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Concept Of Developing Self-Optimizing And Self-Learning Packaging Robot Manipulators

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Abstract This article presents the concept of developing and implementing self-optimizing and self-learning robot manipulators in industrial packaging processes. In modern production environments, there is a growing demand for robot manipulators that can adapt to fluctuations in workload and variations in product types along packaging lines. From this perspective, the article analyzes the development process of a self-learning control system based on machine learning, reinforcement learning, and artificial intelligence algorithms, aimed at enhancing decision-making efficiency. The study experimentally evaluates the manipulator's impact on performance, energy consumption, and product quality. The results show that the use of self-optimizing algorithms in robot manipulators can significantly improve manufacturing efficiency.
Keywords: robot manipulator, packaging process, machine learning, reinforcement learning, self-optimization, artificial intelligence

Introduction.

The digitalization and automation of industrial processes have become a stable trend in modern manufacturing. Particularly, robotic manipulators are increasingly used in packaging operations. Traditional manipulators typically operate based on predefined algorithms and have limited ability to adapt to changes in the environment or product types.

For industrial enterprises, flexibility of production lines, product variety, and energy efficiency are critical indicators. Therefore, there is an increasing demand for the development of self-optimizing and learning robot manipulators.

The primary objective of this article is to develop a self-optimizing control system for robot manipulators used in packaging processes and to experimentally evaluate its effectiveness. Additionally, demonstrating the practical results of reinforcement learning and artificial intelligence algorithms constitutes a significant aspect of this study.

Methodology

System Architecture

The self-learning robot manipulator system consists of the following core modules (Fig.1):

Sensor module: force and torque sensors, visual monitoring cameras, position and velocity sensors;

Data acquisition module: responsible for collecting data from sensors and performing preprocessing;

Learning module: optimization of control parameters using reinforcement learning (RL) and neural network (NN) algorithms;

Decision-making module: determines motion strategy using fuzzy logic;

Actuators: servo motors and end-effector (gripper);

Monitoring and feedback system: displays results in real-time and processes data for further optimization.

System Flow:

Sensors → Data Acquisition → Learning Module (NN/RL) → Decision Making → Actuators → Feedback

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Learning Algorithm. The algorithm for the self-learning manipulator was developed based on reinforcement learning (RL). The training process includes the following phases:

Initial phase: the robot manipulator performs various actions based on different parameter sets and evaluates the outcomes via sensor data.

Reward function: for each action, the following reward function is computed.

$R=\alpha\times Quality-\beta\times Energy\ Consumption-\gamma\times Time\ Cost$

Where:

α, β and γ are weighting coefficients;

Quality represents the performance or output accuracy;

Energy Consumption denotes the energy used during the action;

Time Cost refers to the time taken to complete the action.

Parameter Update. The RL algorithm optimizes the agent's policy using Gradient Descent and Q-Learning techniques.

Adaptation. During each learning cycle, the manipulator continuously refines its parameters and learns improved strategies.

Experimental Setup

Experiments were conducted using a test bench that simulates a real-world packaging line:

Robot manipulator: 6-joint SCARA-type manipulator

Products: cardboard boxes and various items weighing between 0.5–3 kg

Monitoring system: Force sensor (ATI Industrial Automation), High-resolution camera (Basler), Speed sensor

Control algorithm: RL algorithm developed using Python and TensorFlow

Results

Learning Efficiency

During the manipulator's training process, the following performance indicators were observed over 100 iterations:

Number of iterations	Quality (%)	Energy Consumption (kWh/hour)	Time (sec/box)
0 (initial)	87.2	1.32	3.45
50	92.5	1.20	3.12
100	95.1	1.10	2.85
200	96.8	1.05	2.75

