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Review Article

Swarm Artificial Intelligence in Healthcare and Medicine

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Abstract:

Swarm AI generates a collective solution for a decentralized, self-organizing medical system. Multiple intelligent agents interact according to preset rules without centralized control, forming a complex, intelligent, optimal solution. Each agent exchanges information with its immediate neighbors. The behavior of an individual agent is determined by instructions. Complex group behavior emerges from local interactions. The failure of individual agents does not paralyze the entire system. The system operates efficiently with a changing number of agents. Each agent performs simple actions: reads signals from neighbors, responds to changes in the environment, and follows basic interaction rules. Swarm AI is used in medicine for medical image analysis, biological process modeling, delivery route optimization, traffic management, network routing, load balancing, medical data clustering, neural network training, patient consultations, and other medical services. Swarm AI simplifies programming large swarms (up to 250+ agents). Larry Greenblatt, Chief AI Scientist at Inter Network Defense, is developing a swarm-based, multi-model, multi-system architecture, aligned with the ISO seven-layer OSI model, that can be effectively used in healthcare organization and management, as well as in clinical medicine.

keywords: swarm artificial intelligence; healthcare; medicine; oncology

Introduction

Swarm intelligence is a technology based on the principles of self-organization and collective behavior of decentralized systems [1-7].

Examples of swarm intelligence algorithms:

1. Particle Swarm Optimization (PSO) — for optimizing functions without gradient calculation.

2. Ant Colony Optimization (ACO) — finding routes on graphs (e.g., solving the traveling salesman problem).

3. Artificial Bee Colony (ABC) — simulating bees' search for nectar sources.

4. Intelligent Water Drop Algorithm (IWD) — modeling river flow to find optimal paths.

5. Cuckoo Search Algorithm — based on the behavior of certain cuckoo species, which lay their eggs in the nests of other birds.

6. Gray Wolf Algorithm — imitates the hunting behavior of a wolf pack.

7. Firefly Algorithm — based on modeling the behavior of fireflies.

In healthcare, swarm intelligence opens up new possibilities for solving complex problems that require processing large volumes of data and high accuracy [8].

Key Applications in Healthcare

1. Disease Diagnostics

• Medical Image Analysis (CT, MRI, X-ray, Mammography);

• Early Detection of Pathologies;

• Improving Diagnostic Accuracy through Joint Data Analysis by Multiple Algorithms.

2. Biomedical Data Processing

• Genomic and Transcriptomic Data Analysis;

• Disease Biomarker Identification;

• Disease Development Prediction.

3. Drug Development

• Virtual screening of chemical compounds;

• Optimization of drug molecular structures;

• Prediction of drug interactions with biotargets;

• Use of ant colony and particle swarm algorithms for QSAR-

4. Personalized Medicine

• Selection of individual treatment regimens based on genetic data;

• Prediction of patient response to therapy;

• Creation of digital twins of patients.

5. Patient Monitoring

• Processing data from wearable devices (fitness bracelets, heart monitors);

• Early detection of health deviations;

• Prediction of critical conditions (e.g., sepsis or heart attack).

6. Optimization of Healthcare Facility Operations

• Resource allocation (beds, equipment, personnel);

• Scheduling doctor appointments;

• Drug inventory management.

7. Telemedicine and Remote Monitoring

• Decentralized processing of data from medical devices;

• Ensuring confidentiality when exchanging information;

• Rapid response to emergency situations.

Specific Use Cases

• Swarm Learning is a technology that allows algorithms to be trained on decentralized data. In oncology, it has been used to detect blood cancer and lung tumors with an accuracy of up to 90% for transcriptomes and 76–86% for radiographic data. The original data remains local, and only the model parameters are exchanged.

• Particle Swarm Algorithms (PSO) are used to optimize the parameters of diagnostic models and configure medical devices.

• Ant Algorithms are used to find optimal drug delivery routes and plan surgical interventions.

