УДК 621.865.8 : 681.5
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DEVELOPMENT OF AN ADAPTIVE MANIPULATOR FOR AUTOMATION OF THE PACKAGING PROCESS

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Modern market conditions require manufacturers to maintain significant flexibility in their production lines. Traditional mechanized packaging systems lack versatility, as they require extensive changeover times when the product range changes. In response to these challenges, the need arises to implement intelligent robotic complexes. The aim of this work is to design and theoretically substantiate the operability of an adaptive SCARA manipulator capable of functioning effectively in a changing production environment.

To perform pick-and-place operations, which dominate packaging processes in the food, pharmaceutical, and electronics industries, the SCARA kinematic structure (4 degrees of freedom: RRPθ) was selected. It provides an optimal ratio of workspace (1000 mm radius) to the occupied footprint, high speed (end-effector acceleration up to 100 m/s^2), and the necessary stiffness in the vertical direction. The nominal payload is 5 kg, with the capability to handle objects up to 30 kg at reduced dynamic performance.

A distinctive feature of the developed manipulator is a unique linear actuator that integrates two motions (vertical linear translation along the R2 axis and rotation around the R3 axis) into a single compact design. This is achieved through the use of a trapezoidal lead screw and a hollow spline rail with an internal groove, driven by a timing belt transmission from a separate NEMA 23 stepper motor.

The system's adaptability is realized through the integration of multimodal sensory subsystems (specifically 2D/3D machine vision cameras with a processing latency of up to 40 ms) and the use of adaptive control algorithms. This allows the system to automatically identify objects of unpredictable geometry, optimize movement trajectories, and adjust gripping force (5-100 N) using modular gripping devices.

The mechanical design and stress-strain state analysis were performed in the Autodesk Inventor Professional 2025 CAD environment. Finite Element Analysis (FEA), modeling the worst-case loading scenario (a 30 kg payload at a maximum reach of 1000 mm), confirmed the high reliability of the structure. The maximum stress zones do not exceed the allowable limits for the selected materials (7075-T6 aluminum alloy and AISI 304/440C stainless steel). The maximum total displacement of the forearm's free end was only 0.9121 mm, indicating high system stiffness.

To ensure the manipulator can be used in cleanrooms, its design complies with Clean-In-Place (CIP) sanitary and hygienic requirements. The moving joints are sealed to the IP67 standard, and the use of exclusively H1 food-grade lubricants (NSF certified) is specified. The safety of the manipulator's interaction with personnel was analyzed and ensured according to the ISO 10218-1:2025 international standard.

The developed adaptive SCARA manipulator is a highly efficient and reliable solution. Its implementation will significantly reduce downtime caused by changeovers, decrease defect rates, and increase the Overall Equipment Effectiveness (OEE) metric on modern packaging lines.