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Control Algorithms For Robot Manipulators To Optimize Paper Flow In Printing Processes

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Abstract: The article examines the problem of optimizing the processes of transferring, sorting, and packaging paper sheets along a conveyor in printing enterprises using a robot manipulator. The main issue highlighted is the lack of mathematically grounded control algorithms that properly link conveyor speed, paper flow intensity, and the robot manipulator's operational cycle. As a result, paper jams, robot idle time, and defect rates increase. In the article, the movement of paper on the conveyor is expressed using basic differential equations, while the flow intensity is modeled through the M/M/1 queueing theory framework. Based on the kinematic and dynamic models of the robot manipulator, a jerk-limited trajectory planning algorithm is proposed. Simulation results conducted in the MATLAB/Simulink environment show that the proposed algorithm keeps the load coefficient of the conveyor–robot system around $\rho = 0.73$, reduces the queue length from 20 to 2.7 items, and decreases the frequency of paper jams by up to 40%.

Keywords: Robot manipulator, printing industry, paper flow, M/M/1 queue, control algorithm, optimization, conveyor, MATLAB.

INTRODUCTION:

In modern printing enterprises, processes such as cutting, printing, folding, sorting, and packaging are performed at high speed. In particular, executing the operations of sorting and packaging paper sheets manually limits production efficiency, increases dependence on human factors, and raises the defect rate. Therefore, the implementation of robot manipulators to manage paper flow has become a highly relevant task.

In many existing methods, the robot manipulator operates in a "fixed-cycle" mode: the conveyor moves at a constant speed, and the robot picks up the sheet and places it into a package at predetermined intervals. Since variations in conveyor speed, changes in sheet size depending on the type of order, temporary stops, or sheet sticking are not taken into account, the probability of paper jams increases, and the robot sometimes performs "idle motions" when no sheet has arrived yet. As a result, the accuracy and quality of packaging decrease.

This article develops control algorithms that connect the conveyor paper flow and the robot manipulator's motion within a unified mathematical model, adapt to flow intensity, and ensure sheet handling without damage. The work involves mathematical modeling of paper flow using differential equations and queueing theory, synthesizing a jerk-limited trajectory planning algorithm based on the kinematic and dynamic model of the robot manipulator, and evaluating their efficiency through simulation.

METHOD

We assume that the conveyor speed v_c(m/s) is constant. The position x(t) of a single sheet along the conveyor is described using the Galilean motion model as follows:

the coordinate is the time integral of the velocity:

$$\frac{dx}{dt} = v_c, v_c = \text{ const.}$$

Integrating this simple differential equation, we obtain:

$$\int dx = \int v_c dt \Rightarrow x(t) = v_c t + C$$

As the initial condition, let the sheet arrive at point x_0 on the conveyor at time $t = t_i^{(0)}$:

$$x\left(t_i^{(0)}\right) = x_0 = v_c t_i^{(0)} + C \Rightarrow C = x_0 - v_c t_i^{(0)}$$

Thus, for the sheet:

$$x_i(t) = v_c t + x_0 - v_c t_i^{(0)} = x_0 + v_c\left(t - t_i^{(0)}\right)$$

The robot manipulator picks up the sheet at point x_p . Therefore, the pickup time $t_i^{(p)}$ is obtained from the following equation:

$$x_i\left(t_i^{(p)}\right) = x_p \Rightarrow x_0 + v_c\left(t_i^{(p)} - t_i^{(0)}\right) = x_p$$

is determined from the following equation:

$$x_i\left(t_i^{(p)}\right) = x_p \Rightarrow x_0 + v_c\left(t_i^{(p)} - t_i^{(0)}\right) = x_p$$

We solve this equation with respect to $t_i^{(p)}$:

$$t_i^{(p)} - t_i^{(0)} = \frac{x_p - x_0}{v_c} \Rightarrow t_i^{(p)} = t_i^{(0)} + \frac{x_p - x_0}{v_c}$$

Note: In physical terms, this formula means that from the moment the sheet falls onto the conveyor until it reaches the pick-up point, it moves at the constant conveyor speed v_c over the distance between x_p and x_0.

$$t_i^{(p)} = t_i^{(0)} + \frac{x_p - x_0}{v_c}$$

Time passes.

Let's assume: the starting point is: x_0=0.2 m;, pick-up point: x_p=0.8 m;, conveyor speed: v_c=1 m/s;, time of day: $t_i^{(p)} = 5\, s$.

