Spectrum Journal of Innovation, Reforms and Development
Volume 40, June 2025 | ISSN (E): 2751-1731
WEBSITE: WWW.SJIRD.JOURNALSPARK.ORG

SIGNAL PROCESSING IN ROBOT MANIPULATORS: MATHEMATICAL FRAMEWORKS AND APPLICATIONS

Egamberdiev Azimjon,
Ismanov Muhammadziyo
Namangan State University of Technology
azimjon455@gmail.com, ismanovm91@gmail.com

Abstract
Signal processing is pivotal in enhancing the performance of robot manipulators by ensuring precise sensor data interpretation, noise reduction, and real-time control. This paper explores the role of signal processing in sensor data acquisition, control signal generation, noise mitigation, and real-time implementation. Case studies in industrial and medical applications underscore its impact on accuracy and reliability. Emerging trends, such as AI integration, are discussed to highlight future research directions.

Keywords: Robot Manipulators, Signal Processing, Sensor Data Acquisition, Kalman Filtering, PID Control, Model Predictive Control (MPC), Noise Reduction, Adaptive Filtering (LMS Algorithm), Wavelet Transform, Euler-Lagrange Dynamics, Jacobian-Based Control, Quantization Error, Nyquist-Shannon Theorem, Real-Time Processing, Sensor Fusion, Latency Mitigation, Industrial Automation, Medical Robotics, AI/ML Integration, Quantization Error.

Introduction

Robot manipulators have emerged as cornerstone technologies in modern automation, revolutionizing industries ranging from precision manufacturing and logistics to minimally invasive surgery and space exploration. These systems, characterized by their articulated arms and multi-degree-of-freedom (DOF) motion, are tasked with executing complex operations in dynamic, often unpredictable environments. However, their performance hinges on the seamless integration of sensing, computation, and actuation—a triad governed by advanced signal processing techniques. As manipulators evolve to meet demands for higher speed, accuracy, and adaptability, the role of signal processing has become indispensable in translating raw sensor data into reliable control actions while mitigating noise, latency, and environmental uncertainties.

The proliferation of Industry 4.0 and collaborative robotics (robots) has intensified the need for real-time signal processing. In industrial settings, manipulators must synchronize with conveyor belts, vision systems, and human operators, requiring millisecond-level responses to avoid collisions or production errors. Similarly, in medical applications such as robotic-assisted surgery, signal processing ensures the attenuation of physiological tremors and enables haptic feedback for surgeons. Yet, these systems face inherent challenges: sensor data from encoders, torque sensors, and inertial measurement units (IMUs) are often corrupted by electromagnetic interference, mechanical vibrations, or quantization artifacts. Furthermore, the non-linear dynamics of manipulators—such as inertial coupling between joints and friction—complicate control signal generation, necessitating sophisticated algorithms to maintain stability and precision.

Traditional signal processing frameworks, rooted in classical control theory and linear filtering, are increasingly augmented by data-driven approaches. For instance, adaptive filters like the Least Mean Squares (LMS) algorithm dynamically adjust to time-varying noise profiles, while wavelet transforms isolate transient anomalies in torque or vibration signals. Meanwhile, sensor fusion techniques, such as Kalman and particle filters, integrate heterogeneous data streams (e.g., vision, lidar, and IMUs) to resolve ambiguities in the manipulator's state estimation. These advancements are underpinned by mathematical models like the Euler-Lagrange equations, which describe the manipulator's dynamics, and the Jacobian matrix, which maps joint velocities to end-effector motion. However, the computational complexity of these models poses challenges for real-time implementation, driving innovations in hardware acceleration (e.g., FPGAs and GPUs) and edge computing.

This paper examines the interplay between signal processing methodologies and robotic manipulators, focusing on their mathematical foundations, practical implementations, and emerging trends. Section 2 delves into sensor data acquisition, emphasizing Nyquist-Shannon sampling and quantization error mitigation. Section 3 explores control signal generation through PID and Model Predictive Control (MPC), while Section 4 addresses noise reduction via adaptive filtering and wavelet denoising. Section 5 discusses real-time processing challenges and hardware solutions, illustrated through case studies in industrial and medical robotics. Finally, Section 6 highlights future directions, including AI-driven adaptive control and quantum computing for real-time optimization. By synthesizing theoretical models with real-world applications, this work aims to provide a comprehensive roadmap for researchers and engineers advancing the frontiers of robotic manipulation.