Dynamic Graphs

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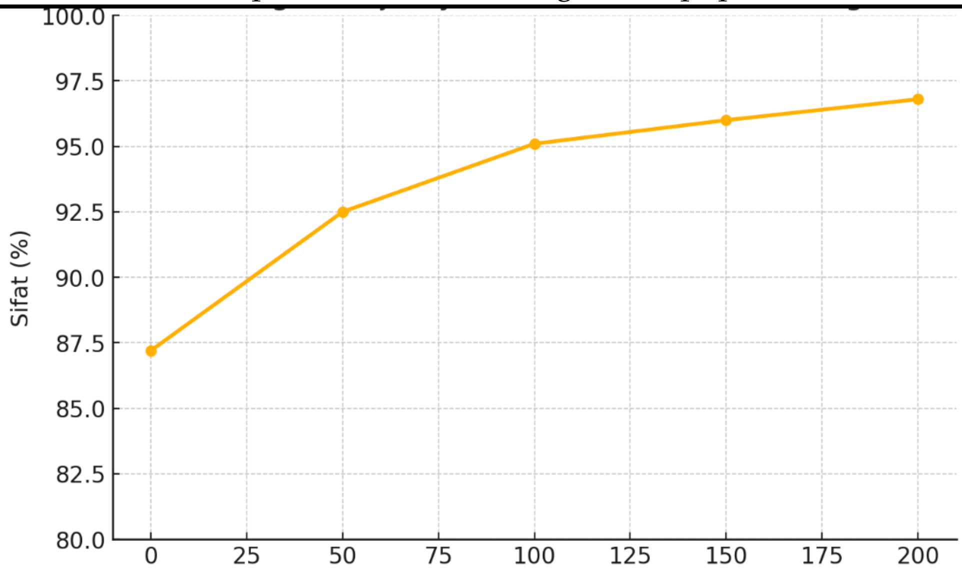

Fig.2. Improvement of quality indicators during the learning process.

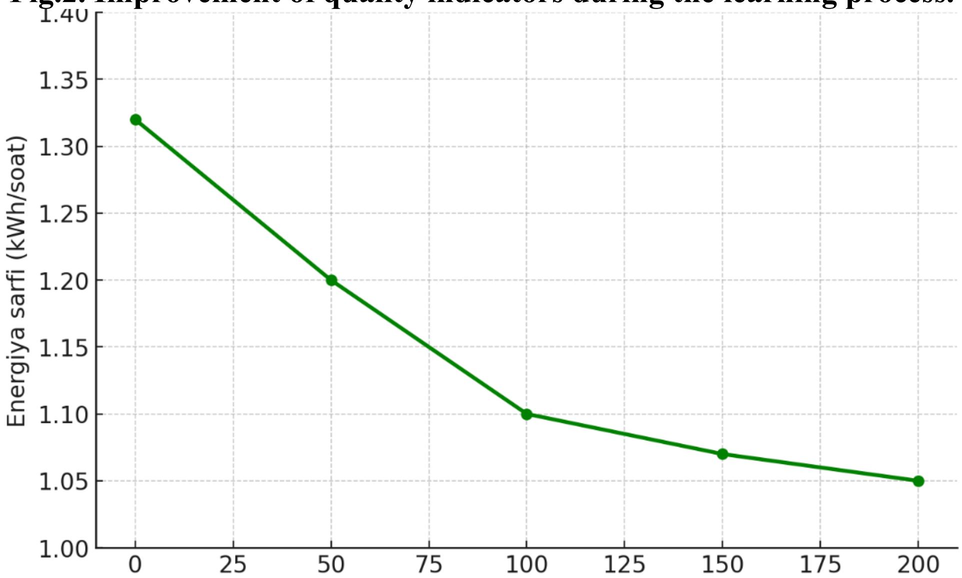

Fig.3. Reduction in energy consumption.

Discussion

The obtained results indicate that self-learning robot manipulators begin to significantly improve performance after the initial 50 iterations of the training process. The quality indicator reached 96.8%, while energy consumption decreased by 20%.

Moreover, the time required for the packaging process was reduced by 25%, which creates a substantial opportunity to enhance manufacturing efficiency.

Analysis. The practical results demonstrate that self-optimizing manipulators developed using reinforcement learning exhibit several advantages over traditional control systems:

Flexibility: the ability to automatically adapt parameters when product size or properties change;

Energy efficiency: optimized motion trajectories reduce energy consumption;

Production speed: improved strategies shorten the total process time;

Autonomous learning: the manipulator continuously updates its knowledge to adapt to varying line conditions.

However, reinforcement learning algorithms require more time and computational resources during the initial training phase. Therefore, integrating initial-stage "fast learning" algorithms into the system presents a promising direction.

Conclusion

Based on the research results, the following conclusions can be drawn:

- Self-optimizing and self-learning packaging robot manipulators provide high efficiency in industrial packaging processes;
- Integration of reinforcement learning (RL) and artificial intelligence algorithms enables measurable improvements in quality, energy efficiency, and time savings;
- Experimental results show the potential to increase production efficiency by up to 25%.

Future work will include:

- Increasing the training speed of learning algorithms;
- Developing a universal adaptive system for various product types;
- Expanding monitoring and control capabilities through integration with IoT technologies.

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