

BEKZAT AMANOV ONDASYNULY
The dynamics and control of a humanoid robot arm
Dissertation submitted for the degree of Doctor of Philosophy (PhD)
in the specialty
6D060300 – Mechanics
ABSTRACT

Relevance of the research topic

At present, the development of robotics and mechatronics is directed not only toward creating systems capable of high precision, high speed, and repeatable motion, but also toward intelligent robotic devices that can interact with humans in a safe, flexible, and adaptive manner. In particular, humanoid robots and robotic arms with multiple degrees of freedom are widely studied in industry, service applications, medicine, teleoperation, remote control systems, and robotics intended for upper-limb rehabilitation. Under such conditions, investigating the motion of a robotic arm while taking into account not only its geometry but also its physical nature, dynamic properties, and actual control laws becomes an important scientific and technical problem.

The motion of a humanoid robotic arm is described as a multi-link, nonlinear, dynamically coupled system. In such a system, the motion of each joint influences the others, while the robot's end-effector must not only reach a required point in space but also maintain a prescribed trajectory, orientation, and smoothness of motion. Therefore, the study of such systems requires the interconnected consideration of kinematics, dynamics, trajectory planning, forward and inverse problems, control theory, numerical simulation, and engineering design.

The relevance of the dissertation is also justified by two specific application domains. The first is remote operation. In this case, the robotic arm must perform precise, understandable, natural, and visually reliable motion according to the commands of an operator or a supervisory control system. Its motion should be intuitive to perceive, the end-effector path should be geometrically meaningful, and the control system should be stable. The second domain concerns robotic systems intended for upper-limb rehabilitation. In this case, the robotic arm directly interacts physically with a human, and therefore its motion must be soft, safe, physiologically appropriate, and adaptive to the condition of the patient. Considering these two different but related tasks within a single humanoid robotic arm defines the scientific and practical significance of this dissertation.

Although classical kinematic and dynamic methods for studying humanoid robotic arms are well known, the problem of jointly substantiating accurate trajectory control and safe force interaction within a single platform, while relating them to remote-operation and rehabilitation scenarios, has not yet been fully resolved. Therefore, building a mathematical model of a 6-DOF humanoid robotic arm, studying its dynamic properties, comparing trajectory planning methods, justifying computed-torque control and impedance control, and performing numerical simulation linked to real prototype parameters constitute a relevant and practically significant research problem.

Aim of the work

The aim of the dissertation is to develop kinematic, dynamic, and control models of a dual-purpose 6-DOF humanoid robotic arm adapted to remote operation and rehabilitation tasks, to scientifically justify trajectory planning methods, and to propose effective control algorithms that ensure accurate, safe, and adaptive motion of the end-effector.

Object of research

The object of research is a dual-purpose 6-DOF humanoid robotic arm.

Subject of research

The subject of research is the kinematics, dynamics, trajectory planning methods, control systems, and motion characteristics of a dual-purpose 6-DOF humanoid robotic arm in remote-operation and rehabilitation modes.

Research objectives

To achieve the stated aim, the following main tasks were solved in the dissertation:

- to analyze scientific literature in the fields of humanoid robotic arms, manipulators, remote operation, robotics for rehabilitation, human–robot interaction, kinematics, dynamics, and control;
- to substantiate the structural scheme of a dual-purpose 6-DOF humanoid robotic arm and determine its functional features;
- to derive the forward and inverse kinematics of the robotic arm using Denavit–Hartenberg parameters;
- to analyze the workspace, singular configurations, and the Jacobian matrix of the robotic arm;
- to construct the dynamic model of the robotic arm on the basis of the Euler–Lagrange method;
- to determine mass-inertial parameters of the links, including mass, center of mass, and inertia tensor, using an engineering model;
- to investigate and comparatively analyze linear interpolation, cubic polynomials, fifth-order polynomials, PTP, LIN, and adaptive trajectory planning methods;
- to justify impedance control for safe force interaction with a human and the environment;
- to numerically verify the forward and inverse dynamics, trajectory tracking, and control algorithms in MATLAB;
- to develop a 3D engineering prototype of the robotic arm in SolidWorks and relate the theoretical model to the actual structural parameters.

