three stages:

- (1) Gaussian blurring to enhance horizontal line continuity,
- (2) MS-model-based segmentation to isolate text regions, and
- (3) morphological erosion and dilation to remove overlapping areas and reconnect broken lines.

Compared with previous level-set-based methods, this approach is faster, parameter-free, and more robust to merged or fragmented text lines. It is considered an efficient alternative to the Mumford–Shah functional for analyzing multi-script handwritten documents.

Papavassiliou, V., Stafylakis, T., Katsouros, V., and Carayannis, G. introduced two novel approaches for line and word segmentation in handwritten documents. They formulated line segmentation as a Viterbi algorithm problem, identifying sequences of text and gap regions along vertical zones. For each zone, text boundaries are modeled using a Hidden Markov Model (HMM), and smoothed projection profiles are employed for fine segmentation. Separators between zones are merged based on proximity and character density, while connected components are assigned to the corresponding lines or separated along skeleton paths when necessary. For word segmentation, the authors proposed a new gap metric based on a soft-margin linear SVM, which evaluates the separation degree between consecutive components and classifies gaps as either “intra-word” or “inter-word.” The boundary threshold is automatically selected across the entire page using kernel density estimation, resulting in a flexible and statistically robust segmentation approach compared to earlier script-dependent methods.

Alaei, A., Pal, U., and Nagabhusan, P. proposed a novel script-independent algorithm for text-line segmentation in freehand handwritten documents. To overcome the limitations of projection and Hough-transform-based techniques, they introduced a “piecewise painting” algorithm, a new technique that divides the image vertically and smooths black (text) and white (background) regions within each block, improving the precision of line separation. Then, morphological dilation is used to merge each line into a single component, while morphological thinning is applied to background regions to generate candidate separator lines. These lines are analyzed and merged based on length, orientation, and proximity, yielding the final segmented lines. The algorithm effectively addresses issues of touching and overlapping characters: in the first case, segmentation is based on minimum stroke thickness, and in the second, components are assigned to their correct line via contour tracing.

Ryu, J., Koo, H. I., and Cho, N. I. developed a parameter-free line segmentation algorithm capable of handling various writing styles without modification. The method is based on connected component analysis, normalizing overly merged components and ensuring consistent interpretation across different scripts and handwriting types. The algorithm consists of three stages: connected component segmentation and normalization, component evaluation, and energy minimization-based line formation, together enabling robust line detection across diverse handwritten documents.

Saabni, R., Asi, A., and El-Sana, J. proposed a language-independent and binarization-free algorithm for text-line segmentation in historical manuscripts. Their approach constructs an energy map by combining character distance transform and gray-level distance transform, and identifies text lines through minimal-energy paths using dynamic programming. The gray-level algorithm eliminates the binarization step entirely, locating the median and boundary lines of each text row using medial and border maps. The method was tested on Arabic, English, Spanish, and Chinese scripts, achieving approximately 98% accuracy on ICDAR 2009 and specialized historical datasets. It remains stable even in documents with uneven, noisy, or curved lines. The authors highlighted the method's advantages: no need for binarization, language independence, and high precision.

Kavitha, A. S., Shivakumara, P., Kumar, G. H., and Lu, T. proposed a new segmentation technique for historical Indus manuscripts, which are degraded, low-contrast, and have uneven backgrounds—conditions under which traditional methods fail. Their approach is based on the observation that text components tend to be less branched and smoother, while non-text components (such as decorative or animal figures) exhibit higher branching. To address this, they combined Sobel and Laplacian filters and used gradient intersections to enhance low-contrast text areas. A skeleton is then extracted from the image, and highly branched components

are discarded as non-text. In the next step, nearest-neighbor clustering groups components based on spatial proximity into text and non-text clusters. The number of branches in each cluster is analyzed—clusters with fewer branches are labeled as text, while those with more are classified as non-text. This technique provides a robust, language-independent segmentation method for degraded and noisy epigraphic documents, demonstrating the efficiency of Sobel–Laplacian fusion and clustering-based analysis.

Khare, V., Shivakumara, P., Navya, B. J., Swetha, G. C., Guru, D. S., Pal, U., and Lu, T. introduced a “Weighted-Gradient Features (WGF)” method for handwritten line segmentation that operates without binarization and is independent of writing system or language. The core idea is to reduce line overlapping by enhancing the middle zone of text through a combination of zero-crossing points and gradient magnitudes. First, Canny edge detection is applied to compute zero-crossing points along text lines, which are then weighted by gradient values to generate a weighted-gradient image. Next, K-means clustering (K=2) separates text and background pixels. Morphological filtering and PCA-based linearity analysis are used to determine text-line orientations and progressively separate touching lines. The method was evaluated on multilingual datasets (English, Hindi, Tamil, Kannada, Oriya) as well as ICDAR 2013, ICDAR 2015-HTR, and Alaei datasets, achieving an F-measure of about 97–98%. It performed robustly on noisy and low-quality documents.