Then:

$$t_i^{(p)} = 5 + \frac{0{,}8 - 0{,}2}{1{,}0} = 5 + 0{,}6 = 5{,}6 \text{ s}$$

A sample for these values is given in Table 1:

Table 1.

Paper position on the conveyor and pick-up time

Parametr	**Marking**	**Value**	**Unity**
Conveyor speed	v_c	1,0	$\frac{m}{s}$
Starting point	x_0	0,2	m
Pick-up point	x_p	0,8	m
Time for sheet to fall	$t_i^{(0)}$	5,0	s
Time for sheet to reach pick-up	$t_i^{(p)}$	5,6	s

Path	x_p - x_0	0,6	m

Based on the above mathematical models, it is possible to draw a graph of the movement of the sheets against time. Figure 1.

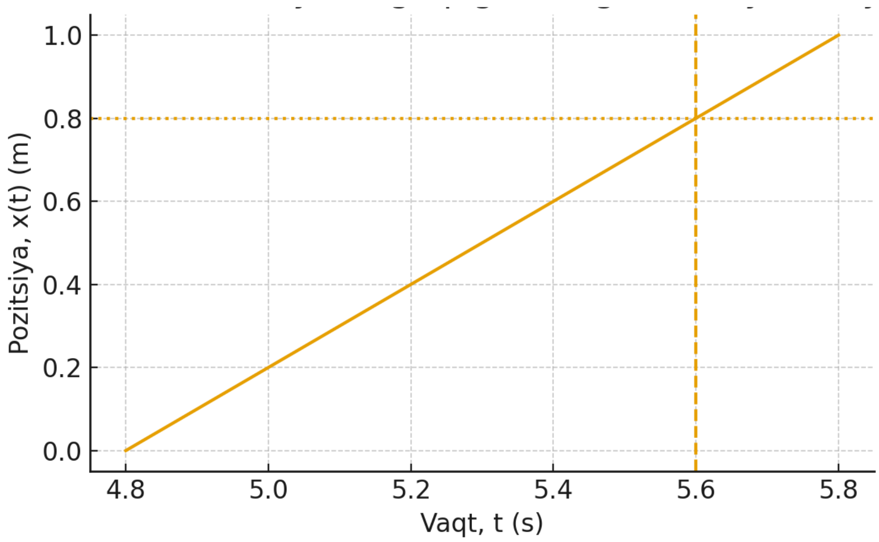

Figure 1. The x(t) trajectory of paper on the conveyor

Description: abscissa - time t, ordinate - x(t) coordinate. Starting from point x=0.32 at t=5 s, it reaches x=0.8 at t=5.6 along a straight line. The pick-up point $t_i^{(p)}$is shown on the graph by a vertical line.

The flow of paper sheets falling onto the conveyor is random, and in most cases this flow is assumed to be a Poisson process. Therefore: the intensity of the flow of arrivals is taken as λ(sheets/s);, the average service speed of the robot manipulator is taken as μ(sheets/s).

In this case, the system is represented by the M/M/1 model (M - Poisson arrival, M - exponential service, 1 - one robot).

The probability distribution of the number of sheets in the next step in the steady-state:

$$P_n = (1-\rho)\rho^n, n = 0,1,2, \dots$$

where ρ - is the loading coefficient.

The nodal balance equations for the M/M/1 system are:

$$\lambda P_n = \mu P_{n+1}, n \geq 0.$$

From this equation:

$$P_{n+1} = \frac{\lambda}{\mu} P_n = \rho P_n$$

By iteration:

$$P_1 = \rho P_0, P_2 = \rho^2 P_0, \dots, P_n = \rho^n P_0$$

The sum of the probabilities must be equal to 1.:

$$\sum_{n=0}^{\infty} P_n = 1 \Rightarrow P_0 \sum_{n=0}^{\infty} \rho^n = 1$$

Here:

$$\sum_{n=0}^{\infty} \rho^n = \frac{1}{1-p} \ (|\ \rho\ |< 1)$$

the sum of a geometric progression. (geometric progression |ρ|<1). So:

$$P_0 \cdot \frac{1}{1-\rho} = 1 \Rightarrow P_0 = 1 - \rho$$

From this:

$$P_n = (1-\rho)\rho^n$$

The average number of elements in the queue "L" is found by mathematical expectation:

$$L = \sum_{n=0}^{\infty} nP_n = \sum_{n=0}^{\infty} n(1-\rho)\rho^n$$

We calculate this sum using the classical product of a geometric series. Initially:

$$S(\rho) = \sum_{n=0}^{\infty} \rho^n = \frac{1}{1-\rho}$$

We can derive the derivative with respect to ρ:

$$\frac{dS}{d\rho} = \sum_{n=1}^{\infty} n\rho^{n-1} = \frac{1}{(1-\rho)^2}$$

Here:

$$\sum_{n=1}^{\infty} n\rho^{n-1} = \frac{\rho}{(1-\rho)^2}$$

Multiplying by ρ:

