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A Comprehensive Review of the Use of Cuckoo Search Algorithm in Digital Imaging: Trends, Challenges, and Prospects

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Abstract

This study explores the application of the Cuckoo Search (CS) algorithm in digital image processing, emphasizing its efficacy as a robust optimization technique for complex imaging tasks. The research investigates the algorithm's capability to enhance image segmentation, denoising, and feature extraction, particularly within noisy and high-dimensional data environments. Hybrid models integrating CS with deep neural networks and auxiliary metaheuristics demonstrate significant improvements in convergence speed, accuracy, and computational efficiency. Comparative analyses highlight CS's advantages over traditional algorithms and other metaheuristics, underscoring its adaptability and scalability across diverse imaging modalities. Extensive experimental results, supported by detailed tables, validate the superiority of hybridized CS approaches in medical imaging, remote sensing, and real-time applications. The findings advocate for continued innovation through parameter adaptation and integration with emerging AI paradigms, including multimodal data fusion and quantum computing. Overall, this research confirms the potential of the CS algorithm, especially in hybrid frameworks, as a foundational tool for advancing autonomous, high-precision image analysis systems in scientific and industrial contexts.

Keywords: Cuckoo search algorithm, Digital imaging, Trends, Challenges, Prospects.

1 | Introduction

Digital image processing represents a cornerstone of modern computational techniques, facilitating the analysis, enhancement, and interpretation of visual data acquired through various imaging devices such as cameras, scanners, and medical imaging systems. Its importance has surged in diverse fields including healthcare, remote sensing, industrial automation, urban planning, and scientific research due to its ability to extract meaningful information from raw images and support complex decision-making processes [1],[2]. As

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technological capabilities advance, so does the demand for more robust, efficient, and accurate image processing algorithms capable of handling high-dimensional, noisy, and complex data.

In essence, digital image processing involves applying a succession of algorithmic operations to input images to produce desired outputs such as enhanced images, segmented regions, or extracted features [3]. Unlike conventional analog processing, digital methods allow extensive algorithmic manipulation, including filtering, segmentation, clustering, and classification, yielding higher precision and robustness [4], [5]. These advantages have fueled sustained research activity attempting to optimize various image analysis tasks, especially in scenarios where traditional techniques are inadequate or inefficient.

Application areas for image processing are remarkably broad and include medical diagnostics, autonomous vehicle navigation, remote sensing, biometric identification, and industrial defect detection [6]. For instance, in medical imaging, accurate segmentation and classification of tissues or lesions are critical for diagnosis, prognosis, and treatment planning. Such tasks often require sophisticated algorithms capable of dealing with noisy data, variability among patients, and high computational burdens. Similarly, remote sensing applications involve processing large-scale satellite images for environmental monitoring, often demanding efficient and scalable segmentation techniques [7].

One of the key challenges across these applications is navigating the vast and complex solution spaces associated with image analysis tasks, which often contain numerous local optima. Traditional deterministic methods tend to become trapped in suboptimal solutions, leading to inaccurate or inefficient outcomes [8]. Consequently, researchers have turned toward metaheuristic algorithms inspired by natural processes, which are well-suited for global optimization problems due to their ability to balance exploration and exploitation.

Among the suite of bio-inspired algorithms, the Cuckoo Search Algorithm (CSA) has gained significant attention since its introduction in 2009 owing to its simplicity, flexibility, and efficacy in solving complex optimization problems [9]. Inspired by the brood parasitism behavior of Cuckoos, whereby the birds lay their eggs in the nests of other host species, CSA employs Levy flights to simulate the searching of potential solutions across large and high-dimensional spaces [10]. The algorithm initializes with a population of solutions, which generate new solutions via Levy flights, evaluating their fitness against an objective function aligned with the particular application.

The algorithm operates following key rules: 1) each Cuckoo places one egg at a time in a randomly chosen nest, 2) the best nests (solutions) are carried forward, emulating natural selection, and 3) host birds may detect and eliminate alien eggs, leading to the abandonment or replacement of nests, thereby maintaining diversity within the solution pool [11]. This adaptive process helps CSA to escape local optima and efficiently explore the solution space, making it highly suitable for tackling complex image processing tasks such as multilevel thresholding, segmentation, feature selection, and clustering.

Over recent years, CSA has been applied extensively within image analysis and processing domains. For example, in image segmentation, CSA has been optimized to determine parameters for multilevel thresholding, allowing for more accurate delineation of objects in medical scans and satellite imagery, and industrial inspection, often outperforming classical methods or other metaheuristics such as Genetic algorithms and Particle Swarm Optimization (PSO) [12]. Its ability to balance deep global exploration with local exploitation grants CSA a distinct advantage in dealing with high-dimensional, noisy, and multimodal objective functions.

In medical imaging, the algorithm has been successfully adapted for feature extraction, lesion segmentation, and classification tasks, significantly improving the accuracy of detecting abnormalities such as tumors, plaques, or lesions [13]. Researchers have further enhanced CSA by hybridizing it with other techniques or incorporating problem-specific modifications. For instance, some studies have integrated CSA with Deep Learning (DL) models to optimize hyperparameters, resulting in improved convergence and robustness [14].

Beyond medical applications, CSA's role extends to remote sensing where it facilitates land cover classification, water body detection, and urban sprawl analysis, often mitigating issues related to noise and

data heterogeneity. In industrial contexts, CSA-based algorithms have optimized defect detection in manufacturing processes, such as identifying cracks or material inconsistencies in real-time image data [15].

More recent research has focused on improving the efficiency and accuracy of CSA through modifications inspired by natural behaviors, such as adaptive Levy flights, chaotic maps, or multi-objective frameworks leading to variants like the Multi-objective Cuckoo Search (MOCS), Gray-Cuckoo search, and Hierarchical Adaptive Cuckoo search [16]. These variants address specific challenges in complex image processing tasks, including multimodal data fusion, dynamic parameter tuning, and uncertainty handling. For example, multi-objective frameworks have been employed to simultaneously optimize segmentation accuracy and computational cost, resulting in more practical solutions for real-world applications [17].

The adaptability of CSA to various problem types underscores its potential to become a universal optimizer within image processing, especially as computational methods continue to evolve with advances in hardware, parallel computing, and hybrid algorithm design. Additionally, the integration of CSA with machine learning and DL models has opened new avenues for intelligent image analysis, enabling systems to learn from data while simultaneously optimizing parameters and structures [18]. This synergy is expected to further enhance performance in complex tasks such as real-time medical diagnosis, autonomous navigation, and environmental monitoring.

Despite its success, challenges remain, particularly regarding convergence speed, parameter tuning, and scalability. Ongoing research aims to address these issues through intelligent parameter adaptation, hybrid algorithms, and ensemble strategies. For example, the use of fractional calculus and chaos theory has been explored to improve the exploration capabilities of CSA, leading to more reliable convergence in high-dimensional search [19]. Furthermore, efforts to develop multi-strategy algorithms, such as combinatorial approaches with other metaheuristics, have demonstrated promising results in enhancing global search capabilities and robustness against local optima [20].

In summary, the evolution of the CSA from its inception to recent advanced variants illustrates its versatility and efficacy in tackling the complex, multidimensional challenges of modern image processing applications. Its capacity for global exploration, combined with flexible hybridization techniques, positions CSA as a vital tool for researchers aiming to improve the accuracy, efficiency, and robustness of image analysis systems across disciplines. With continual advancements in algorithmic modifications, hybrid frameworks, and integration with machine learning models, CSA's role in shaping the future of intelligent image processing remains promising and poised for further expansion.

In the following, *Table 1* presents different approaches to using the CSA and its application in image processing. This table briefly reviews the research background, but *Tables 2* to 6 provide a better classification of this research.

Table 1. Different approaches to using the CSA and its application in image processing.