Grüning, T., Leifert, G., Strauß, T., Michael, J., and Labahn, R. proposed a two-stage approach for text-line detection in historical documents. In the first stage, an ARU-Net neural network classifies each pixel as a baseline, separator, or background. In the second stage, the results are clustered to form the final baselines. This two-stage method provides an accurate, stable, and efficient solution for curved, irregular, and complex historical documents.

Kurar Barakat, B., Cohen, R., Droby, A., Rabaev, I., and El-Sana, J. developed an unsupervised, binarization-free segmentation algorithm for historical manuscripts. It detects streak-like lines crossing text rows using anisotropic Gaussian filters, and converts them into valid text lines through graph-cut optimization. The method automatically adapts to various font sizes via auto-scale selection and a component tree structure, correctly separating touching characters. Tests on cBAD and DIVA-HisDB datasets achieved F-measure = 86.38% and Line IU = 99.46%, respectively. The algorithm is fast, unsupervised, and language-independent, performing effectively on curved, blurred, and low-quality historical pages.

Hu, P., Wang, W., Li, Q., and Wang, T. proposed a method for segmenting overlapping text lines in Tibetan Uchen manuscripts, based on local baseline detection and connected component distribution. The process begins by identifying false lines through horizontal projection and straight-line detection, followed by local baseline extraction. A convolutional neural network then distinguishes between character-to-character and character-to-line overlaps. Finally, skeletonization and watershed segmentation algorithms separate connected components, which are subsequently assigned to appropriate lines according to their position relative to the baseline. The method demonstrated high accuracy in processing curved, distorted, overlapping, and broken lines, proving to be a robust, efficient, and binarization-free solution for Tibetan Uchen manuscripts.

Sahare, P., Tembhurne, J. V., Parate, M. R., Diwan, T., and Dhok, S. B. introduced a graph-based shortest-path approach for script-independent document segmentation. The method treats each pixel as a node and applies the Dijkstra algorithm to identify text-line boundaries through the shortest paths. An energy map is then generated via wavelet transform, and Gaussian filtering with connected component analysis is used to isolate words. The algorithm functions without binarization or language constraints and remains stable on curved or noisy documents, making it an effective and generalized segmentation technique for multi-script historical manuscripts.

Kumar, J., Abd-Almageed, W., Kang, L., and Doermann, D. addressed the text-line segmentation problem in handwritten Arabic manuscripts, tackling challenges such as diacritical marks, curved writing, and closely spaced lines. They modeled the segmentation as a graph-based clustering task, where each connected component’s local orientation is calculated to construct sparsity-based similarity graphs. Lines are first detected using Breadth-First Search (BFS), then refined through proximity-based clustering that automatically determines the number of clusters—eliminating the need for prior knowledge of line count. Diacritical marks are assigned to their respective lines based on bounding box and orientation line analysis. Experiments on a dataset of 125 Arabic pages (1974 lines) achieved up to 95% accuracy. The method performed effectively on curved and densely written lines while maintaining computational efficiency, though minor errors occurred in fully detecting diacritics and tightly touching characters. Overall, the integration of global graph analysis with local orientation estimation makes it a powerful technique for curved-line Arabic manuscripts.

Garz, A., Fischer, A., Sablatnig, R., and Bunke, H. proposed a novel binarization-free approach for text-line segmentation in historical manuscripts. The goal of the study was to develop a segmentation method robust to noise on parchment backgrounds (a writing material made from animal skin), ink bleed-through, stains, and touching text lines. The proposed algorithm works directly on grayscale images, completely avoiding errors that typically arise during binarization.

The algorithm operates through several stages:

1. Interest Point Detection – Local structures such as stroke ends, curves, and junctions are detected using Gaussian difference filtering, forming a simplified model of the document image.
2. Word Clustering – Using the DBSCAN clustering algorithm, high-density points are grouped, each cluster enclosed in a minimal bounding box, with the main text orientation automatically estimated.
3. Component Separation – Overlapping upper and lower parts are separated via linear-scale normalization, identifying minimal-energy paths that respect character shape boundaries.
4. Line Reconstruction – Word clusters are linked with neighboring clusters along the main text direction, and the resulting chain of clusters forms final text lines, merged through a probabilistic map.

This algorithm does not rely on page layout analysis and is independent of language, script, or background conditions. Therefore, it is particularly well-suited for historical documents, uneven pages, or low-contrast texts. The study demonstrated the effectiveness of binarization-free segmentation and established a new paradigm in this field.

Renton, G., Chatelain, C., Adam, S., Kermorvant, C., and Paquet, T. introduced a deep-learning-based approach for handwritten text-line segmentation using a fully convolutional network (FCN) model. The authors represented each text line by its average height, which eliminated problems caused by overlapping lines. The network architecture comprises seven layers: the first two are standard convolutional layers, the next four use dilated convolutions with dilation rates of 2 and 4, and the final layer performs classification. This architecture completely removes the need for a merging stage while preserving spatial relationships between lines.