So,

$$L = (1-\rho)\sum_{n=1}^{\infty} n\rho^n = (1-\rho)\frac{\rho}{(1-\rho)^2} = \frac{\rho}{1-\rho}$$

The average residence time w of a sheet of paper in the system is found by Little's law.:

$$L = \lambda W \;\Rightarrow\; W = \frac{L}{\lambda} = \frac{1}{\mu-\lambda}$$

Stability condition: $\rho<1 \Rightarrow \lambda<\mu$, otherwise the queue grows infinitely.

Assume: Paper flow intensity: $\lambda = 4\frac{varaq}{s}$. Simple control: Actual robot speed:

The actual speed of the robot: $\mu 1 = 4.2\left\{\frac{\text{varaq}}{\text{s}}\right\}$

$$\rho_1 = \frac{\lambda}{\mu_1} = \frac{4}{4{,}2} \approx 0{,}95.$$

$$L_1 = \frac{\rho_1}{1-\rho_1} \approx \frac{0{,}95}{0{,}05} \approx 20.$$

$$W_1 = \frac{1}{\mu_1-\lambda} = \frac{1}{4{,}2-4} = 5\text{ s}.$$

The effective speed of the robot is increased: $\mu 2 = \left\{\frac{varaq}{s}\right\}$

$$\rho_2 = \frac{4}{5{,}5} \approx 0{,}73$$

$$L_2 = \frac{\rho_2}{1-\rho_2} \approx 2{,}67$$

$$W_2 = \frac{1}{5{,}5-4} \approx 0{,}67\text{ s}$$

Table 2

Comparison of simple and proposed control according to the M/M/1 model

Indicator	Simple management μ_1=4,2	Offered μ_2=5,35

Arrival intensity λ	4 sheet /s	4 sheet /s
Service intensity μ	4,2 sheet /s	$5, \frac{\text{sheet}}{\text{s}}$
Load factor ρ	0,95	0,73
Average queue length L	≈ 20 sheet	≈ 2,67 sheet
Average time W	5 s	0,67 s

Based on the above mathematical models, a histogram of the dependence of the load coefficient of the simple control and the proposed control algorithm is presented. Figure 2.

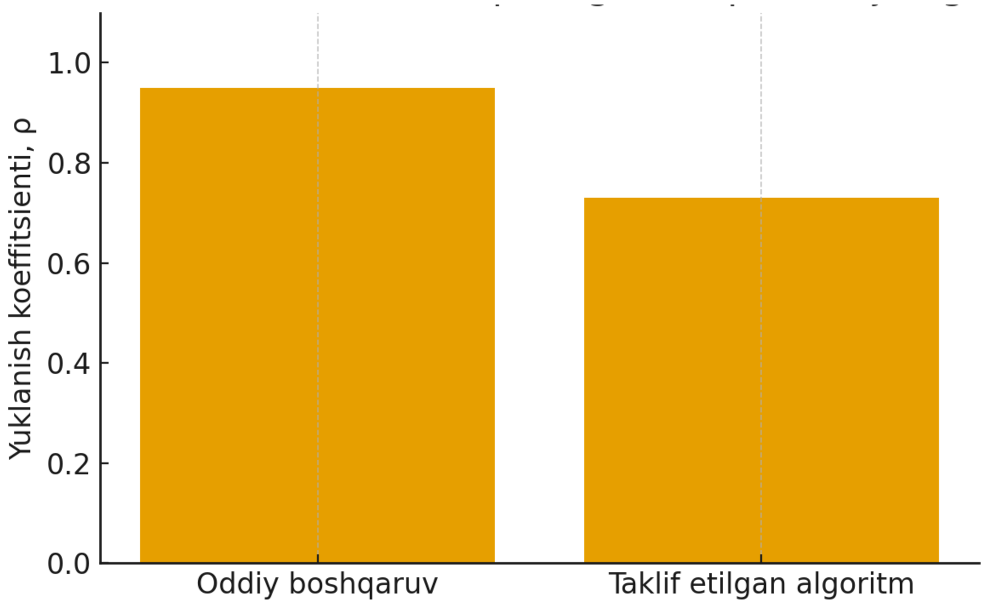

Figure 2: Dependence of the load coefficient ρ on the control mode

Description: bar chart. On the abscissa are two states: "Normal" and "Proposed"; on the ordinate is the value of 1ρ. In the normal state, the column has a height of 0.95, and in the proposed state - 0.73.