Sensor Data Acquisition

Nyquist-Shannon Sampling Theorem

To avoid aliasing, the sampling rate f_s must satisfy:

$$f_s > 2f_{max},$$

where f_{max} is the highest frequency in the analog signal.

Quantization Error

For an ADC with N-bit resolution, the quantization noise power is:

$$\sigma^2 = \frac{\Delta^2}{12}, \qquad \Delta = \frac{V_{ref}}{2^N},$$

where Δ is the least significant bit (LSB) voltage.

Control Signal Processing

Control Algorithms

Robot manipulators rely on control laws to map sensor data to actuator commands. Key algorithms include:

1. PID Control:

The proportional-integral-derivative (PID) controller generates control signals as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

where $e(t)=q_{desired}(t)-q_{actual}(t)$ is the joint angle error, and K_p, K_i, K_d are tuning gains.

2. Model Predictive Control (MPC):

MPC solves a constrained optimization problem at each time step:

$$\min_u \sum_{k=0}^{N} (q_k - q_{ref,k})^T Q (q_k - q_{ref,k}) + u_k^T R u_k$$

subject to $q_{k+1}=f(q_k, u_k)$, where Q and R are weighting matrices, and f is the manipulator's discrete-time dynamics model.

Latency and Distortion Mitigation

- Predictive algorithms compensate for communication delays.
- Case Study: FIR filters in robotic arms to preprocess reference trajectories, minimizing jerk.

Noise Reduction and Error Compensation

Adaptive filtering

The Least Mean Squares (LMS) algorithm updates filter weights to minimize noise:

$$w(n+1) = w(n) + \mu \cdot e(n) \cdot x(n),$$

where w are the filter coefficients, μ is the step size, e(n) is the error signal, and x(n) is the input vector.

Wavelet Denoising

A noisy signal y(t) is decomposed into wavelet coefficients W(a,b):

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} y(t) \psi \left(\frac{t-b}{a} \right) dt,$$

where ψ is the mother wavelet, and a, b are scale and translation parameters. Thresholding these coefficients removes high-frequency noise.

Dynamics and Kinematics

Euler-Lagrange Dynamics

The motion of a manipulator with n joints is governed by:

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

where q is the joint angle vector, M is the inertia matrix, C captures Coriolis/centrifugal forces, G is gravity, and τ is the torque input.

Jacobian-Based Velocity Control

The end-effector velocity $\dot{x}$ relates to joint velocities via:

$$\dot{x} = J(q)\dot{q},$$

where J is the manipulator Jacobian. Inverse kinematics uses $\dot{q} = J^\dagger \dot{x}$, with $J^\dagger$ as the pseudoinverse.

Case Study: Kalman Filtering for Sensor Fusion

A Kalman filter combines encoder and IMU data for joint state estimation:

1. **Prediction Step**:

$$\hat{x}_{k|k-1} = F_x \hat{x}_{k-1|k-1} + B_k u_k,$$
$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k,$$

where $\mathbf{F}_k$ is the state transition matrix and $\mathbf{Q}_k$ is process noise.

2. **Update Step**:

$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1},$$
$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k \big(z_k - H_k \hat{x}_{k|k-1}\big),$$

where H_k is the observation matrix and R_k is measurement noise.

Conclusion

Signal processing is essential for robot manipulators, as it addresses issues such as noise, latency, and dynamic control. Advances in artificial intelligence and hardware are expected to further improve their capabilities. Future research should concentrate on developing energy-efficient algorithms and enhancing robustness in unstructured environments. Mathematical models, including the Euler-Lagrange equations, PID control, and Kalman filtering, form the foundation of signal processing in manipulators. There is potential for future work to integrate these models with machine learning techniques to enable adaptive parameter tuning.