Research methods

The dissertation employs classical and modern methods widely used in robotics, mechanics, and control theory. Kinematic modeling was carried out using Denavit–Hartenberg parameterization. Homogeneous transformation matrices were used to describe the spatial position and orientation of the robotic arm. In forward kinematics, the pose of the end-effector was determined from the joint variables, while in inverse kinematics the joint angles were obtained from the state of the end-effector. A closed-form analytical approach was used in inverse kinematics.

The dynamic equations of the robotic arm were derived using the Euler–Lagrange method. This method made it possible to obtain the equations of motion in generalized coordinates while taking into account the complete kinetic and potential energies of the system. The Jacobian matrix was used to describe the relationship between joint-space motion and Cartesian-space motion. In the analysis of contact and force interaction, the transmission of forces and torques to the links was considered.

Numerical simulation was performed in MATLAB. Forward dynamics and inverse dynamics problems were numerically implemented in MATLAB, and the motion trajectories of the robotic arm, time histories of joint angles, control torques, and spatial motion of the end-effector were investigated. Engineering and geometric modeling was carried out in SolidWorks. For each link, the mass, center of mass, and inertia tensor were calculated and then used in the dynamic model.

Scientific novelty of the dissertation

The scientific novelty of the dissertation is characterized by the following results:

- a comprehensive scientific and methodological framework is proposed for considering remote-operation and rehabilitation tasks within a single 6-DOF humanoid robotic arm;
- a complete kinematic model of a 6-DOF humanoid robotic arm is constructed on the basis of Denavit–Hartenberg parameters, and the forward and closed-form inverse kinematics solutions are systematized;

- the workspace, singular configurations, and the Jacobian matrix of the robotic arm are analyzed from the standpoint of remote-operation and rehabilitation tasks;
- the dynamic model obtained using the Euler–Lagrange method is linked to the mass-inertial parameters of a real prototype;
- trajectory planning methods are comparatively justified according to their application purpose, namely the requirements of motion accuracy, geometric path, motion smoothness, and safe adaptation;
- the feasibility of using computed-torque control for accurate free-space motion and impedance control for safe interaction with a human within a unified robotic architecture is demonstrated;
- principles for selecting virtual mass, damping, and stiffness parameters for rehabilitation modes are proposed;
- trajectory tracking, control torques, and the dynamic response of the system are numerically verified in MATLAB using forward dynamics and inverse dynamics models.

Theoretical and practical significance

The theoretical significance of the research lies in the comprehensive systematization of the kinematic, dynamic, and control models of a 6-DOF humanoid robotic arm. In the dissertation, the motion of the robotic arm is considered not only from the standpoint of kinematics or only control, but as an integrated system. This expands the theoretical foundations for studying multi-link robotic systems and makes it possible to explain how accurate trajectory control and safe force interaction can be combined within one system.

The practical significance is determined by the possibility of applying the proposed models and algorithms to the design of real engineering systems. The dissertation results may be used in remotely controlled service robots, social robots, robotic systems for pointing and guiding actions, as well as intelligent robotic devices intended for upper-limb rehabilitation. The engineering and numerical models developed in SolidWorks and MATLAB may serve as a basis for further improvement of the hardware prototype and for the development of real control software.

Scientific results submitted for defense

The following scientific results are submitted for defense:

- a structural and functional model of a dual-purpose 6-DOF humanoid robotic arm;
- forward and inverse kinematics solutions of the robotic arm based on Denavit–Hartenberg parameters;
- results related to workspace analysis, singular configurations, and the Jacobian matrix;
- a dynamic model obtained using the Euler–Lagrange method;
- a comparative analysis of linear interpolation, cubic and fifth-order polynomials, PTP, LIN, and adaptive trajectory planning methods;
- a computed-torque control method for accurate free-space motion;
- an impedance control method for safe interaction with a human;
- principles for selecting adaptive impedance parameters for rehabilitation modes;
- numerical and engineering modeling results obtained in MATLAB and SolidWorks.

Reliability and validity of the scientific statements, conclusions, and results

The reliability and validity of the results are ensured by the use of widely recognized methods in robotics and mechanics, including Denavit–Hartenberg parameterization, the Euler–Lagrange method, Jacobian analysis, classical trajectory planning approaches, and model-based control theory. The forward dynamics and inverse dynamics problems were numerically verified in MATLAB, and the motion, torques, and tracking accuracy were evaluated for consistency with the theoretical results. The mass-inertial parameters obtained from SolidWorks increased the engineering validity of the model.