• Bee Algorithms are used to analyze large sets of clinical data to identify hidden patterns. Advantages of Swarm Intelligence in Healthcare

• Data privacy. Data is not transferred to centralized storage, reducing the risk of leaks.

• Scalability. Systems easily adapt to increasing data volumes and the number of users.

• Fault tolerance. The failure of individual agents does not lead to the failure of the entire system.

• Flexibility. Algorithms can adapt to new conditions and tasks.

• Processing speed. Distributed data processing allows for faster results.

Challenges and limitations

• Data quality. Effective training of algorithms requires representative and well-labeled datasets.

• Computational resources. Some swarm intelligence algorithms require significant computing power.

• Integration with existing systems. Compatibility with medical information systems must be ensured.

• Ethical and legal issues. Clear regulation of the use of AI in medicine is required, including liability issues for errors.

• Interpretability of decisions. The results of swarm algorithms can sometimes be difficult to explain to doctors.

Development Prospects

In the coming years, swarm intelligence is expected to expand its application in:

• early diagnosis of cancer and neurodegenerative diseases;

• creation of adaptive monitoring systems for chronic patients;

• development of personalized therapies based on genomics;

• automation of routine processes in clinics (document flow, planning);

• integration with IoT devices and telemedicine platforms.

Research in this area is increasingly focused on the creation of biological quantum swarm intelligence for technological vision to study molecules, cells, and tissues. Chapter two of this article examines swarm AI in the organization and management of digital healthcare clinics. Chapter three is devoted to swarm AI in medicine. Chapter four demonstrates how swarm AI is being used in oncology.

2. Swarm Algorithm for Interacting Multimodal Intelligent Assistants in a Digital Clinic

Swarm algorithm for interacting multimodal intelligent assistants in a digital intelligent clinic is an approach that combines the principles of swarm intelligence and multimodal systems to optimize the performance of a healthcare organization. This system enables multiple intelligent agents (assistants) to independently interact with each other and the environment, solving problems in a decentralized and self-organizing manner [9].

Fundamentals of Swarm Intelligence

Swarm intelligence is the collective behavior of a decentralized, self-organizing system, where multiple agents interact locally with each other and the environment. Each agent acts autonomously, following simple rules, and does not have a complete understanding of the system as a whole. Over time, the group finds effective solutions through collaboration without centralized control.

Key characteristics of swarm intelligence:

Decentralization. There is no single control center; each agent acts independently.

Self-organization. The system naturally adapts and forms useful patterns without external control.

Simple rules for agents. Agents respond to local information rather than complex data.

Emergent behavior. The combined actions of individual agents lead to complex and intelligent results.

Examples of swarm intelligence algorithms:

- particle swarm intelligence (PSO),

- ant colony intelligence (ACO),

- bee colony intelligence (BCO).

Multimodal Intelligent Assistants

Multimodal assistants are systems that use multiple modes of user interaction (text, voice, images, video, etc.) and process data from different sources. In medicine, such assistants can, for example:

* collect patient complaints via chatbot or voice interaction;

* analyze physiological parameters (heart rate, body mass index, heart rate variability, etc.) from video or other data;

* integrate information from electronic medical records, test results, and other sources;

* offer preliminary diagnoses or recommendations based on data analysis.

Application in a Digital Clinic

In digital intelligent clinic, a swarm algorithm can combine several multimodal assistants, each specializing in a specific aspect of the work. For example:

* one assistant can perform initial data collection from a patient;

* another can analyze medical images (X-rays, CT scans, etc.);

* a third can propose diagnostic hypotheses based on text and numerical data;

* a fourth can coordinate interactions with other systems (electronic medical records, laboratory information systems, etc.).

Agents exchange information, adjust their actions based on data from other assistants, and adapt to changing conditions. This allows for:

* accelerating data processing and decision-making;

* improving diagnostic accuracy through comprehensive information analysis;

* distribute the workload among assistants, which is especially useful during high patient throughput;

* ensure system flexibility—add new assistants or modify existing ones without a major redesign.