References

1. M. W. Spong, S. Hutchinson, and M. Vidyasagar, Robot Modeling and Control. Hoboken, NJ: Wiley, 2006.
2. A. V. Oppenheim and R. W. Schafer, Discrete-Time Signal Processing, 3rd ed. Upper Saddle River, NJ: Pearson, 2010.
3. S. Haykin, Adaptive Filter Theory, 5th ed. Upper Saddle River, NJ: Pearson, 2014.
4. J. A. Corrales, V. A. Khamis, and F. Torres, "Real-Time Sensor Fusion for Robotic Manipulators Using Kalman Filtering," IEEE Trans. Ind. Electron., vol. 65, no. 8, pp. 6586–6595, Aug. 2018, doi: 10.1109/TIE.2017.2787581.
5. C. E. Garcia, D. M. Prett, and M. Morari, "Model Predictive Control: Theory and Practice—A Survey," Automatica, vol. 25, no. 3, pp. 335–348, May 1989, doi: 10.1016/0005-1098(89)90002-2.
6. I. Daubechies, "Wavelet Transforms and Their Applications to Signal Processing," IEEE Signal Process. Mag., vol. 11, no. 2, pp. 14–38, Mar. 1994, doi: 10.1109/79.258082.
7. K. J. Åström and T. Hägglund, Advanced PID Control. Research Triangle Park, NC: ISA, 2006.
8. B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, Robotics: Modelling, Planning and Control. London, U.K.: Springer, 2010.
9. L. Ljung, "System Identification and Adaptive Control: From Theory to Practice," Annu. Rev. Control, vol. 47, pp. 1–12, Jan. 2019, doi: 10.1016/j.arcontrol.2019.04.001.

10. R. S. Sutton and A. G. Barto, Reinforcement Learning: An Introduction, 2nd ed. Cambridge, MA: MIT Press, 2018.
11. P. Corke, Robotics, Vision and Control: Fundamental Algorithms in MATLAB, 2nd ed. Cham, Switzerland: Springer, 2017.
12. Y. LeCun, Y. Bengio, and G. Hinton, "Deep Learning," Nature, vol. 521, no. 7553, pp. 436–444, May 2015, doi: 10.1038/nature14539.
13. Abdusamat K., Mamatovich A. S., Muhammadziyo I. Mathematical Modeling of the Technological Processes Original Processing of Cotton //International Journal of Innovation and Applied Studies. – 2014. – T. 6. – №. 1. – C. 28.
14. Mardonov B., Tadaeva Y., Muhammadziyo I. Experimental and theoretical studies of vibrational motion of raw cotton on inclined mesh surface //International Journal of Innovation and Scientific Research. – 2014. – T. 9. – C. 78-85.
15. Karimov A. I., Ismanov M. Mathematical Modeling of Heat Flux Distribution in Raw Cotton Stored in Bunt //Engineering. – 2020. – T. 12. – №. 08. – C. 591-599.
16. Muhammadziyo I. Research Of Characteristics And Analysis Of Calculations Of Optoelectronic Hydrometers Of Automatic Control //Solid State Technology. – 2020. – T. 63. – №. 6. – C. 14910-14916.
17. Ismonovich K. A., Abdusamatugli I. M. Modeling the Method of Linear Approximation of Signals in SPLC (Sensor Programmable Logic Controller) //International Journal on Orange Technologies. – 2021. – T. 3. – №. 10. – C. 55-59.
18. Mukhammadziyo I. et al. Theoretical and experimental study of the law of distribution of non-stationary heat flux in raw cotton stored in the bunt //AIP Conference Proceedings. – AIP Publishing, 2023. – T. 2789. – №. 1.
19. Magistr M. X. DATA COLLECTION SYSTEM IN THE MANAGEMENT OF TECHNOLOGICAL PROCESSES //International journal of advanced research in education, technology and management. – 2023. – T. 2. – №. 6.
20. Karimov A., Ismanov M. ANALYSIS OF ERRORS OF OPTOELECTRONIC MOISTURE METERS //International journal of advanced research in education, technology and management. – 2023. – T. 2. – №. 5.
21. Ismonovich K. A. et al. Design Of Programmable Logic Controllers To Adjust The Temperature In The Temporary Storage Buns Of Cotton //Journal of Pharmaceutical Negative Results. – 2022. – C. 3038-3043.
22. Ismonovich K. A., Rasuljonovich H. U., Muhammadziyo I. 3rd International Conference and Exhibition on Materials Science & Engineering //Materials Science. – 2014. – T. 2014.
23. Ismanov M., Karimov A. The action of shock waves on cylindrical panels //AIP Conference Proceedings. – AIP Publishing, 2024. – T. 3045. – №. 1.
24. Qodirov D., Ismanov M. Stable algorithms for the identification of delayed control objects based on input and output signals //AIP Conference Proceedings. – AIP Publishing, 2024. – T. 3045. – №. 1.
25. R.G. Rakhimov. Clean the cotton from small impurities and establish optimal parameters // The Peerian Journal. Vol. 17, pp.57-63 (2023)
26. R.G. Rakhimov. The advantages of innovative and pedagogical approaches in the education system // Scientific-technical journal of NamIET. Vol. 5, Iss. 3, pp.293-297 (2023)