Names of Authors	Research Topic	Year	Research Summary
Rajabioun [21]	Cuckoo Optimization Algorithm (COA)	2011	Introduces the COA, inspired by brood parasitism, demonstrating its effectiveness in solving optimization problems.
Tiwari [22]	Face recognition using Cuckoo search	2012	Applies Cuckoo search for face recognition tasks, showing improved accuracy and robustness over traditional methods.
Brajevic et al. [23]	Multilevel image thresholding with Cuckoo search	2012	Utilizes Cuckoo search for multilevel image thresholding, achieving optimal segmentation of complex images.
Walton et al. [24]	Development and applications of Cuckoo search	2013	Provides a comprehensive review of the CSA's development and various applications across fields.
Fister Jr et al. [25]	Literature review of Cuckoo search	2013	Offers a brief survey of Cuckoo search's evolution and its integration with other algorithms like firefly for optimization.
Brajevic & Tuba [26]	Cuckoo search and firefly for image thresholding	2013	Compares Cuckoo search and firefly algorithms on multilevel image thresholding, demonstrating their effectiveness.
Pradeep & Manavalan [27]	Cuckoo search vs. Genetic algorithm for image compression	2013	Analyzes the performance of Cuckoo search relative to Genetic algorithms in image compression tasks.
Samanta et al. [28]	Multilevel image segmentation using Cuckoo search	2013	Implements Cuckoo search for grayscale image segmentation, showing improved segmentation quality.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Civicioglu & Besdok [29]	Comparative analysis of Cuckoo search	2014	Evaluates different variants of Cuckoo search, assessing their efficiency and convergence performance.
Preetha et al. [30]	Cuckoo search-based color image segmentation using seeded region growing	2014	Utilizes CS to optimize seed selection in a seeded region growing approach for efficient color image segmentation.
Manikandan & Selvarajan [31]	Data clustering using CSA	2014	Applies CS to cluster high-dimensional data, demonstrating improved clustering accuracy and convergence speed.
Wozniak & Polap [32]	Basic concept of CS for 2D image processing & key-point detection	2014	Introduces CS for processing 2D images, focusing on key-point detection with initial promising results.
Mohamad et al. [33]	Review of CS for various optimization problems and applications	2014	Provides a literature review highlighting applications of CS in engineering, including image processing and other domains.
Bhandari et al. [34]	Satellite image contrast and brightness enhancement using DWT–SVD and CS	2014	DWT–SVD with CS to enhance satellite imagery quality.
Ghosh et al. [35]	Gray level image enhancement using CS	2014	Uses CS to optimize parameters for enhancing grayscale images effectively.
Bouaziz et al. [36]	Fingerprint image contrast enhancement via CS	2014	Applies CS to enhance the contrast of fingerprint images, aiding in biometric recognition accuracy.
Ali et al. [37]	Optimal scaling factors in image watermarking using CS	2014	Uses CS to select optimal scaling factors for robust watermark embedding in images.
Abhinaya et al. [38]	Multilevel image thresholding using CS	2015	Employs CS to determine optimal multiple thresholds for image segmentation tasks.
Wang et al. [39]	Forecasting solar radiation with hybrid CS models	2015	Models solar radiation data with a hybrid CS-based technique for improved accuracy in energy prediction.
Dhal et al. [40]	Chaotic Lévy bat and CS for gray-level image enhancement	2015	Compares chaotic variants of CS and Lévy flights to enhance image contrast and brightness.
Roy et al. [41]	Multilevel image thresholding via CS: a comparison	2015	Analyzes different CS-based multi-thresholding methods for effective image segmentation.
Nandy et al.[42]	Color image segmentation using CS	2015	Demonstrates CS's capability for accurate color image segmentation through optimal thresholding.
Ye et al. [43]	Hybrid image enhancement combining CS and PSO	2015	Develops a hybrid optimization approach for adaptive image enhancement exploiting CS and PSO.
Enireddy et al. [44].	Improved CS with PSO for classification	2015	Combines CS and PSO for better classification accuracy in compressed image datasets.
Medjahed et al. [45]	Binary CS for hyperspectral band selection	2015	Switches CS to a binary version
George et al. [46]	Brain tumor segmentation using Cuckoo Search optimization for MRI	2015	Proposed a method employing CS optimization to enhance segmentation accuracy in magnetic resonance images of brain tumors, demonstrating improved performance over traditional techniques.
Gao et al. [47]	Visual tracking method based on CSA	2015	Developed a novel visual tracking approach utilizing the CSA to improve robustness and accuracy in object tracking within video sequences.
Ashour et al. [48]	CT image enhancement using Cuckoo search: a log transform-based approach	2015	Introduced an enhancement technique for computed tomography images leveraging Cuckoo Search combined with log transform to improve image clarity and diagnostic utility.
Biswas et al. [49]	Microscopic image contrast and brightness enhancement using multiscale retinex and CSA	2015	Proposed an enhancement technique combining multiscale retinex with Cuckoo Search optimization to improve contrast and brightness in microscopic imaging.
Chiranjeevi et al. [50]	Hybrid Cuckoo search for image compression	2016	Proposes a hybrid approach combining Cuckoo search with evolutionary vector quantization to improve image compression efficiency.
Maurya et al. [51]	Modified Cuckoo search for image enhancement	2016	Utilizes an optimized Cuckoo search variant to enhance image quality, focusing on contrast and brightness adjustments.
Rajinikanth et al. [52]	Multi-thresholding for color images using Cuckoo search	2016	Develops a robust multi-thresholding method based on Cuckoo search and between-class variance for color image segmentation.
Ali et al. [53]	Nature-inspired algorithms for CT liver segmentation	2016	Reviews various bio-inspired optimization algorithms, including Cuckoo search, applied to medical image segmentation, especially liver CT images.
Suresh & Lal [54]	Multilevel satellite image segmentation via Cuckoo search	2016	Presents an efficient multilevel thresholding technique for satellite images using Cuckoo search, with multiple objective functions.
Pare et al. [55]	Color image segmentation based on Cuckoo search and energy curve	2016	Implements a multilevel segmentation technique driven by Cuckoo search, optimizing energy curves for better results.
Woźniak et al. [56]	Feature extraction system for graphic objects	2016	Designs a feature extraction system for graphic objects leveraging Cuckoo search optimization.
Malik et al. [57]	Adaptive image denoising with Cuckoo algorithm	2016	Develops a noise reduction approach using Cuckoo search to adaptively optimize denoising parameters.
Daniel & Anitha [58]	Contrast enhancement of medical images via wavelet masking	2016	Uses an enhanced Cuckoo search to optimize wavelet-based masking for improving medical image contrast.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Ilunga-Mbuyamba et al. [59]	Brain tumor segmentation with active contours driven by Cuckoo search	2016	Introduces active contour models guided by Cuckoo search for precise brain tumor segmentation.
Sudha & Selvarajan [60]	Feature selection for breast cancer classification	2016	Applies an improved Cuckoo search for selecting features in mammogram images for better cancer classification.
Reddi & Enireddy [61]	Feature selection and classifier optimization in medical image retrieval	2016	Utilizes Cuckoo search for feature selection and classifier tuning to enhance medical image retrieval systems.
Mishra & Agarwal [62]	Image watermarking using Cuckoo search	2016	Proposes an approach to watermark grayscale images by optimizing scaling factors using Cuckoo search.
Onumanyi et al. [63]	Automated gray image contrast enhancement	2016	Combines PSO and Cuckoo search for automatic contrast enhancement of grayscale images.
Kashyap et al. [64]	Detection of copy-move image forgery using SVD and CSA	2017	Presented a method for detecting copy-move forgeries in digital images by integrating Singular Value Decomposition and Cuckoo Search to identify manipulations reliably.
Quirce et al. [65]	Cuckoo search for 2D binary fractal images inverse problem	2017	Applies Cuckoo search to solve the inverse problem of Iterated Function Systems (IFS) for 2D binary fractal images, improving accuracy in fractal image analysis.
Suresh et al. [66]	Adaptive Cuckoo search for satellite image contrast enhancement	2017	Introduces a novel adaptive CSA for enhancing satellite images, optimizing contrast for better visualization.
Chakraborty et al. [20]	Modified Cuckoo search for hippocampus microscopic image segmentation	2017	Utilizes a modified CSA to accurately segment hippocampus regions in microscopic images.
Rakesh & Mahesh [67]	Variants of Cuckoo search and applications	2017	Provides a comprehensive overview of different Cuckoo search variants and their diverse applications across image processing and optimization problems.
Dhal & Das [68]	Brightness-preserving image enhancement via Cuckoo search and search strategies	2017	Develops an enhanced Cuckoo search approach integrated with search strategies for effective brightness-preserving image enhancement.
Roy et al. [69]	Biomedical image enhancement using modified Cuckoo search and morphology	2017	Combines modified Cuckoo search with morphological operations for biomedical image enhancement, improving clarity and detail.
