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ANALYSIS OF METHODS, MODELS AND ALGORITHMS FOR A COLLABORATIVE ROBOTS GROUP DECENTRALIZED CONTROL

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Abstract

The article considers modern methods, models and algorithms for a collaborative robots group decentralized control, conducts a comparative analysis, identifies the main advantages and disadvantages. Particular attention is paid to the problems of scalability, coordination and adaptability in dynamic environments. The need to develop new approaches to increase the efficiency of such systems in the context of modern challenges in robotics is outlined.

Keywords: Decentralized Control, Collaborative Robot, Analysis, Models, Methods, Algorithm, Comparative Analysis.

Introduction

A collaborative robots group decentralized control is one of the key topics in modern robotics, which is gaining particular relevance in the context of the transition to Industry 5.0 [1]-[7]. Unlike Industry 4.0, which is focused on the automation and digitalization of production processes, Industry 5.0 focuses on the harmonious coexistence of humans and technologies, ensuring sustainable development and increasing the level of personalization of production [5]-[11].

In this context, groups of collaborative robots play a central role, as they are able to provide flexibility, autonomy and effective interaction in dynamic environments. Various methods and approaches can also be used here [12]-[34]. Research into methods, models and algorithms for decentralized control is an important step in solving many applied problems related to distributed computing, cooperative execution of complex tasks and resource optimization in multi-robot systems.

Despite significant progress in this area, there are a number of challenges related to ensuring the stability and consistency of robot actions, as well as the adaptation of algorithms to unpredictable changes in the environment. Of particular interest are issues of synchronization, interaction under conditions of limited information, as well as modeling robot behavior in the context of swarm intelligence, game theory and multi-agent systems [35]-[44].

The results of research in this area have not only theoretical but also practical value, as they contribute to the creation of effective solutions for application in such areas as production automation, logistics, agriculture, rescue operations and research of hazardous environments.

In this regard, the analysis of existing methods, models and algorithms of decentralized control is necessary to determine the current state of research, identify their advantages and disadvantages and form prospects for further development that meets the requirements of Industry 5.0.

Related works

The increasing implementation of the principles of the Industry 5.0 concept has led to the emergence of new challenges. Among them, we note the emerging need to control a group of robots. Many scientists have been working on solving this problem

Multi-robot driving is a difficult problem [45]. The article [45] discuss how human-robot collaboration and dialogue provide an effective framework for achieving this.

The study [46] proposes a unified group coordinated control scheme for networked multi-robot systems having multiple targets. There is noted that inspired by the group activities of natural swarms (e.g., a flock of birds, a colony of ants, etc.), a fleet of mobile robots can be collaboratively put into work to accomplish complex real-world tasks. So, this is swarm method.

Scientists in [47] identify three core aspects of “Multi-agent” human-robot interaction systems that are useful for understanding how these systems differ from dyadic systems and from one another. Especially they consider systems containing more than two agents (i.e., having multiple humans and/or multiple robots). They summarize key observations from the current literature, and identify challenges and promising areas for future research in this domain.

The author in [48] notes that Mivar decision-making systems can control groups of small robots and even an unmanned autonomous car in real time.

Enthrakandi Narasimhan, G., & Bettyjane, J. in [49] two co-operating mobile robots with a multilayer control system which utilizes Boolean logic to enable the significance of a relative behaviour. They try to control the robots in uncontrolled environment and also in multitasking environment.

Sathyan, A., & Ma, O. in [50] introduce an approach of collaborative control for individual robots to collaboratively perform a common task, without the need for a centralized controller to coordinate the group. They use multiple robots performing a collaborative task to achieve a common goal.

Researchers in [51] propose a Decentralized Ability-Aware Adaptive Control to implement multi-robot collaboration that is extremely challenging due to the different kinematic and dynamics capabilities of the robots, the limited communication between them, and the uncertainty of the system parameters.