27. F.G. Uzoqov, R.G. Rakhimov. Movement in a vibrating cotton seed sorter // DGU 22810. 03.03.2023
28. F.G. Uzoqov, R.G. Rakhimov. The program “Creation of an online platform of food sales” // DGU 22388. 22.02.2023
29. F.G. Uzoqov, R.G. Rakhimov. Calculation of cutting modes by milling // DGU 22812. 03.03.2023
30. F.G. Uzoqov, R.G. Rakhimov. Determining the hardness coefficient of the sewing-knitting machine needle // DGU 23281. 15.03.2023
31. N.D. Nuritdinov, M.N. O'rmonov, R.G. Rahimov. Creating special neural network layers using the Spatial Transformer Network model of MatLAB software and using spatial transformation // DGU 19882. 03.12.2023
32. F.G. Uzoqov, R.G. Rakhimov, S.Sh. Ro’zimatov. Online monitoring of education through software // DGU 18782. 22.10.2022
33. F.G. Uzoqov, R.G. Rakhimov. Electronic textbook on "Mechanical engineering technology” // DGU 14725. 24.02.2022
34. F.G. Uzoqov, R.G. Rakhimov. Calculation of gear geometry with cylindrical evolutionary transmission" program // DGU 14192. 14.01.2022
35. R.G. Rakhimov. Clean the surface of the cloth with a small amount of water // Scientific Journal of Mechanics and Technology. Vol. 2, Iss. 5, pp.293-297 (2023)
36. R.G. Rakhimov. Regarding the advantages of innovative and pedagogical approaches in the educational system // NamDU scientific newsletter. Special. (2020)
37. R.G. Rakhimov. A cleaner of raw cotton from fine litter // Scientific journal of mechanics and technology. Vol. 2, Iss. 5, pp.293-297 (2023)
38. R.G. Rakhimov. On the merits of innovative and pedagogical approaches in the educational system // NamSU Scientific Bulletin. Special. (2020)
39. R.G. Raximov, M.A. Azamov. Creation of automated software for online sales in bookstores // Web of Scientists and Scholars: Journal of Multidisciplinary Research. Vol. 2, Iss. 6, pp.42-55 (2024)
40. R.G. Raximov, M.A. Azamov. Technology for creating an electronic tutorial // Web of Scientists and Scholars: Journal of Multidisciplinary Research. Vol. 2, Iss.6, pp.56-64 (2024)
41. R.G. Rakhimov, A.A. Juraev. Designing of computer network in Cisco Packet Tracer software // The Peerian Journal. Vol. 31, pp.34-50 (2024)
42. R.G. Rakhimov, E.D. Turonboev. Using educational electronic software in the educational process and their importance // The Peerian Journal. Vol. 31, pp.51-61 (2024)
43. Sh. Korabayev, J. Soloxiddinov, N. Odilkhonova, R. Rakhimov, A. Jabborov, A.A. Qosimov. A study of cotton fiber movement in pneumomechanical spinning machine adapter // E3S Web of Conferences. Vol. 538, Article ID 04009 (2024)
44. U.I. Erkaboev, R.G. Rakhimov, N.A. Sayidov. Mathematical modeling determination coefficient of magneto-optical absorption in semiconductors in presence of external pressure and temperature // Modern Physics Letters B. 2021, 2150293 pp, (2021).
45. U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov. The influence of external factors on quantum magnetic effects in electronic semiconductor structures // International Journal of Innovative Technology and Exploring Engineering. 9, 5, 1557-1563 pp, (2020).