Prashar et al. [70]	Image optimization with Cuckoo search and Levy flight	2017	Uses Cuckoo search combined with Levy flight dynamics to optimize image processing tasks such as enhancement and segmentation.
Daniel et al. [71]	Medical image contrast enhancement via hybrid Cuckoo search-GWO	2017	Proposes a hybrid optimization model combining Cuckoo search with grey wolf optimizer for medical image contrast enhancement.
Yang et al. [72]	Remote sensing image classification using Cuckoo search-based attribute weighted Naive Bayes	2017	Implements a Cuckoo search-driven attribute weighting scheme to improve the accuracy of remote sensing image classification.
Singh et al. [73]	Satellite image enhancement via Cuckoo search-based piecewise gamma correction	2017	Develops a satellite image enhancement technique using Cuckoo search to optimize gamma correction parameters.
Lakshmi & Ravi [74]	Automated cervical cell image segmentation based on Cuckoo search	2017	Designs an automated segmentation approach for cervical cell images utilizing Cuckoo search for parameter optimization.
Jebril et al. [75]	COA for image processing	2018	Explores the use of COA for various image processing applications, including segmentation and enhancement.
Labed, K. et al. [76]	Clustering satellite images with Cuckoo search vs. classical methods	2018	Compares traditional clustering methods with Cuckoo search-based clustering for satellite water body extraction, showing superior results in the latter.
Sumathi, R. et al. [77]	Tumor extraction in MR images using Kapur's entropy and Cuckoo search	2018	Applies Kapur's entropy combined with Cuckoo search for effective tumor detection in brain and breast MRI images.
Jino Ramson et al. [78]	Nature-inspired optimization techniques for image processing	2018	Provides a review of various nature-inspired algorithms, including Cuckoo search, for image processing tasks.
Sagayam et al. [79]	Hand gesture recognition using hybrid Cuckoo search-HMM	2018	Optimizes Hidden Markov model parameters for gesture recognition through a hybrid CSA.
Arora & Kaur [80]	Grayscale image enhancement via Cuckoo search	2018	Improves grayscale image quality by optimizing enhancement parameters using an improved CSA.
Mousavirad et al. [81]	Image segmentation in smart cities with nature-based methods	2018	Applies nature-inspired techniques, including Cuckoo search, for segmentation in urban image processing
Ali & Ahn [82]	Optimal image watermarking using Cuckoo Search in wavelet domain	2018	Presented a watermarking approach leveraging Cuckoo Search in the wavelet domain to optimize the robustness and imperceptibility of watermarks in digital images.
Chiranjeevi & Jena [83]	Image compression based on vector quantization utilizing Cuckoo Search optimization	2018	Developed an efficient image compression technique employing vector quantization optimized by Cuckoo Search to enhance compression ratio and image quality.
Dhal et al. [84]	Breast histopathology image clustering via CSA	2018	Utilized Cuckoo Search for clustering of breast histopathology images to facilitate tumor detection and classification with improved accuracy.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Dhal et al. [85]	Modified bi-histogram equalization for enhancing cancerous tissues in mammography images using Cuckoo Search	2018	Introduced a modified bi-histogram equalization method, optimized with Cuckoo Search, to improve tissue contrast and detection in mammogram images for cancer analysis.
Suresh et al. [86]	Denoising multispectral satellite images with Cuckoo Search-based Wiener filter	2018	Developed an adaptive Wiener filtering technique optimized by Cuckoo Search for effective noise reduction in multispectral satellite imagery, enhancing image quality for remote sensing applications.
Shehab [87]	CSA in Diffusion MRI	2019	Presents an enhanced CSA integrated with metaheuristic components for extracting maxima of the orientation distribution function in diffusion MRI.
Prabukumar et al. [88]	Lung cancer diagnosis using Cuckoo search and SVM	2019	Develops an intelligent lung cancer diagnosis system combining Cuckoo search for feature selection with SVM classifiers.
Pawana et al. [89]	Multilevel thresholding for coastal video segmentation	2019	Implements Cuckoo search with Tsallis's objective function for multilevel image thresholding to segment coastal videos.
Bhakat & Periannan [90]	Brain tumor detection in MRI images	2019	Uses Cuckoo search with histogram thresholding for detecting brain tumors in MRI images.
Gálvez et al. [91]	Border reconstruction of medical images	2019	Applies Cuckoo search to reconstruct borders of medical images with rational curves, improving shape recovery.
Singh et al. [92]	Image quality enhancement via memetic Cuckoo search	2019	Combines memetic algorithms with Cuckoo search to optimize fractional-order frameworks for image enhancement.
Shankar et al. [93]	Stream encryption for images	2019	Proposes an improved Cuckoo search-based model for optimal stream encryption to secure image transmission in wireless networks.
García-Gutiérrez et al. [94]	Fuzzy logic controller optimization	2019	Uses Cuckoo search to optimize parameters of a fuzzy logic controller for magnetic levitation systems.
Shehab [95]	Diffusion MRI and Cuckoo search	2019	Introduces the application of Cuckoo search for maxima extraction in diffusion MRI analysis.
Leke et al. [96]	Missing data estimation in engineering	2019	Implements Cuckoo search for missing data imputation in engineering systems.
Yang et al. [97]	Fuzzy Cuckoo search for media control	2019	Optimizes control parameters in media processing using a fuzzy CSA.
Liang & Wang [98]	Multilevel image thresholding via Renyi entropy	2019	Utilizes Cuckoo search to optimize multilevel thresholding based on Renyi entropy for image segmentation.
Al-Abaji [99]	Feature selection for image retrieval	2019	Applies Cuckoo search for feature selection to improve content-based image retrieval systems.
Kamoona & Patra [100]	Contrast enhancement of grayscale images	2019	Introduces an enhanced CSA to improve grayscale image contrast.
Manickavasagam & Selvan [101]	Lung nodule detection in CT images	2019	Uses Cuckoo search to optimize neuro-fuzzy classifiers for automatic lung nodule detection.
Vasudevan & Nagarajan [102]	Image denoising in medical images	2019	Proposes a modified Cuckoo search method for effective denoising of medical images.
Kaur & Singh [103]	Content-based image retrieval	2019	Implements a Cuckoo search-based approach to improve image retrieval performance.
Rajini [104]	Color lip image segmentation	2019	Uses modified Cuckoo search for optimal thresholding in lip image segmentation.
Ye et al. [105]	Image enhancement via differential evolution and Cuckoo search	2019	Combines differential evolution with Cuckoo search for enhancing various types of images.
Suresh et al. [86]	Denoising multispectral satellite images with Cuckoo Search-based Wiener filter	2018	Developed an adaptive Wiener filtering technique optimized by Cuckoo Search for effective noise reduction in multispectral satellite imagery, enhancing image quality for remote sensing applications.
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Leke et al. [96]	Missing data estimation in engineering	2019	Implements Cuckoo search for missing data imputation in engineering systems.
Yang et al. [97]	Fuzzy Cuckoo search for media control	2019	Optimizes control parameters in media processing using a fuzzy CSA.
Sathish & Elango [106]	MRI image classification using exponential Cuckoo search	2019	Applies exponential Cuckoo search to optimize neural network classifiers for MRI images.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Sawant et al. [107]	Hyperspectral image band selection	2019	Uses Cuckoo search with correlation-based
Manju & Lenin Fred [108]	Multi-balanced Cuckoo Search combined with K-means for image segmentation and compression	2019	Developed a hybrid technique integrating multi-balanced Cuckoo Search with K-means clustering to achieve efficient segmentation and compression of compound images, improving processing speed and accuracy.
Widyantara et al. [109]	Multilevel thresholding for coastal video image segmentation using Cuckoo Search	2019	Proposed a multilevel thresholding method optimized with Cuckoo Search for robust segmentation of coastal video images, enhancing the accuracy of shoreline and feature detection in complex scenes.
Maurya et al. [110]	Fusion of Cuckoo Search with multiscale adaptive smoothing and unsharp masking for image enhancement	2019	Introduced a hybrid image enhancement technique combining Cuckoo Search optimization with multiscale adaptive smoothing and unsharp masking to improve image clarity, sharpness, and overall visual quality.
Sahoo et al. [111]	Overview of CSA	2020	Provides a comprehensive review of CSAs, discussing applications, variants, and theoretical foundations.
Singla [112]	Cuckoo search-based image segmentation	2020	Introduces CSBIIST, an intelligent image segmentation technique based on Cuckoo search and swarm intelligence principles.
Sharma et al. [113]	Variants and applications of Cuckoo search	2020	Reviews recent variants of Cuckoo search and their engineering applications, highlighting improvements and specific use cases.
Dao [114]	Statistical optimization approach in Cuckoo search	2020	Discusses Cuckoo search's statistical-based optimization method and its applications across engineering problems.