Relation of the dissertation to other research works

The content of the dissertation is directly related to current scientific research in the fields of robotics, control systems, and the design of mechatronic devices. The obtained results can complement studies in remote operation, intelligent manipulators, and robotic systems intended for rehabilitation.

Approbation of the research results

The main results and provisions of the dissertation were presented at international and national scientific and technical conferences and were also published in reputable scientific journals:

Baigunchekov, Z., Cao, M., Li, Q., Amanov, B., Zhangabergen, D., Omarov, B., Rakhmatulla, Z., and Yeerzhati, M., *Social Humanoid Robot Ai-Gerim*, IEEE 20th Conference on Industrial Electronics and Applications, ICIEA 2025, DOI: 10.1109/ICIEA65512.2025.11148978.

Baigunchekov, Z., Carbone, G., Zhumasheva, Z., Amanov, B., Zholdassov, Y., Tolenov, S., Tleukhanov, A., *Kinematics of the “Ai-Gerim” Robot Arm*, Mechanisms and Machine Science Conference, 2022, DOI: 10.1007/978-3-031-04870-8_2.

Ibrayev, S., Amanov, B., *Enhancing Orthopedics and Sports Medicine with Lower Limb Exoskeleton Control in Rehabilitation Using Deep Learning-Based Electromyography Signal Classification*, Retos, Open Access, 2024, Vol. 61, pp. 616–625.

Ibrayev, S., Omarov, B., Amanov, B., Momynkulov, Z., *Development of a Deep Learning-Enhanced Lower-Limb Exoskeleton Using Electromyography Data for Post-Neurovascular Rehabilitation*, Engineered Science, Open Access, 2024, Vol. 31, p. 1269.

Personal contribution of the author

The main scientific results, theoretical statements, mathematical models, and the justification of trajectory planning and control algorithms presented in the dissertation were obtained directly by the author. The author carried out the literature review, developed the kinematic and dynamic models of the robotic arm, numerically implemented the forward dynamics and inverse dynamics problems in MATLAB, determined prototype parameters in SolidWorks, and systematized the obtained results.

Structure and volume of the dissertation

The dissertation consists of an introduction, main chapters, a conclusion, a list of references, and appendices. The relevance of the topic, the aim and objectives, the research methods, scientific novelty, theoretical and practical significance, results submitted for defense, and the main conclusions are consistently presented in the work.

Main content of the dissertation

The dissertation consists of an introduction, four main chapters, a conclusion, a list of references, and appendices.

The introduction substantiates the relevance of the research topic, formulates the aim and objectives of the work, defines the object and subject of the research, and presents the scientific novelty and practical significance. The main aim is defined as the modeling of a dual-purpose 6-DOF humanoid robotic arm for remote-operation and rehabilitation tasks, the selection of trajectory planning methods, and the development of corresponding control systems.

The first chapter reviews current research on humanoid robotic arms and their applications in industrial, medical, service, and remote-operation systems. It also addresses rehabilitation robotics, teleoperation, and human–robot interaction. Based on the literature review, the necessity of combining accurate trajectory control and safe force interaction within one robotic system is substantiated.

The second chapter develops the kinematic and dynamic models of the 6-DOF humanoid robotic arm. Forward and inverse kinematics equations are derived using Denavit–Hartenberg parameters, and the workspace, singular configurations, and Jacobian matrix are analyzed. In

addition, the complete dynamic equations of motion are obtained using the Euler–Lagrange formalism, while the mass-inertial parameters of the robotic arm are determined in SolidWorks.

The third chapter is devoted to trajectory planning methods for the robotic arm. Linear interpolation, cubic and fifth-order polynomials, as well as PTP, LIN, and adaptive trajectory planning methods are compared, and their smoothness and application-specific features are analyzed. It is shown that a combination of PTP and LIN is appropriate for remote-operation tasks, whereas adaptive trajectory planning is more suitable for rehabilitation-oriented tasks.

The fourth chapter investigates the control systems of the robotic arm. Computed-torque control is justified for accurate free-space motion, while impedance control is substantiated for safe interaction with a human and the environment. This chapter discusses the mathematical models of the control laws, error dynamics, stability conditions, and the principles of parameter selection for rehabilitation and teleoperation modes.

The conclusion shows that the dissertation develops the mathematical, algorithmic, and applied foundations of a dual-purpose 6-DOF humanoid robotic arm, and that the proposed trajectory planning and control methods ensure accurate motion, directed action, and safe physical interaction with a human.