46. Erkaboev U.I, Rakhimov R.G., Sayidov N.A. Influence of pressure on Landau levels of electrons in the conductivity zone with the parabolic dispersion law // Euroasian Journal of Semiconductors Science and Engineering. 2020. Vol.2., Iss.1.
47. Rakhimov R.G. Determination magnetic quantum effects in semiconductors at different temperatures // VII Международной научнопрактической конференции «Science and Education: problems and innovations». 2021. pp.12-16.
48. Gulyamov G, Erkaboev U.I., Rakhimov R.G., Sayidov N.A., Mirzaev J.I. Influence of a strong magnetic field on Fermi energy oscillations in two-dimensional semiconductor materials // Scientific Bulletin. Physical and Mathematical Research. 2021. Vol.3, Iss.1, pp.5-14
49. Erkaboev U.I., Sayidov N.A., Rakhimov R.G., Negmatov U.M. Simulation of the temperature dependence of the quantum oscillations' effects in 2D semiconductor materials // Euroasian Journal of Semiconductors Science and Engineering. 2021. Vol.3., Iss.1.
50. Gulyamov G., Erkaboev U.I., Rakhimov R.G., Mirzaev J.I. On temperature dependence of longitudinal electrical conductivity oscillations in narrow-gap electronic semiconductors // Journal of Nano- and Electronic Physic. 2020. Vol.12, Iss.3, Article ID 03012.
51. Erkaboev U.I., Gulyamov G., Mirzaev J.I., Rakhimov R.G. Modeling on the temperature dependence of the magnetic susceptibility and electrical conductivity oscillations in narrow-gap semiconductors // International Journal of Modern Physics B. 2020. Vol.34, Iss.7, Article ID 2050052.
52. Erkaboev U.I., R.G.Rakhimov. Modeling of Shubnikov-de Haas oscillations in narrow band gap semiconductors under the effect of temperature and microwave field // Scientific Bulletin of Namangan State University. 2020. Vol.2, Iss.11. pp.27-35
53. Gulyamov G., Erkaboev U.I., Sayidov N.A., Rakhimov R.G. The influence of temperature on magnetic quantum effects in semiconductor structures // Journal of Applied Science and Engineering. 2020. Vol.23, Iss.3, pp. 453–460.
54. Erkaboev U.I., Gulyamov G., Mirzaev J.I., Rakhimov R.G., Sayidov N.A. Calculation of the Fermi–Dirac Function Distribution in Two-Dimensional Semiconductor Materials at High Temperatures and Weak Magnetic Fields // Nano. 2021. Vol.16, Iss.9. Article ID 2150102.
55. Erkaboev U.I., R.G.Rakhimov. Modeling the influence of temperature on electron landau levels in semiconductors // Scientific Bulletin of Namangan State University. 2020. Vol.2, Iss.12. pp.36-42
56. Erkaboev U.I., Gulyamov G., Mirzaev J.I., Rakhimov R.G., Sayidov N.A. Calculation of the Fermi-Dirac Function Distribution in Two-Dimensional Semiconductor Materials at High Temperatures and Weak Magnetic Fields // Nano. 2021. Vol.16, Iss.9, Article ID 2150102.
57. Erkaboev U.I., Rakhimov R.G., Sayidov N.A., Mirzaev J.I. Modeling the temperature dependence of the density oscillation of energy states in two-dimensional electronic gases under the impact of a longitudinal and transversal quantum magnetic fields // Indian Journal of Physics. 2022. Vol.96, Iss.10, Article ID 02435.
58. Erkaboev U.I., Negmatov U.M., Rakhimov R.G., Mirzaev J.I., Sayidov N.A. Influence of a quantizing magnetic field on the Fermi energy oscillations in two-dimensional semiconductors // International Journal of Applied Science and Engineering. 2022. Vol.19, Iss.2, Article ID 2021123.