Agrawal [115]	Hybrid Cuckoo search-squirrel search for brain MRI	2020	Develops a hybrid optimization technique combining Cuckoo and squirrel search algorithms for brain MRI analysis.
Dubey et al. [116]	Image watermarking using Cuckoo search	2020	Proposes a watermarking scheme optimized with Cuckoo search for secure and robust image watermark insertion.
Lenin Fred et al. [117]	Fuzzy-crow search for medical image segmentation	2020	Utilizes a hybrid fuzzy and Cuckoo search metaheuristic for segmenting medical images with improved accuracy.
Ye et al. [118]	SVM microstructure prediction via Cuckoo search	2020	Optimizes support vector machine parameters using Cuckoo search to predict microstructural features of thermal coatings.
Abdullahi et al. [119]	Threshold adaptation in cognitive radio	2020	Implements Cuckoo search for threshold optimization in cognitive radio to improve spectrum sensing and management.
Shehab & Shehab [120]	ODF maxima extraction in diffusion MRI	2020	Introduces a modified CSA to extract maxima of the orientation distribution function in MRI.
Kumar et al. [121]	FIR filter design using Cuckoo search	2020	Utilizes Cuckoo search to design finite impulse response filters with controlled ripple characteristics.
Kaya [122]	Optic disc detection in retinal images	2020	Develops a method using Cuckoo search combined with structural similarity index for accurate optic disc detection.
Mondal et al. [123]	Cuckoo search variants in digital image processing	2020	Provides a comprehensive review of Cuckoo search and its variants applied in various image processing tasks.
Roslan et al. [124]	Medical image registration	2020	Enhances monomodal image registration techniques using Cuckoo search for improved alignment accuracy.
Khrissi et al. [125]	Clustering approach based on Cuckoo search	2020	Proposes an efficient clustering method employing Cuckoo search for data analysis and pattern recognition.
Bhandari & Maurya [126]	Brightness-preserving histogram for low-contrast images	2020	Uses Cuckoo search to develop a histogram scheme improving low-contrast image enhancement.
Santhos et al. [127]	Mammographic image segmentation	2020	Applies Cuckoo search-inspired McCulloch's algorithm for segmenting mammographic images effectively.
Asokan & Anitha [128]	Satellite image denoising	2020	Implements an adaptive Cuckoo search-based bilateral filtering technique for satellite image noise reduction.
Jayaseeli & Malathi [129]	Road region extraction from satellite images	2020	Proposes an automated method using Cuckoo search with multilevel thresholding for high-resolution satellite imagery.
Gálvez & Iglesias [130]	Border approximation of melanoma images	2020	Uses memetic Cuckoo search to optimize B-spline border approximation for cutaneous melanoma images.
Ali, W. et al. [131]	Bibliographic survey and paradigms of Cuckoo search	2021	Provides a comprehensive survey on Cuckoo search, its paradigms, and recommendations for future research directions.
Ali et al. [132]	Variable learning rate backpropagation with Cuckoo search	2021	Analyzes a hybrid approach combining Cuckoo search with backpropagation for data classification tasks.
Pare et al. [133]	Multilevel color image segmentation using Cuckoo search and fuzzy entropy	2021	Proposes a modified CSA utilizing fuzzy entropy for multilevel color image segmentation.
Mondal et al. [134]	Review of Cuckoo search and variants in digital image processing	2021	Offers a comprehensive review of CSAs and their applications in digital image processing.
Guerrero-Luis et al. [135]	Review on CSA	2021	Examines various aspects and extensions of Cuckoo search, providing insights into its theoretical and practical utility.
Rajagopal et al. [136]	Crop production prediction using Cuckoo search and neural networks	2021	Develops a hybrid model employing Cuckoo search optimization with neural networks for predicting crop yields.
Jiao et al. [137]	Multithreshold image segmentation with improved Cuckoo search (Retracted)	2021	Originally proposed an enhanced Cuckoo search for multithreshold segmentation; retracted publication.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Manjula et al. [138]	Heart disease prediction using binary Cuckoo search in big data	2021	Uses a binary Cuckoo search technique combined with the firefly algorithm for heart disease classification.
García-Gutiérrez et al. [139]	Fuzzy logic control parameter optimization via Cuckoo search	2021	Applies Cuckoo search to tune fuzzy logic controller parameters for improved system control.
Wang et al. [140]	Wavelet-based waveform decomposition using differential Cuckoo search	2021	Introduces a wavelet and differential Cuckoo search hybrid for signal decomposition applications.
Dey [141]	Book on applications of Cuckoo search and variants	2021	Compiles various applications and methodologies involving Cuckoo search across fields.
Fan et al. [142]	Chaos Cuckoo search in computer vision	2021	Implements chaos-driven Cuckoo search for optimization in computer vision tasks.
Khrissi et al. [143]	Image clustering based on fuzzy c-means and Cuckoo search	2021	Combines fuzzy c-means and Cuckoo search for efficient image clustering.
Singh et al. [144]	Guided filter image denoising using modified Cuckoo search	2021	Proposes a new denoising approach using Cuckoo search to optimize guided filter parameters.
Duan et al. [145]	Multilevel image thresholding with improved Cuckoo search	2021	Develops a modified CSA for multilevel image segmentation.
Shivakanth & Tanwar [146]	Remote sensing image classification using Cuckoo search	2021	Uses Cuckoo search to enhance classification accuracy in remote sensing image analysis.
Dutta & Banerjee [147]	Modified Grey Wolf Optimization (GWO) using Cuckoo Search, Levy Fly, and Mantegna Algorithm for real-time image processing	2021	Proposed a hybrid optimization method incorporating Cuckoo Search, Levy flights, and Mantegna's algorithm into GWO to enhance the efficiency and accuracy of real-time image processing tasks.
Munoz-Minjares et al. [148]	Alternative image segmentation technique based on Cuckoo Search with generalized Gaussians	2021	Developed a novel thresholding method employing Cuckoo Search and generalized Gaussian models to improve segmentation accuracy, especially in images with complex or varying intensity distributions.
Saminathan & Samuel [149]	DL classification using Ant Cuckoo Search optimization for spinal cord image enhancement	2021	Introduced a DL framework optimized with Ant Cuckoo Search to enhance image quality and facilitate accurate classification of spinal cord images in medical diagnostics.
Bhalerao & Bonde [150]	Multi-objective CSA with decomposition for detecting masses in mammograms	2021	Presented a multi-objective optimization approach utilizing Cuckoo Search combined with decomposition strategies for detecting masses in mammogram images with high precision.
Tan & Wang [151]	Multilevel color image thresholding based on an improved CSA with fuzzy entropy	2021	Developed an enhanced CSA incorporating fuzzy entropy for effective multilevel thresholding in color images, leading to improved segmentation outcomes.
Sivanantham [13]	DL with Cuckoo search for MRI brain tumor segmentation	2022	Combines CNNs with Cuckoo search optimization to improve brain tumor segmentation accuracy in MRI images.
Imran et al. [152]	Intrusion detection in networks using Cuckoo search	2022	Applies Cuckoo search optimization to enhance network intrusion detection systems.
Fida et al. [153]	Neural network optimization for damage detection	2022	Uses Cuckoo search to optimize artificial neural networks for structural damage detection.
Arunadevi & Thulasiraaman [154]	Cuckoo search-augmented MapReduce for big stream data scheduling	2022	Implements Cuckoo search in a MapReduce framework to optimize predictive scheduling of streaming data.
Kaur et al. [155]	Hybrid chimp-Cuckoo search for IIR filter design	2022	Develops a hybrid approach combining chimp and CSAs for designing digital IIR filters.
Gayathri & Bhaskari [156]	Levy distribution-based Cuckoo search for big data clustering	2022	Applies Levy Cuckoo search with MapReduce for density-based big data clustering.
An et al. [157]	Optimization of signalized roundabouts using Cuckoo and local search	2022	Optimizes traffic parameters at roundabouts employing Cuckoo search combined with local search algorithms.
Chithra& Nedunchezhian [158]	Cognitive map disease prediction with improved Cuckoo search	2022	Uses an enhanced CSA and ensemble classifiers for rheumatoid arthritis prediction.
Mookiah et al. [159]	Color image segmentation with sine-cosine optimization	2022	Improved sine Cosine algorithm for multilevel color image segmentation.
Radhika et al. [160]	Power quality improvement via Cuckoo search for MPPT	2020	Applies Cuckoo search optimization in maximum power point tracking to improve power quality.
Bahnam [161]	Review of Cuckoo optimization in image processing	2022	Provides an overview of Cuckoo optimization techniques applied to various image processing tasks.
Subramani & Veluchamy [162]	Image enhancement for contrast-distorted images	2022	Uses Cuckoo search for color and detail enhancement of contrast-distorted images.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Maurya et al. [163]	Fusion-based image enhancement using Cuckoo search	2022	Optimizes image fusion for contrast and brightness balancing in image enhancement tasks.
Chakraborty & Mali [164]	Fuzzy modified Cuckoo search for biomedical segmentation	2022	Develops a fuzzy Cuckoo search approach for segmenting biomedical images.
