BUCHAREST UNIVERSITY OF ECONOMICS STUDIES
Doctoral School of Economic Informatics

DOCTORAL THESIS

Presented and publicly defended by the author:
ALEXANDRU-DANIEL M. STAN

Thesis title:
BIO-INSPIRED COMPUTATION IN IMAGE PROCESSING

Scientific supervisor:
Prof. univ. dr. Cătălina-Lucia Cocianu

Doctoral thesis defense committee:

Prof. univ. dr. Claudiu Herțeliu (chairman)	-	Bucharest University of Economic Studies
Prof. univ. dr. Gabriela Mircea (referent)	-	West University of Timișoara
Prof. univ. dr. Mihaela Muntean (referent)	-	West University of Timișoara
Prof. univ. dr. Paul Pocatilu (referent)	-	Bucharest University of Economic Studies
Prof. univ. dr. Cătălina-Lucia Cocianu (PhD supervisor)	-	Bucharest University of Economic Studies

Bucharest, 2024

BUCHAREST UNIVERSITY OF ECONOMICS STUDIES
Council for Doctoral University Studies
Doctoral School of Economic Informatics

BIO-INSPIRED COMPUTATION IN IMAGE PROCESSING

Alexandru-Daniel STAN

Scientific supervisor: Prof. univ. dr. Cătălina-Lucia Cocianu

Bucharest, 2024

CONTENT

KEYWORDS: bio-inspired computation; image processing; noise removal; image registration; evolutionary strategies; swarm intelligence; particle swarm intelligence; firefly algorithm; accelerated particle swarm intelligence; metaheuristics; hybrid algorithms; memetic algorithms; loss function; fitness function; data filtering; training algorithms;

SUMMARY

Bio-inspired computation represents an interdisciplinary approach that combines principles from biological processes with advanced computing techniques to model efficient and adaptable solutions to challenges in various fields, from banking security to image processing. The most important research directions in bio-inspired computation include evolutionary computing, neural computing, and granular computing. These three directions of bio-inspired computation tend to complement each other and hybridize.

Image processing represents a complex and vast research field, applied in many real-world problems like medical imaging, remote sensing, video surveillance. This field is characterized by a series of essential research and development directions that include image quality enhancement, segmentation and pattern recognition, compression, and image content analysis

Among the fundamental research and development directions addressed in this doctoral thesis are the enhancement of image quality through noise removal and image registration.

The quality and clarity of visual data are essentials in the efficient processing of images, and the presence of noise can compromise these important attributes. Therefore, noise removal is an important preliminary step, essential for preparing images for subsequent operations, such as registration. Noise in images manifests as disturbances or variations in the luminous intensity of pixels that are not present in the original scene, being introduced during the acquisition, processing, or transmission of the image. It negatively affects visual quality, blurring details and reducing the accuracy of visual analysis. Removing noise from images is a critical preprocessing step that facilitates the successful implementation of further processing.

Image registration is a fundamental technique in image processing and analysis, utilized to align two or more digital photographs captured under varying conditions, such as at different times, by different sensors, or from different angles. This technique finds utility in a wide range of fields requiring the analysis or interpretation of information from multiple images. Among these fields, we can list system security, remote sensing, medical imaging, artificial intelligence, astronomy, etc. The interaction between noise removal and image registration becomes a major point of

interest, as the success of registration also depends on the efficiency with which noise is reduced in previous stages.

Exploring bio-inspired computation in image processing represents a major advance in the field of technology. By mimicking the efficiency of biological systems, this approach provides adaptable and robust solutions in image processing, overcoming the limitations of traditional methods. Key aspects of bio-inspired computation in image processing include neural networks, genetic algorithms, evolutionary strategies, and swarm intelligence. Approaches based on bio-inspired computation, anchored in the dynamics of biological systems, have proven particularly adept at managing the complexity of images.

The integration of bio-inspired computation in enhancing image quality through noise removal and image registration has profound implications across multiple disciplines. In medical imaging, it can improve the accuracy of diagnoses; in remote sensing, it enhances the analysis of environmental changes; in security, it strengthens authentication and authorization capabilities. These developments not only push the boundaries of what is achievable in image processing but also highlight the potential of bio-inspired computation approaches to revolutionize technology by mimicking the efficiency and adaptability of natural systems.

In this work, two key areas of image processing were explored through the application of biologically inspired algorithms, providing significant contributions to both the theory and practical application of these algorithms in real-world scenarios.

The first problem addressed is the removal of correlated Gaussian noise from images, integrating decorrelation and compression techniques into advanced neural network architectures. Compared to other methods described in the literature, it was experimentally established that the proposed solution is more efficient according to the main quality evaluation metrics, reinforcing its applicability in various image processing contexts. The experiments conducted confirmed the utility of the proposed methodology in the context of image processing, offering an efficient alternative for the removal of correlated Gaussian noise.