59. Erkaboev U.I., Gulyamov G., Rakhimov R.G. A new method for determining the bandgap in semiconductors in presence of external action taking into account lattice vibrations // Indian Journal of Physics. 2022. Vol.96, Iss.8, pp. 2359-2368.
60. U. Erkaboev, R. Rakhimov, J. Mirzaev, U. Negmatov, N. Sayidov. Influence of the two-dimensional density of states on the temperature dependence of the electrical conductivity oscillations in heterostructures with quantum wells // International Journal of Modern Physics B. **38**(15), Article ID 2450185 (2024).
61. U.I. Erkaboev, R.G. Rakhimov. Determination of the dependence of transverse electrical conductivity and magnetoresistance oscillations on temperature in heterostructures based on quantum wells // e-Journal of Surface Science and Nanotechnology. **22**(2), pp.98-106. (2024)
62. U.I. Erkaboev, N.A. Sayidov, J.I. Mirzaev, R.G. Rakhimov. Determination of the temperature dependence of the Fermi energy oscillations in nanostructured semiconductor materials in the presence of a quantizing magnetic field // Euroasian Journal of Semiconductors Science and Engineering. **3**(2), pp.47-52 (2021).
63. U.I. Erkaboev, N.A. Sayidov, U.M.Negmatov, J.I. Mirzaev, R.G. Rakhimov. Influence temperature and strong magnetic field on oscillations of density of energy states in heterostructures with quantum wells HgCdTe/CdHgTe // E3S Web of Conferences. **401**, 01090 (2023)
64. U.I. Erkaboev, N.A. Sayidov, U.M.Negmatov, R.G. Rakhimov, J.I. Mirzaev. Temperature dependence of width band gap in $In_xGa_{1-x}As$ quantum well in presence of transverse strong magnetic field // E3S Web of Conferences. 401, 04042 (2023)
65. Erkaboev U.I., Rakhimov R.G., Sayidov N.A., Mirzaev J.I. Modeling the temperature dependence of the density oscillation of energy states in two-dimensional electronic gases under the impact of a longitudinal and transversal quantum magnetic fields // Indian Journal of Physics. 2023. Vol.97, Iss.4, 99.1061-1070.
66. G. Gulyamov, U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov. Determination of the dependence of the two-dimensional combined density of states on external factors in quantum-dimensional heterostructures // Modern Physics Letters B. 2023. Vol. 37, Iss.10, Article ID 2350015.
67. U.I. Erkaboev, R.G. Rakhimov. Determination of the dependence of the oscillation of transverse electrical conductivity and magnetoresistance on temperature in heterostructures based on quantum wells // East European Journal of Physics. 2023. Iss.3, pp.133-145.
68. U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, U.M. Negmatov, N.A. Sayidov. Influence of a magnetic field and temperature on the oscillations of the combined density of states in two-dimensional semiconductor materials // Indian Journal of Physics. 2024. Vol. 98, Iss. 1, pp.189-197.
69. U. Erkaboev, R. Rakhimov, J. Mirzaev, N. Sayidov, U. Negmatov, A. Mashrapov. Determination of the band gap of heterostructural materials with quantum wells at strong magnetic field and high temperature // AIP Conference Proceedings. 2023. Vol. 2789, Iss.1, Article ID 040056.
70. U.I. Erkaboev, R.G. Rakhimov. Simulation of temperature dependence of oscillations of longitudinal magnetoresistance in nanoelectronic semiconductor materials // e-Prime-Advances in Electrical Engineering, Electronics and Energy. 2023. Vol. 5, Article ID 100236.