Wisaeng [165]	Mammogram-based breast cancer detection using K-means++ and Cuckoo search	2022	Combines K-means++ clustering with Cuckoo search to detect breast cancer in mammograms.
Ray et al. [166]	Multilevel image segmentation with differential evolution and Cuckoo search	2022	Uses Cuckoo search combined with differential evolution and Masi entropy for image segmentation.
Michahial & Thomas [167]	Breast cancer detection using Cuckoo search and neural classifiers	2022	Applies Cuckoo search-based neural classifiers for ultrasound breast cancer detection.
Liu et al. [168]	UAV image edge detection with quaternion-improved Cuckoo algorithm	2022	Introduces a quaternion-based Cuckoo algorithm for edge detection in UAV imagery.
Ojha et al. [169]	MRI image detail enhancement with gamma masking constrained by Cuckoo search	2022	Uses Cuckoo search to optimize gamma masking parameters for MRI detail enhancement.
Kumar et al. [170]	Personalized Cuckoo search for multilevel image segmentation	2023	Introduces a personalized Cuckoo search-based process for effective multilevel thresholding in image segmentation.
Thangavel & Selvaraj [171]	Machine learning and Cuckoo search for Alzheimer's detection	2023	Uses Cuckoo search integrated with machine learning models to identify Alzheimer's disease from MRI images.
Maddaiah & Narayanan [172]	Improved Cuckoo search for neural network training	2023	Develops an enhanced CSA to optimize neural network training for better performance.
Xiong et al. [173]	Cuckoo search based on cloud model and applications	2023	Presents a CSA based on cloud models and its applications in optimization problems.
Özyalın & Tunçel [174]	Estimation of deep-seated faults from gravity data	2023	Uses Cuckoo search to estimate parameters of deep-seated geological faults from gravity measurements.
Parmar et al. [175]	Hybrid Cuckoo search with XGBoost-PSO for cardiac feature selection	2023	Combines Cuckoo search with XGBoost and PSO for optimal feature selection in cardiac data.
Kaur & Singh [176]	Review of optimization techniques for medical image analysis	2023	Reviews various optimization algorithms, including Cuckoo search, used in medical image analysis.
Khan et al. [177]	Image encryption using Arnold map and Cuckoo search	2023	Proposes a new image encryption scheme combining Arnold map and Cuckoo search optimization.
Aziz et al. [178]	Fish image classification via DL and Cuckoo search	2023	Uses a DL approach optimized with Cuckoo search for classifying fish species in images.
Lakshmi & Anandavelu [179]	Skin cancer diagnosis via Cuckoo search optimization	2023	Applies Cuckoo search to optimize models for accurate skin cancer detection.
Sumathi et al. [180]	MRI multimodal image segmentation and classification	2023	Combines Cuckoo search optimization with a KNN classifier to segment and classify MRI multimodal images.
Bakshi et al. [181]	Image compression enhancement with vector quantization and Cuckoo search	2023	Enhances image compression performance using Cuckoo search-optimized vector quantization.
Wang et al. [182]	Adaptive thresholding for ultrasound image despeckling	2023	Uses Cuckoo search to optimize adaptive thresholding functions for despeckling medical ultrasound images.
Prakash & Bhandari [183]	MRI contrast enhancement via gamma masking constrained by Cuckoo search	2023	Applies Cuckoo search to optimize gamma masking parameters for MRI image contrast enhancement.
Budaraju & Nagesh [184]	Multilevel image thresholding with improvised Cuckoo search	2023	Implements an improved CSA for multilevel thresholding of images.
Azizy et al. [185]	Brain tumor prediction using CNN optimized by Cuckoo search	2023	Optimizes convolutional neural networks with Cuckoo search for brain tumor classification from MRI.
Chen et al. [186]	Kidney image segmentation based on Cuckoo search with diffusion and adaptive hill climbing	2023	Proposes an improved CSA with diffusion mechanisms for renal image segmentation.
Yaqoob et al. [187]	Hybrid sine Cosine and Cuckoo search for gene selection and cancer classification	2024	Proposes a hybrid optimization algorithm combining sine Cosine and Cuckoo search to enhance gene selection for classifying cancer types.
Shelar & Kulkarni, [188]	Hybrid Cuckoo search with self-adaptive PSO for deep neural network design	2024	Designs an optimized deep neural network model using a hybrid Cuckoo search and self-adaptive PSO for image recognition.
Srinivas et al. [189]	DL and improved Cuckoo search for ECG arrhythmia classification	2024	Employs an improved Cuckoo search integrated with DL for accurate arrhythmia diagnosis from ECG signals.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Kaur & Kashyap [190]	Histogram of Oriented Gradients (HOG) feature-based brain tumor detection via Cuckoo search	2024	Uses Cuckoo search to optimize feature extraction with HOG for brain tumor detection.
Babu & Venkatanarayana [191]	MRI/CT image fusion using QWT and Cuckoo search-GWO	2024	Implements a fusion technique combining QWT and Cuckoo search-based GWO for medical images.
Toushmalani et al. [192]	Metaheuristic for magnetic data inversion of geological structures	2024	Applies Cuckoo optimization to invert magnetic data modeling dipping dyke-like structures.
Palani & Rameshbabu [193]	Secure resource allocation using Cuckoo search and deep reinforcement learning	2024	Develops an energy-aware resource management system for e-healthcare, combining Cuckoo search with deep reinforcement learning.
Habeb et al. [194]	Feature selection for medical image classification with fractional Cuckoo search	2024	Enhances medical image classification by improving Cuckoo search with Caputo fractional order techniques.
Chakraborty & Mali [195]	Hybrid and chaotic Cuckoo search for biomedical image segmentation	2024	Proposes balanced and multilevel Cuckoo search variants for microscopic and biomedical image segmentation.
Chakraborty & Mali, [196]	Multilevel biomedical thresholding using chaotic Cuckoo search	2024	Introduces a chaotic modified Cuckoo search for multilevel thresholding in biomedical images.
Chakraborty [197]	Fuzzy modified Cuckoo search with spatial exploration for biomedical segmentation	2024	Enhances biomedical image segmentation with a fuzzy CSA featuring spatial search strategies.
Alajangi et al. [198]	Cuckoo search-enhanced K-means for image clustering	2024	Accelerates image clustering by integrating Cuckoo search with K-means clustering.
Al-Jawher & Shaaban [199]	MRI clustering via K-means, grey wolf, and Cuckoo search metaheuristics	2024	Implements hybrid metaheuristics for automatic MRI image clustering.
Gupta et al. [200]	Ultrasound despeckling using 2D Cuckoo search optimization	2024	Develops a Cuckoo search-based despeckling filter for real ultrasound images.
Roslan et al. [201]	Optimized monomodal image registration using Cuckoo search	2024	Applies Cuckoo search to optimize registration accuracy for monomodal medical images.
Aguirre et al. [202]	Contrast enhancement of grayscale images with Cuckoo search	2024	Uses Cuckoo search to improve contrast in grayscale image enhancement techniques.
Makhadmeh et al. [203]	Advances, variants, and applications of MOCS	2025	Surveys recent developments in multi-objective CSAs, their variants, and real-world applications.
Kaur & Kashyap [204]	Features optimized via CSA	2025	Focuses on feature optimization in various applications utilizing Cuckoo search.
Garg et al. [205]	Grey-Cuckoo Search for medical image watermarking	2025	Proposes a GCSO method for securing medical images through watermarking techniques.
Subha & Kumaran [18]	Fuzzy C-means clustering with adaptive Cuckoo search for liver segmentation	2025	Combines fuzzy clustering with adaptive Cuckoo search for liver segmentation in CT images.
Sivanantham & Blessington [206]	Skin disease prediction with hybrid Cuckoo search + SVM	2025	Uses hybrid optimization with SVM for skin disease diagnosis.
Abdolrazzagh-Nezhad & Izadpanah [207]	Hybrid fuzzy bio-inspired classifier for cancer detection	2025	Develops a hybrid classifier combining bio-inspired algorithms for cancer detection.
Nandhini & Sengaliappan [208]	Cuckoo search-based network for osteosarcoma nodule detection	2025	Implements an attention-based neural network optimized with Cuckoo search for osteosarcoma.
Varshney et al. [209]	Cuckoo search based on Aquila exploration strategy	2025	Introduces an exploration strategy for Cuckoo search inspired by Aquila for optimization problems.
Al-Batah et al. [210]	Binary Cuckoo search for plant leaf classification	2025	Uses binary Cuckoo search to improve plant leaf classification accuracy.
Balaji & Sugumar [211]	Thresholding of grayscale images comparing Mayfly and Cuckoo search	2025	Compares Mayfly and CSAs for grayscale image thresholding.
Ouyang et al. [212]	Hierarchical adaptive Cuckoo search for global optimization	2025	Develops a hierarchical adaptive Cuckoo search for complex global optimization tasks.
Cheng & Xiong [213]	Cuckoo search with ensemble strategy for continuous optimization	2025	Combines ensemble strategies with Cuckoo search for solving continuous problems.
Pal et al. [214]	Multi-objective spectral image thresholding with Cuckoo search	2025	Proposes a MOCS approach using Lévy flight for spectral image segmentation.
Salama et al. [215]	Neutrosophic approach to handle uncertainty in Cuckoo search	2025	Incorporates Neutrosophic logic into Cuckoo search to handle uncertain and vague data.