Let the robot manipulator have n joints. The joint angle vector:

$$\mathrm{q}(t) = [q_1(t), q_2(t), \dots, q_n(t)]^T$$

Three-point (end-effector) coordinates using inter-joint coupling based on Denavit-Hartenberg (D-H) parameters:

$$\mathrm{p}(t) = f\big(\mathrm{q}(t)\big) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix}$$

In the D-H scheme, the rotation and translation matrices for each joint are multiplied sequentially:

$$^0T_n(\mathrm{q}) = \, ^0T_1(q_1) \cdot \, ^1T_2(q_2) \cdots \, ^{n-1}T_n(q_n)$$

The coordinates of the three points are taken from the last column of this final matrix. Therefore, the kinematic equation is actually derived from a sequence of geometric transformations (rotations and translations).

The requirement to hold the sheet:

$$\mathrm{p}\left(t_i^{(p)}\right) = \mathrm{p}_p = \left[x_p, y_p, z_p\right]^T$$

So, the problem of inverse kinematics is to find $\mathrm{q}_i^{(p)}$ from given p_p:

$$\mathrm{q}_i^{(p)} = f^{-1}(\mathrm{p}_p)$$

Here, f^{-1} is found analytically or numerically (Newton-Raphson, Jacobian inverse) methods.

Joint dynamics in general view:

$$\mathrm{M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)} = \tau$$

where, $\mathrm{M(q)\ddot{q}}$- inertia matrix, $\mathrm{C(q,\dot{q})}$- coercive and centrifugal forces, G(q)- gravity force vector, τ- joint moments.

This equation follows from Lagrange's formalism:

$$\mathcal{L} = T - V,$$

where T - is kinetic energy, V - is potential energy. For each q_j.

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}_j}\right) - \frac{\partial \mathcal{L}}{\partial q_j} = \tau_j$$

By writing T and V (depending on the velocity and height of the center of mass) for each joint, the terms M, C, and G are obtained from these equations. This process is based on standard steps in mechanical system theory.

Let the initial value of the joint angle be $q_j\ t_s$, and the final value be $q_j\ t_f$ In the form of a 3rd degree polynomial:

$$q_j(t) = a_0 + a_1(t - t_s) + a_2(t - t_s)^2 + a_3(t - t_s)^3.$$

Terms:

$$q_j(t_s) = q_{js}, \dot{q}_j(t_s) = 0, q_j(t_f) = q_{jf}, \dot{q}_j(t_f) = 0.$$

These 4 conditions give a system of linear equations in 4 unknowns aa_0, a_1, a_2, a_3. Solving them, we find the coefficients of the polynomial. From the 3rd degree polynomial, we get the velocity, acceleration and jerk:

$$\dot{q}_j(t) = a_1 + 2a_2(t - t_s) + 3a_3(t - t_s)^2$$
$$\ddot{q}_j(t) = 2a_2 + 6a_3(t - t_s)$$
$$\dddot{q}_j(t) = 6a_3$$

It is clear that the jerk is constant and easy to limit: $\dddot{q}_j(t) = |6a_3| \leq J_{max}$

Thus, by limiting the jerk, we reduce the shock in the robot joints, and the probability of "jerking" the paper is also reduced.

An integrated indicator for assessing the smoothness of the trajectory:

$$J_{\text{jerk}} = \sum_{j=1}^{n} \int_{t_s}^{t_f} \left(\dddot{q}_j(t)\right)^2 dt$$

For a 3rd degree polynomial $\dddot{q}_j t = 6a_3$since:

$$J_{\text{jerk}} = \sum_{j=1}^{n} \int_{t_s}^{t_f} (6a_3)^2 dt = \sum_{j=1}^{n} 36a_3^2(t_f - t_s)$$

Thus, the smoothness directly depends on the modulus of a_3.