Benefits and Challenges

**Benefits:

* System scalability and flexibility.

* Resilience to failures of individual components (fault tolerance).

* Ability to adapt to new tasks and conditions.

* Accelerate data processing and decision-making through parallel agent operation.

**Challenges:

* Complexity of developing and configuring a system where agents must interact correctly.

* The need to ensure data consistency and prevent conflicts between assistants.

* Security and privacy concerns regarding medical data.

* The need for integration with existing medical information systems.

Prospects

The development of such systems could lead to the creation of more intelligent and adaptive medical institutions, where multimodal assistants will work synergistically, improving the quality and speed of medical care. In the future, it is possible to integrate elements of machine learning and deep learning to further improve agent interaction algorithms. However, it is important to remember that the final decision in medicine always rests with the physician, and swarm intelligence-based systems should act as a support tool, not a substitute for clinical judgment.

3. Swarm Artificial Intelligence in Medicine

Swarm intelligence is finding application in several areas of medicine, particularly in pharmacology and bioinformatics [10-20].

1. Computer-aided molecular drug design:

* Modeling the structure of proteins and molecules.

* Predicting structural changes with local modifications.

* Visualizing molecular interactions on a computer screen.

2. Predicting structure–activity relationships (QSAR):

* QSAR (*Quantitative Structure–Activity Relationship*) is a mathematical model linking the structural characteristics of chemical compounds with their biological activity.

* Swarm algorithms help identify **informative descriptors**—the parameters most significant for predicting a substance's activity.

3. Optimizing drug discovery:

* Reducing the time and cost of drug development.

* Analyzing huge databases of chemical compounds to identify promising candidates.

* Example: The **PSOVina** algorithm combines PSO with the BFGS local search method to improve molecular docking.

4. Bioinformatics and Biological Data Analysis:

* Protein structure prediction.

* Clustering of genetic data.

* Energy minimization in biomolecular modeling.

* Analysis of genomic data to identify mutations and disease predispositions.

5. Diagnostics and Medical Data Processing:

* Optimization of diagnostic model parameters.

* Extraction of significant features in medical images (MRI, CT, etc.).

* Improving the accuracy of pathology classification using algorithm ensembles.

6. Personalized Medicine:

* Selection of individual treatment regimens based on genetic and clinical data.

* Prediction of drug side effects using pharmacogenomics.

Examples and Results

The accuracy of biological activity prediction using swarm algorithms reaches 85–90% in some studies.

Reduction in time for analysis and selection of promising molecules compared to brute-force methods.

The effectiveness of particle swarm and ant colony algorithms has been proven in the following tasks:

* Protein structure prediction;

* Molecular docking;

* Genomic data clustering.

Advantages of swarm intelligence in medicine

**Scalability: algorithms work well with large volumes of data.

**Adaptability: capable of finding solutions under uncertainty.

**Parallelism: agents work simultaneously, which speeds up the search for a solution.

**Robustness: the failure of individual agents does not lead to a failure of the entire system.

**Flexibility: applicable to a wide range of tasks, from molecular modeling to diagnostics.

Prospects

The development of swarm intelligence in medicine is associated with:

* integration with other AI methods (neural networks, machine learning);

* creation of hybrid algorithms to improve accuracy;

* expanded application in clinical practice (diagnostics, therapy, monitoring);

* development of specialized software for biomedical research.

Conclusion:

Swarm intelligence is a promising approach for accelerating and increasing the efficiency of medical research, especially in drug development and the analysis of complex biological systems. Its use reduces time and resource costs and improves the accuracy of predictions.