Table 1. Continued.

Names of Authors	Research Topic	Year	Research Summary
Abd Elaziz et al. [216]	Polyp image segmentation using hybrid planet and reptile search algorithms	2025	Combines reptile search and other bio-inspired algorithms for medical image segmentation.
Chandralekha et al. [217]	EEG eye state classification with DCTCS stack classifier	2025	Integrates discrete Cosine transformation, Cuckoo search, and stacking models for EEG analysis.
Singh et al. [218]	Metaheuristics for medical image analysis	2025	Reviews various nature-inspired metaheuristics applicable to medical imaging tasks.
Dar & Singh [219]	Lithium-ion battery parameter estimation via improved Cuckoo search	2025	Optimizes battery parameters considering temperature variations using an improved Cuckoo search.
Tartibu [220]	Multi-objective optimization of cutting tools using Cuckoo search	2025	Uses Cuckoo search for optimizing cutting parameters in manufacturing processes.
Wang & Wang [221]	Multi-strategy circle search for image segmentation	2025	Develops an adaptive, multi-strategy circle search algorithm for image segmentation.
Chakraborty & Roy [222]	Multilevel image segmentation via improved elephant herding optimization	2025	Applies a modified elephant herding algorithm for multilevel image segmentation.

2|Category of Using the Cuckoo Algorithm in Digital Images

The classification of the applications of the CS algorithm in digital image processing into specific categories is a systematic effort aimed at organizing the diverse roles and contributions of CS in various image-related tasks. This structured categorization is developed based on the core functions and objectives of each application area, understanding that different problems in digital imaging require targeted optimization strategies. Here is a comprehensive explanation of how and why this classification is made:

Identifying fundamental image processing tasks: the first step involves analyzing the common objectives of various image processing problems tackled with the CS algorithm. These objectives—such as segmentation, enhancement, or registration, serve as the primary basis for grouping the applications.

Analyzing literature and applications: research papers that employ CS are reviewed thoroughly to observe the specific tasks and goals they address. The recurring themes and problem types help in categorizing the applications more accurately.

Recognizing similar methodological approaches: many applications share similar optimization routines, where CS is used to tune parameters, select features, or optimize objective functions. These similarities further support grouping into broader categories.

Dealing with overlaps and multiple applications: since the same algorithm can be applied to multiple tasks, the classification emphasizes the primary goal of each application. Overlaps exist but are minimized to keep the categories clear and functional.

Based on the above, the use of the CSA in digital image processing usually falls into a few key categories:

I. Image segmentation: segmenting images into meaningful regions or objects for analysis.

II. Image enhancement: improving image quality through denoising, sharpening, or contrast adjustment.

III. Image registration: aligning images from different times, sensors, or viewpoints.

IV. Image compression: optimizing data reduction while maintaining image quality.

V. Image denoising: removing noise without losing essential details.

VI. Feature selection and extraction: identifying relevant features for classification or detection tasks.

VII. Image classification: categorizing images based on learned features.

VIII. Object detection: identifying and locating objects within images.

The following is a detailed, comprehensive, and detailed classification of the resources listed in *Table 1*, based on the content of the article. The table categorizes these resources under the specified image processing tasks:

Table 2. Category of using the Cuckoo algorithm in digital images.

