ABSTRACT

of the dissertation by Gui-Jun Wu on the topic: "Control Algorithm and Dynamics of a Lower Limb Rehabilitation Robot Based on an Innovative Electric Drive", submitted for the degree of Doctor of Philosophy (PhD) in the field of 650500 – Theoretical and Applied Mechanics.

1. The dissertation was completed at the Department of "Mechanics and Industrial Engineering" of the Kyrgyz State Technical University named after I. Razzakov.

2. The topic and academic supervisors were approved by the Academic Council of the Kyrgyz State Technical University named after I. Razzakov (Protocol No. 3 dated November 24, 2021).

3. Academic Supervisors:

Turatbek Bolotbekovich Duishenaliev, Doctor of Technical Sciences, Professor, Kyrgyz State Technical University named after I. Razzakov.

Igor Vladimirovich Merkuryev, Doctor of Technical Sciences, Professor, National Research University “Moscow Power Engineering Institute,” Moscow, Russia.

4. **Relevance of the Research Topic:**

Impairments in lower limb motor functions caused by stroke and spinal cord injuries significantly affect the patient’s recovery of motor activity and independence. Traditional rehabilitation requires intensive labor from specialists and is associated with high costs. The development of a robot capable of providing support, guided movement, and individualized control is crucial to improving the quality and accessibility of medical rehabilitation.

5. Research Objective:

To develop a robotic system for supporting and training the lower limbs and lower back of the patient using adaptive and intelligent control methods.

6. Research Tasks:

To achieve the stated goal, the dissertation addressed the following tasks:

A review of the current state and development trends of lower limb rehabilitation robots was conducted, and key technical requirements and challenges were identified.

A multi-degree-of-freedom robotic structure was developed, including modules for vertical lifting, horizontal movement, and lumbar support.

Kinematic and dynamic models of the system were constructed using the Denavit–Hartenberg method and Lagrange equations, taking into account the reduction of friction through the application of nano-lubrication.

Combined control algorithms were implemented based on the admittance approach, PID regulation, and sliding mode control to ensure stable and smooth control.

A patient intention recognition module was developed based on pressure and torque sensor signals using a modified fuzzy logic control method.

A comparison of Kalman, FIR, and IIR filters was conducted, and the optimal solution for real-time sensor signal filtering was selected.

A fully functional experimental prototype was created and tested, confirming the system’s operability under conditions close to clinical environments.

7. Scientific Novelty of the Research:

Within the framework of the study, a mathematical model of a multi-link rehabilitation robot was developed based on the Denavit–Hartenberg method and Lagrange equations, incorporating reduced friction through the use of nano-lubrication. An adaptive combined control algorithm was proposed, integrating impedance and PID regulation as well as sliding mode control to enhance robustness. For the first time, a hybrid eddy current brake was integrated into the lifting column, enabling contactless smooth braking. Wear-resistant composite materials (high-chromium cast iron and high-manganese steel) and nanotechnologies were used to improve structural reliability. The control system was implemented based on pressure and torque sensor signals using a modified fuzzy control method. The advantage of the Kalman filter for real-time applications was confirmed through comparison with FIR and IIR filters.

8. Practical Significance:

The developed rehabilitation robot system for lower limbs was realized as a fully functional experimental prototype and successfully tested under conditions close to real clinical rehabilitation. The proposed technical solution incorporates a multi-degree-of-freedom structure, a hybrid eddy current brake with smooth braking, and impedance, sliding mode, and PID control algorithms to ensure flexible interaction with the patient.

The system effectively relieves the lumbar region, assists patient movements during training, and activates patient participation in the recovery process. The implementation of signal filtering algorithms and intention recognition significantly expands the possibilities of intelligent human–machine interaction.

The results obtained have practical significance for the development of serial medical rehabilitation devices, possess high commercialization potential, and can be integrated into clinical practice.

9. Main Provisions Submitted for Defense:

A multi-degree-of-freedom rehabilitation robot structure is proposed, featuring vertical and horizontal actuators, lumbar support, and a mobile platform.