So we see that the issues of robot group control are very diverse. Further in this article we will consider methods, models and algorithms of decentralized robot group control.

Classification of modern methods, models and algorithms for a collaborative robots group decentralized control

A collaborative robots group decentralized control is a hot topic in robotics, especially in the context of Industry 4.0 and Industry 5.0. The main goal of decentralized systems is to ensure the operation of a group of robots without a single control center, using local interaction and data exchange between robots. Let us classify existing methods of a collaborative robots group decentralized control in the context of Industry 5.0, which is presented in Figure 1.

Let us conduct a comparative analysis of methods for a collaborative robots group decentralized control, identify their advantages and disadvantages, and present the results in Table 1.

The presented methods (Fig. 1 and Table 1) of for a collaborative robots group decentralized control have significant potential, but at the same time they face a number of significant limitations that complicate their effective application. Distributed algorithms, although they ensure the stability of the system and its scalability, are often unable to provide a high level of coordination between robots in large groups, which can lead to uncoordinated actions or conflicts in the performance of tasks.

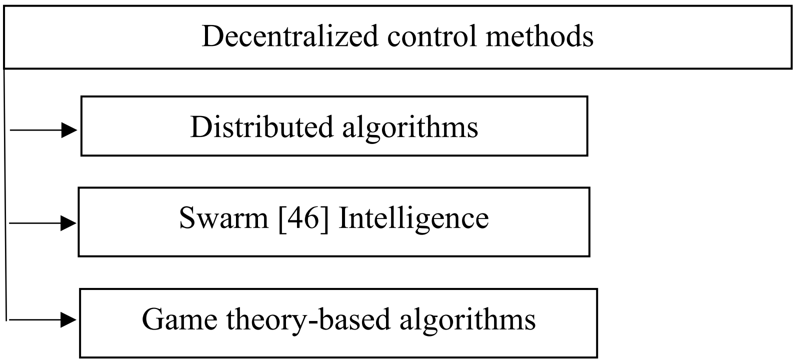

Figure 1: Classification of methods for a collaborative robots group decentralized control

The lack of complete information due to the locality of decision-making also limits the accuracy and efficiency of such systems. Swarm intelligence algorithms demonstrate excellent adaptability to changes in the environment, but their tendency to local extremes and the inability to always guarantee a globally optimal solution create risks for solving complex tasks. In turn, algorithms based on game theory provide high efficiency in resource allocation, but their computational complexity and vulnerability to unfair actions or failures of individual system components can significantly reduce the reliability of operation.

Table 1: Comparative analysis of methods for a collaborative robots group decentralized control

Method	Description	Advantages	Disadvantages
Distributed algorithms	In these algorithms, each robot makes decisions based on local information (obtained from sensors, neighboring robots, or the environment)	Lack of dependence on a central node, which makes the system more resilient to failures. Scalability: adding new robots does not require significant changes to the system.	High complexity of coordinating actions in large groups. Limited accuracy due to insufficient information.

Swarm Intelligence	Based on modeling natural systems (ant colonies, flocks of birds)	High adaptability to changes in the environment. Ability to achieve optimal solutions without centralized management.	A global optimal solution is not always guaranteed. Possibility of local extrema in search problems
Game theory-based algorithms	Robots are considered as players who seek to maximize their benefits. The concept of Nash equilibrium is used.	Efficiency in resource allocation. High formalization of the mathematical model	Requirements for a significant amount of calculations. Vulnerability to malicious actions (in case of partial failure).

All these shortcomings indicate that existing methods often do not take into account the specific needs of group dynamics of collaborative robots in complex and dynamic environments, such as flexibility in decision-making, synchronization of actions and data integration. This emphasizes the need for further research aimed at creating new or improving existing algorithms that can take into account these challenges and ensure high efficiency of decentralized management.

Let us develop a classification of the decentralized management model, which is presented in Figure 2.

