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FEATURES OF THE USE OF QUANTUM COMPUTING IN CONSTRUCTING TRAJECTORY OF COLLABORATIVE MOBILE ROBOT

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This paper considers the features of the application of quantum computing to construct trajectories of a collaborative mobile robot. Compared with classical pathfinding algorithms and evolutionary stochastic methods, quantum approaches provide an efficient search for globally optimal solutions in complex and dynamic environments through the use of superposition and parallel computing. The proposed models formalize the trajectory planning problem in the form of a QUBO formulation, which allows taking into account safety constraints, avoiding collisions, and scaling the system for multi-robot scenarios in Industry 5.0.

The current stage of development of robotic systems is associated with the transition to the new paradigm of Industry 5.0, in which a special place is occupied by collaborative mobile robots capable of interacting with other agents and humans in a single dynamic working environment [1,2]. The key challenge remains the problem of constructing optimal trajectories of movement of such robots in complex multifactorial conditions, including the presence of moving obstacles, resource limitations, the need to ensure safety and flexible adaptation to changes in the external environment. Classical optimization methods, such as pathfinding algorithms (A*, D*, RRT), evolutionary methods or stochastic approaches, have high computational complexity and limited efficiency when solving problems in multidimensional spaces with a large number of variables. This makes the study of quantum computing methods relevant, which can provide a fundamental advantage in the speed of solving optimization problems and finding the global extremum. A comparison of classical pathfinding algorithms (A*, D*, RRT), evolutionary methods, and stochastic approaches from quantum computing is presented in Table 1 [3-5].

The peculiarities of using quantum computing in constructing trajectories of movement of a collaborative mobile robot are that the problem of planning movement in a complex dynamic environment with a large number of factors and constraints is translated into the form of optimization models suitable for implementation on quantum algorithms [6,7]. The construction of trajectories begins with the formalization of the environment in the form of a set of discrete positions $i \in \mathcal{V}$ and time steps $t \in \mathcal{T}$. For this, binary variables are introduced $x_{i,t}$, which take the value 1 if the robot is in position i at time t , and 0 otherwise. The main parameters are the number of positions N , number of time steps T , and the set of admissible transitions \mathcal{E} . This provides a basis for encoding the robot's motion in a discrete representation suitable for quantum algorithms.

The motion planning problem is given in the form of unconstrained quadratic optimization (QUBO), which is written as:

$$\mathcal{F}(x) = w_L F_L + w_E F_E + w_S F_S + \sum_k \lambda_k C_k$$

Where: F_L - minimizes path length; F_E - takes into account energy consumption; F_S - reduces the risk of collisions; C_k - reflect constraints on position uniqueness and fixed start/finish points; w_L, w_E, w_S - weighting factors; λ_k - set of admissible transitions \mathcal{E} . The purpose of this model is to provide a universal form for calculating the optimal trajectory on quantum machines.

Table 1 – Comparative table of classical pathfinding algorithms and quantum computing

Comparison criterion	Classical pathfinding algorithms (A*, D*, RRT)	Evolutionary methods and stochastic approaches (GA, PSO, SA, etc.)	Quantum computing for trajectory construction
1	2	3	4
Problem type	Finding the shortest path on a graph or in space	Global trajectory optimization considering complex cost functions	Quadratic Optimization (QUBO/Ising) with Many Variables
Optimality of solution	A* gives the optimal path (subject to heuristics); D* is efficient in dynamic environments	Solutions are approximate, do not guarantee global optimum, but work well in complex environments	Provides global/quasi-global optimum search through quantum superposition search
Computational complexity	Grows exponentially with space size (especially A*)	High, depends on population/iteration size; often polynomial, but difficult for high dimensions	Translates to QUBO (NP-hard), but quantum algorithms can process exponential spaces in parallel
Scalability for multi-threaded systems	Highly complicated (exponential growth of search space)	Naturally scalable, but requires more iteration resources	Quantum representation allows encoding multiple agents in a single QUBO model
Advantages	Easy to implement, known optimality guarantees (A*), efficient in small environments	Flexible, able to handle complex nonlinear models	Fast exploration of large spatial domains, prospects for global optimization
Disadvantages	Poorly scaled in high dimensions and with many agents	Slow convergence, stochastic results, need for parameter tuning	Requires specialized quantum hardware, currently limited by the number of qubits
Application scenarios	Static or moderately dynamic environments, small number of robots	Complex, multidimensional environments, multi-objective tasks	Large dynamic environments, multi-tasking systems, Industry 5.0, problems with a large number of variables

The QUBO functional is translated into the form of the Ising Hamiltonian, which makes it possible to provide a physical implementation of the optimization problem in the form of quantum evolution:

$$H_P = \sum_{i<j} J_{ij} s_i s_j + \sum_i h_i s_i, \quad s_i \in \{-1; +1\}$$

Where: J_{ij} - interaction coefficients; h_i - local fields that describe the individual influences on each qubit.

The kinematic model of a mobile robot is described by the equations:

$$\dot{x}(t) = v(t)\cos\theta(t), \quad \dot{y}(t) = v(t)\sin\theta(t), \quad \dot{\theta}(t) = w(t)$$

Where: v – speed; θ – angle; w - angular velocity, as well as limitations v_{max}, w_{max} . In discrete form, it imposes conditions on a set of transitions \mathcal{E} . The purpose of this model is to check the feasibility of the trajectory found by the quantum algorithm.

For a multi-collaborative environment of robot interaction, variables are introduced $x_{i,t}^{(r)}$ for every robot r . Fines are added to the function $M_{col} x_{i,t}^{(r)} x_{i,t}^{(s)}$, which prohibit multiple robots from being in the

same position at the same time, as well as additional deadlines for maintaining a safe distance D_{min} . The parameters are the number of robots K , penalty coefficients M_{col} and minimum safe distance. The purpose of the model is to ensure coordinated and safe movement in the team.

The obtained research results indicate that the use of quantum computing in constructing trajectories of movement of a collaborative mobile robot allows to increase the efficiency of finding optimal solutions in complex dynamic environments. Quantum models provide faster processing of multidimensional data, consideration of safety constraints and scalability in multi-robot scenarios. Thus, the proposed approach opens up prospects for the creation of intelligent robot control systems within the framework of the Industry 5.0 concept.

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АНАЛІЗ AI-АСИСТЕНТІВ ДЛЯ IDE VISUAL STUDIO CODE

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Проаналізовано провідні AI-асистенти, інтегровані у середовище Visual Studio Code (зокрема, GitHub Copilot, Codeium, Cursor, Tabnine). Показано переваги та недоліки кожного інструменту для комерційної розробки. Обґрунтовано необхідність застосування багатокритеріального підходу для об'єктивної оцінки їхнього функціоналу та визначення оптимального інструменту для IT-команд, враховуючи критерії продуктивності, безпеки та архітектурного розуміння.