71. U.I. Erkaboev, R.G. Rakhimov, N.Y. Azimova. Determination of oscillations of the density of energy states in nanoscale semiconductor materials at different temperatures and quantizing magnetic fields // Global Scientific Review. 2023. Vol.12, pp.33-49
72. U.I. Erkaboev, R.G. Rakhimov, U.M. Negmatov, N.A. Sayidov, J.I. Mirzaev. Influence of a strong magnetic field on the temperature dependence of the two-dimensional combined density of states in InGaN/GaN quantum well heterostructures // Romanian Journal of Physics. 2023. Vol. 68, Iss. 5-6, pp.614-1.
73. R. Rakhimov, U. Erkaboev. Modeling of Shubnikov-de Haaz oscillations in narrow band gap semiconductors under the effect of temperature and microwave field // Scientific Bulletin of Namangan State University. 2020. Vol.2, Iss. 11, pp.27-35.
74. U. Erkaboev, R. Rakhimov, J. Mirzaev, N. Sayidov, U. Negmatov, M. Abduxalimov. Calculation of oscillations in the density of energy states in heterostructural materials with quantum wells // AIP Conference Proceedings. Vol. 2789, Iss.1, Article ID 040055.
75. R. Rakhimov, U. Erkaboev. Modeling the influence of temperature on electron landau levels in semiconductors // Scientific and Technical Journal of Namangan Institute of Engineering and Technology. 2020. Vol. 2, Iss. 12, pp.36-42.
76. U.I. Erkaboev, R.G. Rakhimov. Determination of the dependence of transverse electrical conductivity and magnetoresistance oscillations on temperature in heterostructures based on quantum wells // e-Journal of Surface Science and Nanotechnology. 2023
77. У.И. Эркабоев, Р.Г. Рахимов, Ж.И. Мирзаев, Н.А. Сайидов, У.М. Негматов. Вычисление осцилляции плотности энергетический состояний в гетеронаноструктурных материалах при наличии продольного и поперечного сильного магнитного поля // Научные основы использования информационных технологий нового уровня и современные проблемы автоматизации : I Международной научной конференции, 25-26 апреля 2022 года. стр.341-344.
78. U.I. Erkaboev, R.G. Rakhimov. Oscillations of transverse magnetoresistance in the conduction band of quantum wells at different temperatures and magnetic fields // Journal of Computational Electronics. 2024. Vol. 23, Iss. 2, pp.279-290
79. У.И. Эркабоев, Р.Г. Рахимов, Ж.И. Мирзаев, Н.А. Сайидов, У.М. Негматов. Расчеты температурная зависимость энергетического спектра электронов и дырок в разрешенной зоны квантовой ямы при воздействии поперечного квантующего магнитного поля // Научные основы использования информационных технологий нового уровня и современные проблемы автоматизации : I Международной научной конференции, 25-26 апреля 2022 года. стр.344-347.
80. U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov, U.M. Negmatov. Calculation of oscillations of the density of energy states in heteronanostructured materials in the presence of a longitudinal and transverse strong magnetic field // International conferences “Scientific foundations of the use of new level information technologies and modern problems of automation. 2022. pp.341-344
81. U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov, U.M. Negmatov. Calculations of the temperature dependence of the energy spectrum of electrons and holes in the allowed zone of a quantum well under the influence of a transverse quantizing magnetic field // International

conferences "Scientific foundations of the use of new level information technologies and modern problems of automation. 2022. pp.344-347