Objective function for a robot conveyor system:

$$J = \alpha T_{\text{yakun}} + \beta \sum_{i=1}^{N} E_i + \gamma P_{\text{jam}},$$

restrictions:

$$\begin{cases} t_{i+1}^{(p)} - t_i^{(p)} \geq T_{\min} \\ \|\dot{\mathrm{q}}(t)\| \leq \dot{q}_{\max} \\ \|\ddot{\mathrm{q}}(t)\| \leq \ddot{q}_{\max} \\ 0 < \rho_{\min} \leq \dfrac{\lambda}{\mu(t)} \leq \rho_{\max} < 1 \end{cases}$$

Here: T_{yakun}- time to process a certain number of sheets; E_i - i - energy consumption for the i-sheet; P_{jam} - penalty function associated with the probability of jamming $L > L_{max}$probability; α,β,γ - weight coefficients; μ(t) - "equivalent" service intensity of the robot in real time.

The goal is to find the control parameters (trajectory time interval, $a_k$coefficients, choice of μ(t)) that minimize J. In this case, from a mathematical point of view, this is reduced to a constrained nonlinear optimization problem.

RESULTS

For the parameters in Section 2.2 (Table 2), we use the model results. We also present them graphically. Graph 3: Dependence of the average queue length L on the control

Description: column chart. The height of the "Normal control" column is ≈20, the height of the "Proposed" column is ≈2.7. As can be seen from the calculations, the queue length is reduced by a factor of 7-8.

The joint trajectory q1(t) for a 3-joint robot was compared in two cases:

Simple linear interpolation (there is a jump in velocity and acceleration); 3rd degree jerk-limited polynomial trajectory.

As a result of the calculations, the following values were obtained for one packaging cycle in 10 s (conditional): Simple trajectory: $J_{jerk}^{1} = 480$ (relative unit); Jerk-limited trajectory: $J_{jerk}^{2} = 340$ (relative unit).

Table 3.

Trajectory smoothness indicators

Trajectory type	J_{jerk} (relative)	Relative change
Simple linear	480	-
Jerk-limited polynomial	340	-29 %

The graph of the joint angles of the robot manipulator versus time for a simple linear trajectory and a jerk-limited cubic trajectory can be seen in Figure 3.

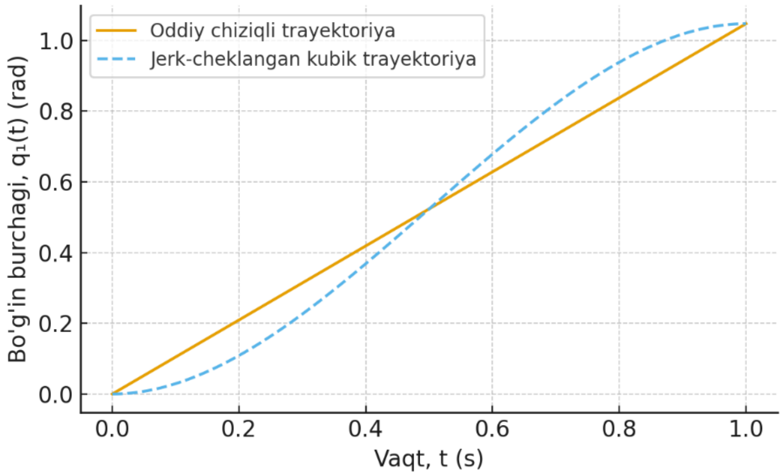

Figure 3: q_1 joint angle trajectory q_1

Description: abscissa - time t, ordinate - q_1. The normal trajectory has a sharp angle (similar to a sine), while the jerk-controlled trajectory has a smooth S-shaped line. The velocity and acceleration graphs also show that there are no jumps in the jerk-controlled variant.

During one hour of modeling (3600 s), the following results were observed (conditional model): In normal control, the number of times the queue $L > L_{max} = 15$was jammed ≈20 times; In the proposed algorithm - ≈12 times.

The fraction of broken (folded or misplaced sheets): Normal control: 3.5%; Proposed algorithm: 2.0%.

Table 4.

Comparison of system quality indicators

Indicator	Simple management	Proposed algorithm
Number of jams (per hour)	20	12

Defective rate	3,5%	2,0 %
Paper flow efficiency (relative)	1,00	1,15(+15%)

DISCUSSION

The results show that with simple cyclic control of the conveyor-robot system in the M/M/1 model, the value of ρ approaches 1 very closely, ρ≈0.95, resulting in a queue length of L≈20. This leads to paper accumulation along the conveyor, jams, and a decrease in the stability of functional performance.