A combined control algorithm “admittance + PID + adaptive sliding mode” was developed, ensuring stable and smooth tracking of the desired velocity under external disturbances.

A fuzzy control module based on pressure and torque sensor data was implemented, enabling real-time recognition of patient intentions (e.g., forward movement, turning).

A hybrid eddy current brake was used for the first time in the lifting module, providing safe and adjustable braking in emergency situations.

Sliding guides made of composite material (high-chromium cast iron and Hadfield steel) were used, ensuring the strength, toughness, and wear resistance of the structure.

A nano-lubrication technique was applied, reducing the friction coefficient and simplifying the construction of the dynamic model.

A complete dynamic model of the rehabilitation robot was formulated and experimentally validated, based on D-H parameters and Lagrange equations.

10. Testing and Publication of Research Results:

During the dissertation work, the author obtained intermediate results in the fields of dynamic modeling, control algorithm development, and the creation of a prototype of a lower limb rehabilitation robot. These results are reflected in several scientific publications and invention patents.

Merkuryev I.V., Duishenaliev T.B., Wu G., Zhuravlev O.V. Control of a Lower Limb Rehabilitation Robot Based on Super-Spiral Sliding Mode and Admittance Controller // Mechatronics, Automation and Robotics. – 2025. – No. 15. – pp. 33–44. – DOI: 10.26160/2541-8637-2025-15-33-44. (RSCI)— The article is devoted to the development of control methods for lower limb rehabilitation robots.

Wang F., Guo W., Wu G., Li S. Research on Braking Characteristics of Hybrid Excitation Rotary Eddy Current Retarder // World Electric Vehicle Journal. – 2024. – Vol. 15, No. 10. – p. 443.

(Scopus)— The article presents the design of a hybrid eddy current brake mounted in the lower part of the lifting column, providing smooth braking in the event of a sudden fall of the patient.

Wu G., Merkuryev I.V., Liang Z., Duishenaliev T.B., Yuan G., Guo X. Microstructure and Tensile Behavior of High-Chromium Cast Iron/Hadfield Steel Composite Fabricated by Hot Rolling Process // Materials Research Express. – 2025. – Vol. 12, No. 2. – p. 026510. (Web of Science)— The study presents the development of a composite material made from high-chromium cast iron and Hadfield steel, used in the sliding joints between the lifting column and the lumbar support module.

Yang K., Xiong Y., Wu G., Lin H., Tang J., Wu C., Chen H., Wang Y. Multi-Dimensional Nano-Additives for Their Superlubricity: Tribological Behaviors and Lubrication Mechanisms // Advanced Materials Interfaces. – December 23, 2024. – Article No. 2400796. – DOI: 10.1002/admi.202400796. (Web of Science)— The article is devoted to the use of nanomaterials and superlubrication technology in the robot's lifting module, which significantly reduced the friction coefficient and allowed its influence to be neglected in dynamic equations.

Wu Y., Du S., Wu G., Guo X., Wu J., Zhao R., Ma C. Minimum Maximum Regularized Multiscale Convolutional Neural Network and Its Application in Intelligent Fault Diagnosis of Rotary Machines // ISA Transactions. – 2025. (Web of Science)— The paper proposes a diagnostic and fault prediction algorithm for electric drives based on a multiscale convolutional neural network, ensuring the reliability of the lifting module during patient rehabilitation.

The author also participated in the IX International Scientific and Practical Conference "Mechatronics, Automation, and Robotics" (St. Petersburg, Russia).

A total of 6 scientific articles were published, of which 3 are indexed in Web of Science, 1 in Scopus, and 1 in RSCI. Additionally, 2 patent applications for inventions were submitted and registered in the People's Republic of China. These results form the basis of the main provisions and scientific novelty of the dissertation.

11. Keywords:

Lower limb rehabilitation robot; admittance control; sliding mode control; fuzzy control; Kalman filter; nano-lubrication; eddy current braking; motor fault diagnosis; composite materials.