

Features of the Development of a Humanoid Robot Control System on ESP8266MOD(12F)

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Abstract— The abstracts consider approaches to the development of a decentralized control system for a small-sized humanoid robot based on ESP8266MOD(12F) taking into account the requirements of Industry 5.0. A control architecture combining fuzzy logic, adaptive algorithms and inter-agent interaction to achieve individual and group goals within a robotic team is presented. Particular attention is paid to the mathematical description of the system's behavior, as well as the practical implementation of control in conditions of limited hardware resources. The work is aimed at the development of cognitive collaborative robotics in educational and scientific applications.

Keywords— *Humanoid Robot, ESP8266MOD, Decentralized Control, Fuzzy Logic, Collaborative Robotics, Industry 5.0.*

I. INTRODUCTION

In the context of the development of the Industry 5.0 concept, which emphasizes harmonious interaction between humans and intelligent technologies, there is a growing need to create effective, flexible, and scalable control systems for collaborative robots [1]. Of particular interest are humanoid robots capable of group interaction, decision-making under uncertainty, and adaptation to environmental changes [2]. In this context, it is advisable to use small-sized, energy-efficient, and cost-effective platforms, such as ESP8266MOD(12F), which provide sufficient computing power and wireless communication capabilities [3]. The research presented in the abstracts is devoted to the development of a control system for a small humanoid robot that functions as a separate autonomous unit or as an element of a collective multi-robot system [4]. Special attention is paid to the control architecture, which involves the implementation of both individual and group goals using a decentralized approach, using adaptive algorithms, fuzzy logic and interaction models. The proposed solution opens up new opportunities for research in the field of cognitive robotics, including dynamic task distribution, local planning, action coordination and feedback-based learning. The choice of the hardware base on ESP8266MOD(12F) is justified by the need for scalability of solutions, which allows creating large groups of inexpensive robots for real-time experiments. Thus, this work contributes to the development of the direction of intelligent control systems in the field of educational,

scientific and industrial applications with an orientation on the principles of human-centric automation.

II. CONTROL ARCHITECTURE DEVELOPMENT

The proposed architecture for controlling small-sized humanoid robots consists of several hierarchically connected levels, which are presented in Figure 1.

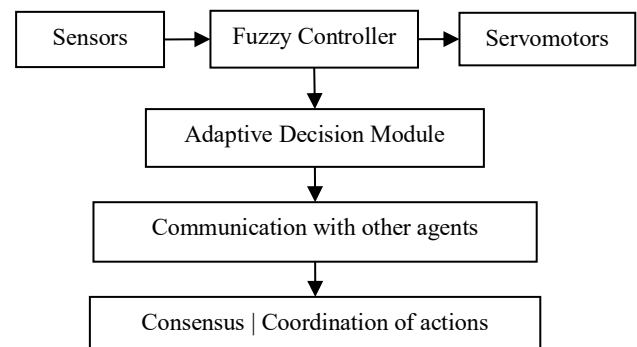


Figure 1 – Control Architecture

The architecture consists of several hierarchically related layers:

- local sensor-actuator control (on each ESP8266MOD), solves the following tasks: data collection from sensors (IMU, IR/Ultrasound, pressure sensors, infrared trackers) [5]; direct control of body servomotors based on fuzzy logic rules [6]; determination of the local state of the robot: position, orientation, proximity to the target.
- intelligent decision-making module (Rule & Policy Layer), solves the following tasks: Fuzzy rule-based decision-making system (based on current input data); module for adapting rule parameters using reinforcement mechanisms (Reinforcement Learning) [7]; Prioritization of individual and group goals.
- decentralized interaction and communication (Mesh Communication Layer), solves the following tasks: data exchange between robots via Wi-Fi (ESP-NOW/MQTT); goal coordination through a local consensus mechanism; role distribution and behavior planning according to the BDI (Belief-Desire-Intention) cognitive architecture model [8].

As can be seen, the proposed architecture for controlling small-sized humanoid robots is an autonomous cognitive unit that assesses the situation, makes decisions and coordinates with others, forming an "intelligent swarm"

III. CONTROL SYSTEM MATHEMATICAL DESCRIPTION

The use of fuzzy logic control in humanoid robot control systems is appropriate due to the ability of fuzzy systems to work effectively under conditions of uncertainty, incomplete sensor data, and complexity of motion dynamics. Unlike classical PID controllers, the fuzzy approach allows for easy integration of heuristic rules based on experience or observations, and also ensures smoothness and stability of motion in a wide range of situations [9]. This is especially important for small-sized robots, where the high level of sensor noise, limited computing resources, and unpredictability of contacts with the environment make rigid mathematical modeling impractical or excessively complex [10]. Fuzzy logic allows for real-time behavior adaptation, providing flexibility and stability in controlling balance, walking, and interaction with other robots. Based on this, the following application control function is proposed:

$$u_i(t) = \mathcal{F}(e_i(t), \dot{e}_i(t); \theta_i) \quad (1)$$

Where: $u_i(t)$ - control action on the i -th servomotor at time instant t ; $e_i(t)$ - position error; $\dot{e}_i(t)$ - derivative of error; $\mathcal{F}$ - fuzzy function based on type rules Mamdani; θ_i - a set of weights adapted through reinforcement.