Let us conduct a comparative analysis of decentralized control models for a collaborative robots group, identify their advantages and disadvantages, and present the results in Table 2.

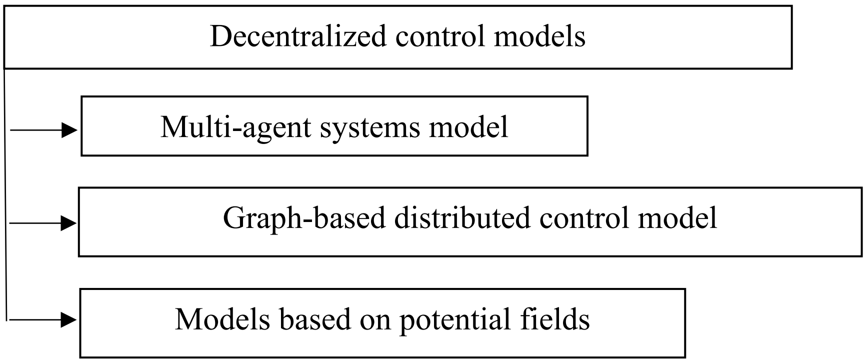

Figure 2: Classification of decentralized control models for a collaborative robots group

Table 2: Comparative analysis of decentralized ccontrol models for a collaborative robots group

Model	Description	Advantages	Disadvantages
Multi-agent systems model	Each robot acts as an agent with its own goals, capable of autonomous decision-making.	Ability to perform complex tasks by distributing tasks between agents. High autonomy and adaptability.	High requirements for creating an agent interaction model. Difficulty in ensuring consistency between agent actions.
Graph-based distributed control model	A group of robots is represented as a graph, where nodes are robots and edges are their connections.	Transparency for modeling relationships and interactions. Using formal mathematical methods.	The difficulty of maintaining graph connectivity in the face of dynamic changes..
Models based on potential fields	Each robot moves in space under the influence of forces created by the	Easy to implement for basic navigation tasks.	The problem of getting stuck in local minima.

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Volume 2, Issue 2

	environment, other robots, or target points.	Low computational cost.	The inability to guarantee global optimization.

Existing models of a collaborative robots group decentralized control demonstrate significant advantages, but their shortcomings limit the effectiveness of application in real conditions. The multi-agent system model provides high autonomy and adaptability of each robot, but at the same time complicates the creation of an effective model of interaction between agents. This can lead to problems with the consistency of actions, especially in the context of performing joint tasks in dynamic environments. The graph-based distributed control model allows for the formalization of robot interaction, but its application is complicated by the need to maintain the connectivity of the graph in conditions of constant changes, such as the failure of individual robots or a change in the environment. Models based on potential fields are characterized by simplicity of implementation and low computational costs, but they have significant limitations, in particular, the tendency to get stuck in local minima and the inability to achieve global optimization. In general, each of the models has a certain area of effective application, but none of them is universal for solving the problems of decentralized control in large groups of robots with a high degree of autonomy. These limitations indicate the need to improve existing approaches and create new ones that could take into account the complexity of modern robotic systems, in particular their ability to operate in a dynamic environment, interact without conflicts and effectively achieve common goals.

Let us classify a modern decentralized control algorithm, which is presented in Figure 3.

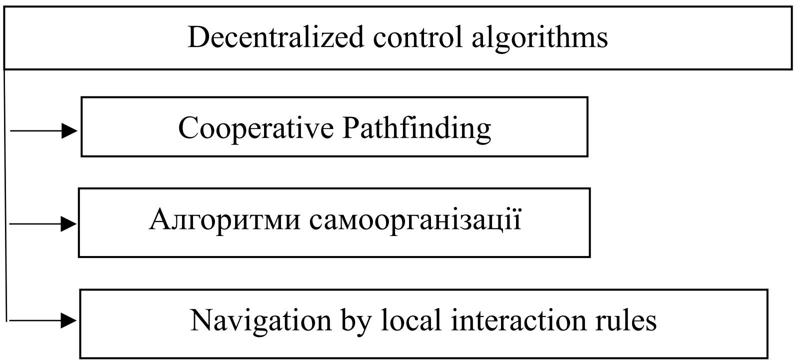

Figure 3: Classification of algorithms for a collaborative robots group decentralized control

Let us conduct a comparative analysis of algorithms for a collaborative robots group decentralized contro, identify their advantages and disadvantages, and present the results in Table 3.