Vo, Q. N., Kim, S. H., Yang, H. J., and Lee, G. S. also proposed an FCN-based method for handwritten document segmentation. Their model labels each pixel as text or background, generating a line map. A line adjacency graph (LAG) is then applied to this map to correctly assign touching or partially overlapping characters to their respective lines. The FCN-pool3 architecture achieved outstanding results with F-measure = 98.56%, recognition accuracy (RA) = 98.68%, and detection rate (DR) = 98.45% on the ICDAR 2013 dataset, remaining stable for text lines slanted up to $\pm 5^\circ$. The approach offers fast processing (≈ 5 seconds per page on GPU), language independence, and compatibility with multilingual documents (English, Greek, Bengali). The study proved that the FCN+LAG combination outperforms traditional geometric methods for handwritten text-line segmentation.

Daldali, M., and Souhar, A. proposed a content-preserving rescaling technique for Arabic handwritten manuscripts. The algorithm operates directly on grayscale images, using energy maps to find the lowest-energy paths corresponding to text-line boundaries. It applies dynamic programming to detect inter-line gaps and then merges local maxima via projection-profile analysis to construct the final baselines. The method is binarization-free, language-independent, and robust to curved or overlapping text lines, making it a reliable segmentation technique for degraded historical Arabic documents.

Gader, T. B. A., and Echi, A. K. introduced a deep-learning model named AR2U-Net for Arabic handwritten text-line segmentation. Based on the U-Net architecture, it incorporates residual blocks, recurrent convolutions, and an attention mechanism, enhancing performance in detecting complex, curved, and overlapping lines. The AR2U-Net method is recognized as an advanced, binarization-free, and language-independent model that performs robustly on intricate Arabic manuscripts.

Mechi, O., Mehri, M., Ingold, R., and Essoukri Ben Amara, N. proposed a two-stage deep-learning framework for text-line segmentation in historical Arabic and Latin manuscripts. In the first stage, several fully convolutional networks (U-Net, Dilated FCN, RU-Net, Adaptive U-Net) were compared, with Adaptive U-Net found to be the most effective for detecting the X-height (main text body) region of text. In the second stage, structural post-processing was applied, reconstructing final text baselines using sequence-length smoothing and diacritic component analysis. The proposed two-stage model successfully combines deep learning and structural analysis, achieving high-precision, language-independent segmentation even on complex, curved, and noisy historical documents.

Barakat, B. K., Droby, A., Alaasam, R., Madi, B., Rabaev, I., and El-Sana, J. developed a two-stage approach for handwritten text-line segmentation based on a Fully Convolutional Network (FCN) and energy minimization. In the first stage, the FCN identifies streak-like lines corresponding to text rows; in the second stage, a graph-cut optimization method assigns each pixel to its respective text line. The approach incorporates Gestalt's principle of proximity, taking into account the spatial coherence of visual elements, which enables accurate segmentation of curved, overlapping, and irregular-height lines. The method was evaluated on the VML-AHTE, VML-MOC, and DIVA-HisDB datasets, achieving F-measure = 94.3%, 68.7%, and Line IU = 100%, respectively. The proposed FCN+EM model operates without binarization, is language- and orientation-independent, and provides an effective segmentation solution for complex, curved, and uneven historical documents.

Droby, A., Kurar Barakat, B., Alaasam, R., Madi, B., Rabaev, I., and El-Sana, J. presented a Mask R-CNN–based deep-learning algorithm for text-line segmentation in historical manuscripts. The main idea is to divide the page into smaller patches and segment line fragments within each patch using Mask R-CNN; these are then merged into full-page lines via a line-aggregation algorithm. To refine results, an enhancement stage automatically corrects merged or split lines. The algorithm performs well without binarization and can handle Arabic manuscripts with diacritics, curved, intersecting, or uneven lines, producing higher accuracy than previous deep-learning methods.

Özşeker, İ., Demir, A. A., and Özkaya, U. proposed a Generative Adversarial Network (GAN)–based model for text-line segmentation in complex handwritten documents. The segmentation task is formulated as an image-to-image translation problem, where the model generates corresponding line masks for each input document image. The GAN architecture consists of a U-Net generator and a PatchGAN discriminator. The proposed GAN-based method effectively detects historical, curved, multi-directional, and overlapping lines, offering binarization-free and language-independent segmentation. Moreover, it achieves higher accuracy than Mask R-CNN and FCN+EM approaches.

CONCLUSIONS AND SUGGESTIONS

This study consolidates both traditional and modern approaches to text-line segmentation in handwritten and historical documents, clearly illustrating their evolutionary development. The analysis covers methods ranging from projection, Hough, and morphological techniques to probabilistic, energy-minimization, graph-based approaches, and modern deep-learning architectures such as ARU-Net, Adaptive U-Net, Mask R-CNN, and GAN. Findings indicate that binarization-free, language-independent, and adaptive methods perform more robustly under challenging conditions such as curved baselines, touching characters, uneven backgrounds, and noise. However, challenges remain for dense lines, strong degradation, and diacritic marks. Promising future directions include integrating multimodal features, self-supervised learning, and adaptive post-processing mechanisms. This comprehensive analysis provides a strong scientific foundation for improving digitization processes and establishing more consistent and equitable evaluation metrics in historical document segmentation research.

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