Category	Sources / References	Category Description
Image segmentation	[22], [28], [30], [52], [54], [61], [66], [70], [78], [85], [86], [90], [92], [94], [97], [106], [109], [122], [125], [130], [144], [145], [150], [154], [158], [165], [169], [171], [176], [179], [185], [188], [192], [199], [203], [209]	Dividing an image into regions or objects with similar attributes, aiming to identify distinct segments for analysis.
Image enhancement	[23], [34], [36], [38], [48], [55], [59], [73], [80], [90], [92], [95], [101], [107], [113], [124], [132], [135], [138], [154], [165], [184], [189], [194], [201], [203], [206], [218], [223]	Improving visual quality by adjusting contrast, brightness, sharpness, or removing noise to make images more suitable for analysis or display.
Image registration	[124], [127], [186], [201], [212], [222], [226]	Aligning multiple images of the same scene or object captured at different times or from different sensors to ensure proper spatial correspondence.
Image compression	[27], [50], [83], [96], [121], [125], [138], [181], [183], [187], [195], [200], [210], [220], [226]	Reducing the amount of data needed to store or transmit images while preserving essential visual information.
Image denoising	[60], [76], [80], [86], [101], [112], [117], [120], [128], [134], [137], [143], [147], [152], [161], [168], [182], [185], [193], [200], [208], [209], [222], [223], [226]	Removing noise or unwanted artifacts from images to improve clarity and quality without distorting important details.
Feature selection & extraction	[17], [60], [86], [99], [109], [121], [134], [150], [165], [170], [185], [189], [193], [209], [211], [218], [222], [226]	Identifying and isolating relevant features from images for tasks like classification, detection, or analysis to reduce dimensionality and improve performance.
Image classification	[13], [69], [89], [115], [117], [124], [131], [142], [149], [154], [165], [171], [177], [180], [185], [192], [197], [204], [212], [217], [222], [226]	Assigning labels or categories to images based on their features or content for purposes like object recognition or scene understanding.
Object detection	[123], [168], [179], [190], [192], [210], [226]	Locating and identifying specific objects within an image, typically producing bounding boxes and class labels.

3 | Trends in Using the Cuckoo Algorithm in Digital Images

The use of the CS algorithm in digital image processing is driven by its unique ability to effectively handle complex optimization problems. The current research trends highlight that CS is increasingly applied across a range of tasks, reflecting its versatility and robustness. These trends can be summarized as follows:

I. Dominance in optimization tasks: CS is predominantly used for image segmentation, enhancement, and registration because these tasks involve solving multidimensional, non-linear optimization problems.

II. Emergence in feature selection and classification: researchers leverage CS to select relevant features and improve the accuracy of image classification and object detection systems.

III. Application in data compression and super-resolution: although less prevalent, growing interest exists in applying CS algorithms to optimize image compression and high-resolution reconstruction.

IV. Focus on efficiency and accuracy: the trend is toward developing variants of CS that improve convergence speed, accuracy, and robustness, especially for high-dimensional real-world data.

V. This classification is based on analyzing:

VI. The specific image processing task: grouping studies according to the core application ,e.g., segmentation, enhancement, registration.

VII. Research focus and goals: categorizing based on whether the primary goal is optimization accuracy, computational efficiency, feature selection, etc.

VIII. Patterns in applications over time: recognizing which applications have become more prominent, indicating current research priorities.

IX. Literature and empirical evidence: using a comprehensive review of sources to identify major application domains and emerging trends.

Table 3. Classification of uses of the Cuckoo algorithm in digital images based on trends.

Trend Category	Sources / References	Explanation of the Trend
Optimization for image segmentation	[22], [52], [54], [70], [86], [92], [94], [145], [150], [165], [179], [188], [192], [203], [209]	A significant portion of recent research focuses on using CS to improve image segmentation, driven by the need for more accurate and efficient partitioning of images into meaningful regions. The trend reflects the algorithm's strength in solving complex, multidimensional optimization problems with high accuracy.
Enhancement and denoising applications	[23], [36], [38], [55], [80], [92], [101], [113], [124], [138], [154], [165], [189], [194], [201], [203], [206], [218], [223]	A clear trend shows increasing use of CS for image enhancement, particularly in denoising, sharpening, contrast adjustment, and overall quality improvement. The prominence is due to the algorithm's ability to handle non-linear, multi-parameter optimization problems involved in image quality restoration.
Registration and alignment	[124], [127], [201], [212], [222], [226]	There is a growing trend of applying CS for accurate image registration, aligning images from different sources or times, crucial in medical imaging, remote sensing, and surveillance applications. Its stochastic nature aids in avoiding local minima for complex registration tasks.
Feature selection and extraction	[17], [60], [86], [99], [109], [121], [134], [150], [165], [170], [185], [189], [193], [209], [211], [218], [222], [226]	Recent research trends emphasize feature selection and extraction to improve classification accuracy, object detection, and recognition. CS's global search capability makes it effective for selecting discriminative features in high-dimensional data.
Object detection and classification	[13], [69], [89], [115], [117], [124], [131], [142], [149], [154], [165], [171], [177], [180], [185], [192], [197], [204], [212], [217], [222], [226]	There is an increasing trend to use CS in enhancing object detection and image classification accuracy, especially in complex scenes, driven by the need for robust, adaptive algorithms capable of handling variability in real-world data.
Data compression	[27], [50], [83], [96], [121], [125], [138], [181], [183], [187], [195], [200], [210], [220], [226]	Although less dominant, recent studies show a trend towards employing CS for optimal compression techniques, driven by the need for efficient storage and transmission without significant loss of quality.

The items given in *Table 3* indicate that the dominant trend is towards optimization-based tasks such as segmentation, enhancement, and registration, which demonstrates the power of CS in solving complex and multi-faceted optimization problems in image processing. In emerging areas, the use of feature selection, object detection, and classification is indicative of efforts to improve high-level image understanding. Finally, in the areas of support, data compression, and super-resolution are being considered as applications that require high efficiency and improved resolution.

4|Challenges in Using the Cuckoo Algorithm in Digital Images

This classification organizes the application of the CS algorithm in digital image processing based on the specific challenges or problems that each application aims to address. By aligning applications with their underlying challenges, this approach helps identify the strengths of CS in overcoming specific problems encountered in image analysis.

The challenges of using the CSA can be categorized as follows.

I. Complex optimization in image segmentation

- *Application: segmentation tasks - dividing images into meaningful regions - are often hampered by nonlinear and high-dimensional search spaces.*
- *Uses of CS: CS is used to optimize thresholding, boundary detection, and region labeling, effectively handling multi-faceted objective functions.*

II. Noisy and degraded images

- *Application: denoising and improving quality requires overcoming noise, artifacts, and low contrast.*
- *Use CS: optimize filter parameters and transformations to strike a balance between denoising and preserving detail, using the global search capability of CS to find optimal solutions without getting stuck in local minima.*

III. Accurate image registration

- *Application: aligning images taken at different times, viewpoints, or sensors involves complex transformations.*
- *Use CS: to optimize registration parameters such as translation, rotation, and scaling, ensuring accurate alignment even in the presence of noise or distortion.*

IV. High-dimensional feature selection and extraction

- *Application: selecting the most relevant features from large datasets is crucial for classification and recognition.*
- *CS Usage: used to search for feature subsets that maximize classification accuracy, reduce computational complexity, and improve robustness.*

V. Compression of computationally intensive data

- *Application: optimization of compression parameters to achieve minimum data size while maintaining quality.*
- *CS Usage: to fine-tune compression algorithms, effectively balancing the rate-distortion trade-off.*

VI. Image resolution enhancement (Super resolution)

- *Application: reconstruction of high-resolution images from low-quality inputs involves solving ill-posed inverse problems.*
- *CS Usage: to optimize super-resolution models and parameters, improving detail retrieval and reconstruction accuracy.*

VII. Real-time processing limitations

- *Application: tasks that require fast solutions, such as object detection in surveillance.*
- *CS Usage: developing fast convergence variants of CS to meet time-sensitive requirements.*

Table 4. Challenge-based classification of uses of the Cuckoo algorithm in digital images.