The second problem explored in this thesis relates to image registration, applied in the context of digital signature authentication within banking security systems. The developed methodologies were based on evolutionary algorithms as well as swarm intelligence algorithms, using both standard and enhanced variants of these techniques. Additionally, hybrid and memetic approaches were proposed and implemented, aiming to enhance the performance and quality of the results obtained.

The first proposed methodology in the case of rigid transformation (§5.1.1) and for affine perturbation (§5.2.1) explores the use of evolutionary strategies and the impact of different combinations of recombination and selection operators. The methodology utilizes mutual information as a similarity measure (fitness function). The results were evaluated using both qualitative and quantitative metrics, widely accepted in the literature. The best results were obtained using the $(\mu + \lambda)$ selection mechanism in combination with the proposed convex hybrid recombination schemes for both the solution part and the parameter part. Additionally, the results obtained using the proposed method surpassed the performance of traditional registration methodologies.

The subsequent proposed registration techniques are based on the evolutionary strategy ES (convex hybrid recombination, $(\mu + \lambda)$) combined with the local search algorithm ES-2M (two-member evolutionary strategy) (§5.1.1). In the hybrid implementation, the ES algorithm generates a solution that is subsequently optimized through ES-2M. In the second version, the ES-2M algorithm is directly integrated within the ES, forming a memetic algorithm. The process begins with the use of ES-2M for local improvement of a small fraction of the initial population, thus setting the stage for ES. Subsequently, at the end of each iteration and before the selection of the new generation, if the most performant individual in the current population does not surpass the quality of the best previous individual, a new small fraction of the population is locally optimized using ES-2M. Mutual information ratio is used both as a similarity indicator and as a fitness function. From an accuracy standpoint, the best results were obtained using the memetic algorithm. Conversely, in terms of performance, the best results were achieved using the hybrid algorithm. In both cases, the results obtained were superior compared to the PAT registration and registration algorithms based solely on evolutionary strategies.

Registration methodologies based on the firefly algorithm were also proposed (§5.1.3, §5.2.3). The first method introduced two rules for updating the positions of the fireflies, which consider not only the quality of the attractor but also the values within the variable ranges. In the second method, two new registration approaches were developed that integrate the firefly algorithm with evolutionary strategies. Normalized Mutual Information (NMI) is used as both a similarity metric and a fitness function. The proposed algorithms were tested against other standard algorithms, including PAT registration, yielding positive results. In terms of accuracy, the best results were obtained using the firefly algorithm. In terms of performance, the best results followed from the use of the hybrid algorithm. The results highlight the superior adaptability of hybrid and memetic methods in efficiently registering binary images, achieving near-perfect accuracy with values close to 100%. The developed algorithms stand out due to their remarkable efficiency, demonstrated by significantly reduced running times.

A simplified version of the firefly algorithm, called Accelerated Particle Swarm Optimization (APSO), is used for registering binary images. To enhance the efficiency of the algorithm, new update rules and methods for auto-adapting parameters were proposed. Hybrid variants that are based on ES (Evolutionary Strategies) and APSO were also introduced (§5.2.3). Mutual Information Ratio (MIR) is used as the similarity metric. In terms of accuracy, the best results were obtained using the firefly algorithm. However, the execution time was significant compared to the proposed hybrid algorithms. From this perspective, the ES-APSO algorithm provides good results within a shorter execution time. Additionally, the auto-adaptive version of APSO surpasses both versions of non auto-adaptive APSO in some situations. All results of the proposed methodologies are significantly superior to those obtained using the One Plus One algorithm.

By proposing robust methodologies based on bio-inspired algorithms for the registration of images distorted by rigid and affine transformations, this work contributes significantly to enhancing security through the automatic identification of customers signatures. The proposed algorithms have shown a high success rate according to qualitative and quantitative metrics and have validated their integration into the information systems of organizations such as banks, which process a large number of signatures daily. These techniques have demonstrated the ability to improve accuracy and efficiency in authentication and verification processes, which is crucial in preventing fraud and ensuring a high level of security. By utilizing these methodologies, not only digital signatures but also other types of images can be registered, facilitating implementations in various fields.

For the future, this thesis paves the way for the continuous exploration of bio-inspired algorithms in new and innovative scenarios. With the potential to model and enhance systems in fields such as autonomous navigation, intelligent surveillance, and even natural resource management through remote sensing, research in this area is essential. The integration of these advanced image processing systems will continue to improve human interactions with technology, leading to developments that will shape the future of digital interactions.

The continuation of research and development in this direction promises not only significant technological improvements but also a better understanding and application of biological principles in engineering and computer science, opening new horizons for innovation and progress in the digital age. This thesis thus makes a significant contribution to the field of research, providing a solid foundation for future innovations and the continuous development of bio-inspired applications in information technology and other critical sectors of society.