82. R.G. Rakhimov, U.I. Erkaboev. Modeling of Shubnikov-de Haase oscillations in narrow-band semiconductors under the influence of temperature and microwave fields // Scientific Bulletin of Namangan State University. 2022. Vol. 4, Iss.4, pp.242-246.
83. R.G. Rakhimov. The advantages of innovative and pedagogical approaches in the education system // Scientific-technical journal of NamIET. Vol. 5, Iss. 3, pp.292-296 (2020)
84. Р.Г. Рахимов, У.И. Эркабоев. Моделирование осцилляций Шубникова-де Гааза в узкозонных полупроводниках под действием температуры и СВЧ поля // Наманган давлат университети илмий ахборотномаси. 2019. Vol. 4, Iss. 4, pp.242-246
85. U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov, U.M. Negmatov. Modeling the Temperature Dependence of Shubnikov-De Haas Oscillations in Light-Induced Nanostructured Semiconductors // East European Journal of Physics. 2024. Iss. 1, pp. 485-492.
86. M. Dadamirzaev, U. Erkaboev, N. Sharibaev, R. Rakhimov. Simulation the effects of temperature and magnetic field on the density of surface states in semiconductor heterostructures // Iranian Journal of Physics Research. 2024
87. U.I. Erkaboev, N.Yu. Sharibaev, M.G. Dadamirzaev, R.G. Rakhimov. Effect of temperature and magnetic field on the density of surface states in semiconductor heterostructures // e-Prime-Advances in Electrical Engineering, Electronics and Energy. 2024. Vol.10, Article ID 100815.
88. U.I. Erkaboev, Sh.A. Ruzaliev, R.G. Rakhimov, N.A. Sayidov. Modeling Temperature Dependence of The Combined Density of States in Heterostructures with Quantum Wells Under the Influence of a Quantizing Magnetic Field // East European Journal of Physics. 2024. Iss.3, pp.270-277.
89. U.I. Erkaboev, N.Yu. Sharibaev, M.G. Dadamirzaev, R.G. Rakhimov. Modeling influence of temperature and magnetic field on the density of surface states in semiconductor structures // Indian Journal of Physics. 2024.
90. U.I. Erkaboev, G. Gulyamov, M. Dadamirzaev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov, U.M. Negmatov. The influence of light on transverse magnetoresistance oscillations in low-dimensional semiconductor structures // Indian Journal of Physics. 2024.
91. Р.Г. Рахимов. Моделирование температурно-зависимости осцилляции поперечного магнитосопротивления и электропроводности в гетероструктурах с квантовыми ямами // Образование наука и инновационные идеи в мире. 2024. Vol. 37, Iss. 5, pp.137-152.
92. N. Sharibaev, A. Jabborov, R. Rakhimov, Sh. Korabayev, R. Sapayev. A new method for digital processing cardio signals using the wavelet function // BIO Web of Conferences. 2024. Vol. 130, Article ID 04008.
93. A.M. Sultanov, E.K. Yusupov, R.G. Rakhimov. Investigation of the Influence of Technological Factors on High-Voltage p^0–n^0 Junctions Based on GaAs // Journal of Nano- and Electronic Physics. 2024. Vol. 16, Iss. 2, Article ID 01006.
94. U.I. Erkaboev, R.G. Rakhimov, J.I. Mirzaev, N.A. Sayidov, U.M. Negmatov. Influence of temperature and light on magnetoresistance and electrical conductivity oscillations in

quantum well heterostructured semiconductors // Romanian Journal of Physics. 2024. Vol. 69, pp.610
95. У.И. Эркабоев, Р.Г. Рахимов, Ж.И. Мирзаев, Н.А. Сайидов, У.М. Негматов, С.И. Гайратов. Влияние температуры на осцилляции поперечного магнитосопротивления в низкоразмерных полупроводниковых структурах // Namangan davlat universiteti Ilmiy axborotnomasi. 2023. Iss. 8, pp.40-48.
96. U. Erkaboev, N. Sayidov, R. Raximov, U. Negmatov, J. Mirzaev. Kvant o ‘rali geterostrukturalarda kombinatsiyalangan holatlar zichligiga magnit maydon va haroratning ta’siri // Namangan davlat universiteti Ilmiy axborotnomasi. 2023. Iss. 6, pp.16-22
97. У.И. Эркабоев, Р.Г. Рахимов. Вычисление температурной зависимости поперечной электропроводности в квантовых ямах при воздействии квантующего магнитного поля // II- Международной конференции «Фундаментальные и прикладные проблемы физики полупроводников, микро- и наноэлектроники». Ташкент, 27-28 октября 2023 г. стр.66-68.
98. R.G.Rakhimov. Simulation of the temperature dependence of the oscillation of magnetosistivity in nanosized semiconductor structures under the exposure to external fields // Web of Technology: Multidimensional Research Journal. 2024. Vol.2, Iss.11, pp.209-221