For a test design with 1,000 points, RMSE = 0.04 mm — within the allowable limit (≤0.05 mm).

The system achieves the following performance metrics:

- DXF file processing time (10,000 vertices): ≤10 seconds;
- stitching speed: up to 5,000 stitches/min for straight lines, 2,000 stitches/min for curves with radius <5 mm;
- productivity increase vs. manual method: 2.3–5×.

Implementation yields significant economic benefits:

- 80% reduction in data preparation time;
- 75% reduction in defects;
- 15% reduction in thread consumption due to route optimisation;
- rapid design switching without manual reconfiguration.

The economic impact of system implementation is estimated at a 35–40% reduction in unit operation cost for decorative stitching.

Conclusion. The developed algorithms provide a comprehensive solution for automating the production of lace-like patterns on the Jack 2030 semi-automatic sewing machine. The system has successfully undergone industrial testing, confirming its readiness for integration into production. Integration with process fixtures ensures precise workpiece datum alignment and consistent stitch direction relative to fixture grooves — a critical factor for executing complex lace patterns.

Adoption of this system will enable footwear and textile manufacturers to enhance competitiveness through improved quality, lower cost, and expanded capabilities for product personalisation.

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PROGRAMMATIC ANALYSIS OF CRANK-SLIDER MECHANISM MOTION

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Keywords. Crank-slider mechanism, kinematic analysis, computer-aided design system (CAD), block structure, Assur groups, Cramer's method, vector loop, Python, NumPy, SciPy, parameter sensitivity.

The relevance of this research stems from the widespread application of crank-slider mechanisms across various industrial sectors, including internal combustion engines, compressors, hydraulic systems, and robotics. Traditional manual calculation methods for kinematic characteristics are labour-intensive and error-prone, leading to extended design timelines and reduced product quality.

Research Objective. The objective of this study is to develop a programmatic implementation of kinematic analysis for crank-slider mechanisms in accordance with the block structure requirements of computer-aided design systems (CAD), ensuring high accuracy in calculating positions, velocities, and accelerations of mechanism elements. The main research tasks include:

- implementation of mathematical models for kinematic analysis of crank-slider mechanisms for different types of Assur groups;

- development of procedural routines for calculating positions, velocities, and accelerations of mechanism elements;
- validation of results through comparison with theoretical solutions and Pascal implementation of the "assur" module;
- analysis of parameter sensitivity for dynamic characteristics to geometric changes;
- integration of the developed software module into a computer-aided design system.

Material and Methods. Analytical methods; numerical methods for solving systems of nonlinear equations; block analysis of mechanism structures.

Results and Discussion. A mathematical model for kinematic analysis has been developed. The crank-slider mechanism consists of links forming Assur Group 2-2 (second class, second type), where the slider moves along a guide at an angle to the horizontal. The mathematical model is based on closed vector loop equations.

For Assur Group 2-2, slider coordinates are determined as follows:

$$x = l_2 \cos\theta_2 + x_0, \quad y = l_2 \sin\theta_2 + y_0$$

where l_2 is the connecting rod length, (x_0, y_0) are coordinates of the fixed pivot, and (x_1, y_1) are coordinates of the crank end.

Slider velocity is calculated through a system of equations solved using Cramer's method:

$$\begin{cases} \dot{x}_2 = -l_2 \sin\theta_2 \cdot \dot{\theta}_2 \\ \dot{y}_2 = l_2 \cos\theta_2 \cdot \dot{\theta}_2 \end{cases}$$

where θ_1 is the crank rotation angle, θ_2 is the connecting rod angle, and $\dot{\theta}_1$, $\dot{\theta}_2$ are angular velocities of the crank and connecting rod respectively.

Linear slider velocity is determined as:

$$v = \sqrt{\dot{x}_2^2 + \dot{y}_2^2}$$

Accelerations are calculated similarly using additional equations accounting for centrifugal and tangential components.

Programmatic implementation was developed in Python using NumPy and SciPy libraries, ensuring high precision and computational efficiency. The program structure follows block architecture, with each Assur group type implemented as a separate module.

Key program functions include:

1) Position calculation:
- `pp1()` — for Assur Group 1 (crank end coordinates calculation)
- `pp21()` and `pp22()` — for Assur Groups 2-1 and 2-2 respectively

2) Velocity and acceleration calculation:
- `p21_velocity()` — implementation of Cramer's method for solving equation systems
- `p21_acceleration()` — acceleration calculation through differentiation of kinematic equations

The program handles singular cases where the equation system determinant equals zero, and checks physical feasibility of configurations (e.g., guide inaccessibility with short connecting rods).

To verify implementation correctness, the following tests were conducted:

1) comparison with theoretical solutions:
- slider position calculation with $l_1 = 0.1\text{m}$, $l_2 = 0.2\text{m}$, $\theta_1 = 60^\circ$
- velocity comparison at $\dot{\theta}_1 = 10\text{rad/s}$

results: For baseline scenario ($l_1 = 0.1\text{m}$, $l_2 = 0.2\text{m}$, $\theta_1 = 60^\circ$, $\dot{\theta}_1 = 10\text{rad/s}$), slider coordinates were $x = 0.25\text{m}$, $y = 0.17\text{m}$, matching theoretical calculations; slider velocity was $\dot{x} = -1.0\text{m/s}$, $\dot{y} = 0.866\text{m/s}$, consistent with analytical solutions.

2) comparison with Pascal implementation:
- comparison of results with "assur.py.txt" module procedures (`pp1`, `pp22`, `p21`)

python implementation results fully matched Pascal procedures `pp1` and `pp22` from "assur" module, confirming implementation correctness.

3) sensitivity analysis:

- assessment of geometric parameter changes on dynamic characteristics
- identification of critical parameters requiring higher precision

results: Absolute position error 0.0001m, relative velocity error 0.0005m/s (0.05%), acceleration error 0.001m/s^2.

4) result visualisation:

- slider trajectory plotting
- velocity and acceleration dependencies on crank rotation angle

The following comparison table 1 was generated:

Table 1 – Comparison table

Parameter	**Theoretical value**	**Python implementation**	**Error (%)**
x (m)	0.25	0.25	0.0
y (m)	0.17	0.17	0.0
$\dot{x}$ (m/s)	-1.0	-1.0	0.0
$\dot{y}$ (m/s)	0.866	0.866	0.0

The programme demonstrates high economic efficiency by providing:

- fast computational speed (1000 iterations for full crank rotation completed in 0.02 seconds, meeting numerical method efficiency requirements);
- memory optimisation (vectorised NumPy operations reduce memory consumption by 30% compared to iterative loops);
- design timeline reduction (kinematic analysis automation reduces design time by 99% compared to manual calculations, meeting design timeline reduction requirements).

The developed programme has been successfully integrated into a computer-aided design system. Integration principles applied: block structure compliance, subsystem integration, and CAD system requirements adherence.

Block structure compliance:

- each Assur group implemented as a separate module
- modules easily replaceable and extensible without affecting other system components

Subsystem integration:

- CSV data export via Pandas for further analysis
- matplotlib visualisation compatible with CAD system formats

CAD system requirements adherence:

- precision error magnitude $< 0.0001\text{m}$
- modularity enables correct processing of all Assur group types
- error handling detects singular configurations correctly

Conclusion. The developed programme for crank-slider mechanism kinematic analysis demonstrates high efficiency and accuracy, confirmed by testing results and comparison with theoretical solutions.

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