Self-organization algorithms, despite their high adaptability to changing conditions, have significant limitations that affect their effectiveness in the tasks of a collaborative robots group decentralized control.

The use of approaches such as clustering in motion or mutual following provides simplicity in implementing basic tasks of resource allocation or coordination, but does not guarantee the performance of the system at the group level.

The lack of clear mechanisms for controlling the general behavior can lead to inefficient use of resources and loss of time for error correction. Navigation based on local interaction rules, such as Boids algorithms, is convenient for modeling natural behavior, but their accuracy is insufficient for complex tasks that require a high level of coordination between robots.

Table 3: Comparative analysis of algorithms for a collaborative robots group decentralized control

Algorithm	Description	Advantages	Disadvantages
Cooperative Pathfinding	Used to avoid collisions between robots and ensure the performance of collective tasks. (Algorithm A* with task distribution between robots. Algorithms D* and LPA*)	Efficiency for complex navigation tasks. Providing dynamic route replanning.	High computational costs in large groups.

Self-organization algorithms	Used for clustering, sorting or resource allocation tasks. (Clustering in Motion. Follower-Leader.	High adaptability to conditions.	No guarantees regarding the performance of the system as a whole.
Navigation by local interaction rules	Algorithms based on Boids model movement in a flock, with the following rules of behavior: collision avoidance, speed equalization, attraction to neighbors.	Easy to implement. High flexibility.	Insufficient accuracy in tasks with high coordination requirements.

The dependence on local information and simple interaction rules limits the ability to take into account global goals and the context of the entire system.

Such algorithms are flexible in solving problems in unstable conditions, but their effectiveness in complex scenarios, where synchronization of actions and consideration of long-term strategies are required, is significantly reduced. Thus, although self-organization methods are useful for basic tasks of decentralized control, their limitations indicate the need for additional approaches that could provide both adaptability and high accuracy and consistency of the work of a group of robots.

Conclusion

Analysis of existing methods, models and algorithms for a collaborative robots group decentralized control reveals significant limitations that limit their effectiveness in complex and dynamic environments. Distributed algorithms demonstrate scalability and fault tolerance, but their effectiveness is reduced due to limited accuracy and complexity of coordination in large groups. Swarm intelligence algorithms provide adaptability to changes, but are prone to local extrema and do not guarantee the achievement of global optima. Game theory-based methods provide formalization and efficient resource allocation, but require significant computational resources and may be vulnerable to partial failures.

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Volume 2, Issue 2

Multi-agent system models allow tasks to be distributed among autonomous agents, but the complexity of coordinating the actions of agents and high requirements for their interaction limit their practicality. Graph models are effective for modeling connections, but require constant maintenance of connectivity in dynamic conditions. Potential field-based methods are simple to implement, but prone to getting stuck in local minima, which limits their applicability to complex problems.

Cooperative routing algorithms allow for dynamic replanning of routes, but require significant computational resources in large systems. Self-organization algorithms, although they demonstrate adaptability, do not guarantee system performance at the group level, while methods based on local interaction (e.g. Boids) have insufficient accuracy for problems with high coordination requirements.

These shortcomings indicate the need to develop new methodologies that can combine adaptability, efficiency, and consistency of system operation. Modern approaches should take into account the increasing complexity of tasks in robotics, integrate elements of artificial intelligence, deep learning, and cyber-physical systems, while ensuring scalability, energy efficiency, and stability in dynamic conditions.

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