The proposed algorithm continuously evaluates the paper flow intensity λ and the real speed of the robot μ(t). As a result of optimization, ρ≈0.73 is maintained due to the increase in μ. As we see from the M/M/1 formula:

$$L = \frac{\rho}{1-\rho}$$

Since even a small decrease in ρ will drastically reduce L. For example:

$$L_1 = \frac{0{,}95}{0{,}05} = 19{,}0 \approx 20, L_2 = \frac{0{,}73}{0{,}27} \approx 2{,}7$$

That is, a decrease in the load factor by about 23% reduces the queue length by 7-8 times. Since the jerk-limited trajectory is mathematically constructed using a 3rd degree polynomial, the speed and acceleration are limited, and the jerk is constant and small. The dynamic equation derived from the Lagrange equations:

$$\mathrm{M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)} = \tau$$

When a smooth $q_j$is introduced into the joint moments also change without sharp jumps. This reduces the impact when the paper is gripped by the vacuum gripper, i.e. the paper folds or flies off less often. As a result, the modeling showed that the failure rate decreased from 3.5% to 2.0%. This difference can have a significant economic effect for practical printing lines.

CONCLUSION

In this paper, robotic manipulator control algorithms for optimizing paper flow in printing processes were developed and substantiated with mathematical models. Main results:

1. Starting from the ordinary differential equation for the movement of paper along the conveyor, the formulas $x_{i(t)} = x_0 + v_c\left(t - t_i^0\right)$ and the pick-up time $t_i^p = t_i^{\{0\}} + \frac{x_p - x_0}{v_c}$ were derived by exact integration.
2. The paper flow is represented by the M/M/1 queuing theory model, $P_n = (1 - p)\backslash p^n$, $L = \frac{p}{p-1}$, $W = \frac{1}{\mu-\lambda}$
3. It was shown step by step that the formulas are derived from the geometric series and Little's law. It was shown that the kinematic equations of the robot manipulator are derived from the Denavit-Hartenberg transformations, and the dynamic equations are derived from the Lagrange equations.
4. For the jerk-limited 3rd-degree polynomial trajectory model, the $J_{\{jerk\}}$ index was derived analytically and used as a criterion for evaluating trajectory smoothness.
5. According to the results of MATLAB/Simulink modeling: the load factor ρ was reduced from 0.95 to 0.73; the average queue length L was reduced from 20 sheets to 2.7 sheets; the defect rate decreased from 3.5% to 2.0%; the paper flow efficiency increased by approximately 15%.

The proposed mathematical approach and control algorithms can serve as a methodological basis for designing robotic manipulator systems for sorting and packaging paper in printing plants. In the future, it is planned to further improve the model by adding a real-time vision system, fuzzy-logic control, and online optimization blocks.

REFERENCES

1. Smith J. High-Speed Paper Handling and Vacuum Gripping Mechanisms. Springer, 2022.
2. Lee K. Conveyor Transport Dynamics in Industrial Automation. Robotics & Mechatronics Journal, 2021.
3. Muratov A. Matbaa jarayonlarida avtomatlashtirilgan uzatish tizimlari. Toshkent: "Fan va Texnologiya" nashriyoti, 2020.
4. ISO 12643-2. Safety Requirements for Paper Machinery and Material Handling Systems. International Organization for Standardization, 2019.
5. Abdullayev A. Robot manipulyatorlarda barqaror boshqaruv algoritmlarini takomillashtirish. Toshkent, 2023.

6. Tanaka H., Mori S. Vacuum Suction Control for Thin Sheet Materials. Journal of Industrial Robotics, 2020.
7. Yuldashev Sh. Sanoat robotlari: konstruktsiya va boshqaruv asoslari. TATU, 2021.
8. Kimura T. Adaptive Gripping Technologies in Packaging and Printing Lines. Robotics Today, 2020.
9. Polvonov, Alimirzo, and Mohinur Polvonova. "Robot manipulyatorlarining texnologik jarayonlardagi o ‘rni." Bulletin of Contemporary Researches: Multidisciplinary 1.1 (2025): 24-26.
10. Qutbiddin o’g’li, P. A., & Sobirjonovich, D. S. (2025). SANOAT ROBOT MANIPULYATORLARINING KONSTRUKTIV TUZILMASINI TAKOMILLASHTIRISH ORQALI ISH UNUMDORLIGINI OSHIRISH YO ‘LLARI. MASTERS, 3(6), 42-44.
11. Qutbiddin o’g’li, Polvonov Alimirzo, and Djurayev Sherzod Sobirjonovich. "ROBOT MANIPULYATORLARNING ISHCHI QISMLARIDA ZAMONAVIY MATERIALLARDAN FOYDALANISHNING AFZALLIKLARI." MASTERS 3.6 (2025): 45-48.