An individual objective function is necessary to determine and quantify the effectiveness of a particular task by an individual robot [11]. It allows the robot to make decisions based on its own goal, optimizing the trajectory, energy expenditure, or time to reach it. Such a function forms the basis for adapting behavior in a dynamic environment, especially when the robot acts autonomously. It also serves as a basis for coordination with group goals within the framework of collective interaction. The following function is proposed within the framework of these studies:

$$J_k^{ind} = \int_0^T (w_1 \|x_k(t) - x_{target,k}(t)\|^2 + w_2 \phi_k(t)) dt \quad (2)$$

Where: J_k^{ind} - individual goal achievement function for the robot k ; $x_k(t)$ - robot k position; $x_{target,k}(t)$ - target position; $\phi_k(t)$ - penalty function for power consumption or instability; w_1, w_2 - weighting factors.

Group coordination by humanoid robots is proposed to be implemented through consensus, which ensures consistency of actions between robots operating in a common environment without centralized control. This approach allows each agent to adapt its behavior taking into account the states of its neighbors, contributing to synchronization of movement, task distribution, or collision avoidance. Consensus algorithms are especially effective in conditions of limited communication, where decisions are made based on local information. This ensures scalability and system resilience to failures of individual agents, which is critically important in multi-robot cognitive teams. The mathematical model of group coordination through consensus has the following form:

$$\dot{x}_k(t) = -\sum_{j \in \mathcal{N}_k} a_{kj} (x_k(t) - x_j(t)) \quad (3)$$

Where: $x_k(t)$ - robot k position; $\mathcal{N}_k$ - set of robot neighbors k ; a_{kj} - the weight of the connection between k and j , what determines trust in a neighbor.

Model 3 implements the behavior of coordinated movement or achieving a group goal.

To formalize the balance between the individual actions of each robot and the common goal of the group, it is proposed to use an integrated objective function for the entire swarm. It allows you to coordinate the behavior of the swarm in such a way that achieving a global result does not contradict the local goals of the agents, ensuring the coordinated performance of complex tasks. Thanks to such a function, the system can dynamically adapt the weight between individual initiative and group coherence depending on the context. This allows you to avoid conflicts, duplication of actions or inefficient allocation of resources. It also serves as an optimization criterion for learning or self-organization within the framework of a cognitive architecture, ensuring the purposeful evolution of swarm behavior. The general representation of the integrated objective function for the entire swarm has the following form:

$$J^{team} = \sum_{k=1}^N \alpha J_k^{ind} + (1 - \alpha) J^{sync} \quad (4)$$

$$J^{sync} = \sum_{(k,j) \in E} \|x_k(t) - x_j(t)\|^2 \quad (5)$$

Where: J^{team} - combined swarm productivity function; J^{sync} - consistency between agents; E - set of interaction pairs; $\alpha \in [0,1]$ - balance factor between individual and group goals.

The developed mathematical description of the control system for small-sized humanoid robots combines adaptability, flexibility and the ability to collective behavior, which is fully consistent with the principles of Industry 5.0, where the emphasis is on human-centricity and cooperation between technologies [12]. Thanks to fuzzy regulation, decentralized consensus and an integrated objective function, the system allows for the implementation of both autonomous individual actions and coordinated interaction between robots in a dynamic environment [13]. Implementation on ESP8266MOD(12F) provides low power consumption, accessibility and sufficient computing power for embedded algorithms, which makes the solution scalable and suitable for a wide range of educational, research and production tasks [14-16]. This approach creates the basis for cognitive teams capable of self-organization, adaptation and effective interaction with humans and other technical agents.

IV. CONCLUSION

The study substantiated the feasibility of creating a control system for small-sized humanoid robots based on the ESP8266MOD(12F) microcontroller, which corresponds to the concepts of Industry 5.0 and the development of cognitive teams. The proposed architecture allows for the implementation of both individual and group goals using a decentralized approach, fuzzy logic, and models of local interaction between robots. The developed mathematical description formalizes the key elements of behavior — regulation, adaptation, consensus, and the integrated swarm objective function — which ensures consistency and efficiency of actions even under conditions of limited computing resources. The system demonstrates flexibility, scalability, and resilience to environmental changes and failures of individual agents, which is critically important for collective robotics. Practical implementation on the ESP8266MOD(12F) confirmed the viability of the concept and its suitability for building intelligent low-cost robots

within research and educational platforms. The results obtained can be used for further development of autonomous robotic systems in the fields of logistics, education, humanitarian aid, and interactive service.

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