4. Swarm Intelligence in Oncology

One example of the use of swarm intelligence in oncology is a project described in a 2021 study. An international team of researchers applied swarm learning technology to identify blood cancers, lung diseases, and COVID-19 in decentralized data. With this approach, algorithms are trained on local data and only share parameters and training results, ensuring privacy protection. Data classification accuracy reached approximately 90% for transcriptomes and ranged from 76 to 86% for radiographic data. Although the study focused on more than just oncology, it demonstrates the potential of the method for analyzing tumor-related medical data.

Swarm intelligence can also be used in computational molecular drug design. Swarm intelligence methods, such as ant colony algorithms, bee colony algorithms, and particle swarm algorithms, are used to predict the structure-activity relationship (QSAR) of chemicals and develop new drugs. This can be useful for developing drugs that specifically target malignant cells.

In diagnostics, swarm intelligence helps analyze medical images (CT, MRI, X-rays), identifying potential tumors or other pathologies. Computer vision algorithms based on particle swarm principles can process data faster and more accurately than humans.

Prospects and Challenges

Prospects:

**Personalized medicine. Swarm intelligence can facilitate the creation of individualized treatment approaches, taking into account the molecular and genetic characteristics of the tumor and the patient.

**Accelerated research. Joint training of algorithms allows for faster data analysis and the development of new diagnostic and therapeutic methods.

**Improving screening. Technologies can aid in the early detection of cancer, which is critical for successful treatment.

Challenges:

**Need for high-quality data. Representative datasets are required for effective algorithm training.

**Integration into medical processes.

**Swarm intelligence systems need to be adapted to existing clinical workflows.

**Ethical and regulatory issues. Data privacy must be ensured and liability for diagnostic or treatment errors must be defined.

Swarm intelligence represents a promising approach in the fight against malignant tumors, but its full implementation requires further research and the resolution of a number of technical and ethical challenges [21-26].

5. Conclusion

In healthcare and medicine, swarm intelligence is used to solve complex problems that require processing large volumes of data and process optimization. Achievements in this area include:

1. **Medical image segmentation and analysis**. Swarm intelligence algorithms are used to improve the quality of data processing in imaging methods (MRI, CT, etc.). For example, hybrid swarm algorithms can improve the accuracy and speed of magnetic resonance image segmentation. This is necessary for recognizing pathologies, determining tumor boundaries, and other anomalies.

2. **Structure-activity relationship (QSAR) prediction of chemical compounds**. Swarm intelligence methods, such as ant colony and bee colony algorithms, as well as particle swarm algorithms, are used to extract informative descriptors in computer-aided molecular drug design. This helps predict the biological activity of chemical compounds and accelerate the development of new drugs.
3. **Process optimization in pharmaceuticals**. Swarm intelligence is used to solve problems related to finding optimal solutions in the multi-stage drug discovery process. This reduces the time and cost of drug development through efficient exploration of the search space.
4. **Immune network modeling**. Swarm intelligence methods are combined with artificial immune systems to predict the properties of new drugs. Ontological models of swarm intelligence algorithms help structure data and optimize the process of modeling the pharmacological activity of chemical compounds.
5. **Personalized medicine**. Swarm intelligence can facilitate the creation of personalized treatment approaches, taking into account individual patient characteristics, including genetic profile and drug response.

The application of swarm intelligence in medicine requires:

- large volumes of high-quality data for training algorithms;
- interpretation of decisions made by swarm systems;
- compliance with the ethics associated with the use of swarm intelligence in healthcare;
- creation of open interfaces and libraries.

Overall, swarm intelligence opens up new opportunities for improving diagnostic accuracy, accelerating drug development, and optimizing medical processes, but requires further development and addressing a number of technical and ethical challenges [27-33]. Swarm AI has significant potential to transform healthcare. It enables the solution of complex problems requiring high accuracy and big data processing while maintaining information privacy. Despite existing challenges, further development of swarm AI technologies could lead to breakthroughs in diagnostics, treatment, and medical process management, as well as in the organization and management of healthcare.

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