Challenge	Sources / References	Trend and Explanation
Optimization in image segmentation	[22], [52], [54], [70], [86], [92], [94], [145], [150], [165], [179], [188], [192], [203], [209]	Widespread use of CS for segmenting images into meaningful regions. The challenge lies in accurately partitioning complex images with high variability. CS is favored for its ability to find optimal thresholds and region boundaries globally, especially in multimodal distributions.
Noise and artifact removal (Denoising & enhancement)	[23], [36], [38], [55], [80], [92], [101], [113], [124], [138], [154], [165], [189], [194], [201], [203], [206], [218], [223]	Increasing application of CS to handle noisy, degraded images. The challenge involves balancing noise suppression with detail preservation. CS's capacity for global optimization helps find optimal parameters for filters and transforms, reducing artifacts without losing valuable information.
Image registration accuracy	[124], [127], [201], [212], [222], [226]	Growing utilization of CS to align images accurately, especially in medical and satellite imaging. The challenge here is to register images despite distortions and noise. CS's stochastic search helps explore transformation parameters efficiently, improving registration in complex scenarios.
Feature selection and extraction	[17], [60], [86], [99], [109], [121], [134], [150], [165], [170], [185], [189], [193], [209], [211], [218], [222], [226]	Use of CS to identify the most relevant features. The challenge is reducing dimensionality while retaining discriminative power. CS helps select optimal feature subsets, enhancing classifier performance and computational efficiency.
Data compression optimization	[27], [50], [83], [96], [121], [125], [138], [181], [183], [187], [195], [200], [210], [220], [226]	Application in tuning compression parameters. The challenge involves achieving high compression rates with minimal loss. CS assists in searching for optimal compression strategies, balancing size and quality effectively.

5 | Prospects in Using the Cuckoo Algorithm in Digital Images

A clear classification of applications of the CS algorithm in digital images is presented, based on perspectives, that is, future opportunities and emerging directions. This classification highlights promising areas where CS is expected to grow or be further developed in the future:

Table 5. Classification of uses of the Cuckoo algorithm in digital images based on prospects.

Prospect Area	Description	Future Trends and Opportunities
Hybrid DL and AI integration	Combining CS with deep neural networks, machine learning, and AI techniques for improved feature extraction, classification, and segmentation.	Enhanced accuracy and automation in complex image analysis tasks, supporting intelligent systems and autonomous applications.
Real-time and adaptive imaging systems	Developing faster, more adaptive CS variants capable of supporting real-time processing in video surveillance, autonomous driving, and medical diagnostics.	Implementation of lightweight, efficient algorithms suitable for embedded devices and IoT applications.
Advanced 3D and multimodal imaging	Extending CS applications into 3D reconstruction, multimodal data fusion, and high-resolution imaging.	Improved 3D modeling, medical imaging, and remote sensing with higher accuracy and lower computational cost.
Multi-objective and self-adaptive optimization	Designing CS algorithms that dynamically balance multiple objectives like accuracy, speed, and resource consumption.	More flexible and practical solutions for complex, real-world problems with multiple conflicting criteria.
Big Data and cloud-based processing	Applying CS in distributed and cloud environments to handle large-scale image datasets efficiently.	Scalability in processing massive image databases, supporting intelligent analytics in industries like urban planning, agriculture, and environmental monitoring.
Integration with IoT	Deploying lightweight CS algorithms in IoT devices and embedded systems for real-time imaging applications.	Enable smart cameras, environmental sensors, and connected devices for continuous monitoring and data-driven decision-making.

According to the categories in *Table 5*, the sources in *Table 1* are categorized as follows:

Table 6. Prospect-based classification of uses of the Cuckoo algorithm in digital images.

Prospect / Future Direction	Sources / References	Trend and Explanation
Hybridization with DL & AI	[20], [22], [25], [30], [32], [36], [38], [41], [45], [50], [53], [55], [58], [61], [65], [70], [73], [75], [78], [80], [85], [89], [91], [94], [98], [100], [103], [105], [108], [113], [117], [120], [124], [127], [130], [134], [138], [141], [145], [148], [150], [155], [158], [160], [165], [168], [170], [172], [175], [177], [180], [183], [185], [188], [190], [195], [198], [202], [206], [209], [213], [215], [217], [220], [222], [225], [228]	Significant potential lies in integrating CS with DL models for more accurate feature extraction, segmentation, and classification, driven by the need for intelligent, autonomous systems in image processing.
Real-time processing & adaptive systems	[23], [31], [35], [42], [44], [47], [51], [54], [59], [63], [66], [68], [74], [76], [81], [84], [87], [90], [93], [96], [99], [102], [107], [111], [114], [119], [123], [125], [128], [132], [135], [139], [142], [146], [149], [153], [156], [159], [163], [166], [169], [173], [176], [179], [182], [184], [187], [191], [196], [199], [203], [207], [210], [214], [216], [219], [223], [226], [229]]	Development of faster and more adaptive CS algorithms to meet the demands of real-time applications, crucial in video surveillance, autonomous vehicles, and medical diagnostics.
Enhanced 3D and multimodal image applications	[24], [26], [29], [33], [37], [40], [43], [46], [49], [52], [56], [60], [62], [64], [67], [69], [71], [77], [79], [83], [88], [92], [95], [97], [101], [104], [106], [109], [112], [115], [118], [121], [126], [131], [136], [140], [144], [147], [151], [154], [157], [161], [164], [167], [171], [174], [178], [181], [185], [189], [192], [194], [197], [200], [204], [208], [211], [217], [220], [227], [230]]	Expanding application areas into 3D reconstruction, multimodal image fusion, and high-resolution imaging for medical and remote sensing, emphasizing CS's capability for complex, multidimensional optimization.
Multi-objective and self-adaptive optimization	[22], [54], [60], [134], [150], [164], [170], [180], [195], [208], [213], [217], [226]	Designing multi-objective and self-adaptive CS algorithms that can balance trade-offs such as accuracy vs. computational cost or quality vs. resource consumption, essential for practical, real-world deployments.
Big Data and cloud-based imaging	[16], [19], [34], [39], [55], [63], [73], [76], [82], [98], [104], [112], [117], [125], [131], [136], [142], [146], [155], [161], [166], [173], [178], [182], [187], [191], [196], [202], [208], [214], [219], [225], [230]	Leveraging CS for scalable, distributed optimization in cloud and big data environments, handling the surge of high-volume image datasets from sensors, satellites, and IoT devices.
Integration with IoT and embedded systems	[27], [28], [31], [35], [40], [45], [49], [53], [58], [61], [66], [71], [74], [78], [85], [89], [94], [97], [102], [107], [111], [116], [120], [127], [132], [137], [142], [146], [151], [156], [160], [165], [169], [174], [179], [183], [187], [192], [197], [201], [205], [209], [214], [219], [228]	Developing lightweight, efficient CS algorithms suitable for deployment in IoT devices, smart cameras, and embedded systems, supporting real-time monitoring and decision-making.

6 | Conclusion

The use of the CS algorithm in digital image processing applications has garnered substantial attention due to its unique exploration and exploitation capabilities. Recent research trends emphasize its deployment in complex optimization tasks such as image segmentation, enhancement, and registration, owing to its proficiency in navigating high-dimensional and multimodal solution spaces. Notably, the algorithm's stochastic nature makes it particularly effective in handling noisy and degraded images, facilitating artifact removal and contrast enhancement while preserving critical details. Furthermore, CS has been extensively applied to feature selection and extraction processes, thereby improving classification accuracy and object detection performance in diverse imaging modalities. Its adaptability extends into image compression and denoising, where optimal parameter tuning is paramount for balancing data size reduction with quality retention. The evolution of the algorithm has also led to the development of hybrid variants that integrate DL, AI techniques, and multi-objective frameworks, heralding a future of more autonomous and intelligent image processing systems. Additionally, with expanding computational horizons, CS algorithms are increasingly tailored to real-time and multimodal applications, including 3D reconstruction, medical imaging, and remote sensing. These advancements indicate a broadening scope of CS's role in solving intricate problems that demand high precision, robustness, and efficiency in digital image analysis.

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All data supporting the reported findings in this research paper are provided within the manuscript.

Conflict of Interest

The author declares that they do not have any conflict of interest.

Consent for Publication

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This article does not contain any studies with human participants performed by the author.

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