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Investigation of distributed dynamic loads induced by the self-mass of manipulator links and their visualization on interactive 3D computer models

ANNOTATION

of the dissertations for the degree
Doctor of Philosophy (PhD) in the educational program
8D07117 - "Robotic systems"

Relevance of the research topic. One of the key aspects of designing manipulators is to ensure the strength and rigidity of their links throughout the entire workflow. The analysis of the stress-strain state of the links is complicated by the fact that the manipulator is in motion, which leads to the appearance of distributed dynamic loads of a complex nature, due to the mass of the links in each of their sections. These loads change their magnitude and direction, depending on the kinematic characteristics of the links.

In order to more correctly analyze the nature of the stress-strain state for the full working cycle of spatial manipulators, it is necessary to take into account, in addition to the concentrated forces applied to the system, distributed dynamic loads, which change their values and directions depending on the physical, geometric and kinematic characteristics of the links. Therefore, it is necessary, first of all, to establish the regularity of the distribution of distributed dynamic loads.

Therefore, the development of an analytical methodology for dynamic calculations of spatial manipulators taking into account distributed dynamic loads is relevant. The advantage of the analytical method is the accuracy and speed of calculation. The study of dynamic loads on manipulators plays a key role in the development of more reliable and efficient robotic systems.

The purpose of this dissertation is to study distributed dynamic loads caused by the self-weight of robot manipulator links, followed by the development of algorithms and programs for their visualization in the form of interactive 3D computer models, which creates the basis for improving the accuracy, reliability and efficiency of analysis and design of robotic systems.

The object of research is spatial manipulators with several degrees of freedom.

The subject of the study is distributed dynamic loads of spatial manipulators.

In accordance with this goal, the following **research objectives are defined:**

- Perform an overview of current theoretical and applied research on creating interactive 3D models and analyzing the kinematics and dynamics of spatial manipulators.
- Develop an algorithm and program code for creating fully visualized interactive 3D models of spatial manipulators, including links, kinematic pairs, grippers, etc., within the Maple software environment, controlled by generalized coordinates.
- Develop an algorithm and program code that determine the kinematic characteristics of the manipulator links, which relate to both the base and coordinate systems associated with the links, as well as linear and angular accelerations.

– To develop a method for analytical determination of the distribution patterns along the link axes of dynamic loads that arise due to their own masses during accelerated movement of links in spatial manipulators.
– To develop an algorithm and program code for constructing visual diagrams of distributed dynamic loads in mutually perpendicular planes formed by the main axes and the longitudinal axis of links in interactive 3D models of spatial manipulators.

Research methods: modern analytical methods for solving problems of machine mechanics.

The scientific novelty of the work is as follows:

1. An algorithm and code for programs are developed that create three-dimensional models of manipulators that are clearly visible from all sides of three-dimensional space and their movement controlled by generalized coordinates in the Maple software environment.

2. The regularities of the distribution of dynamic loads are established: two distributed transverse dynamic loads lying in mutually perpendicular planes coinciding with the main axes of the cross-sections of the links and with the longitudinal axis of the links; longitudinal distributed dynamic loads acting along the axis of the links and distributed torques arising from the own masses of links with constant cross-sections during their movements in space.

3. An algorithm and software code were developed, that creates visual plots of the above dynamic loads along the link axes, interactive three-dimensional models of manipulators.

Theoretical and practical significance of the study. The developed method can be used for further theoretical investigation of the stress-strain state of elements of spatial manipulators and automation of this research using modern computer programs. The practical significance of the study is the application of the developed methodology in the design of new innovative robotic manipulators that solve new scientific and production tasks that will affect the socio-economic and scientific and technical development of the Republic of Kazakhstan

Scientific provisions submitted for defense:

– An algorithm and program code are developed that creates three-dimensional models of manipulators that are clearly visible from all sides of three-dimensional space and their movement controlled by generalized coordinates in the Maple software environment.

– An algorithm and a program code are developed, that determines the kinematic characteristics of manipulators relative to the base and link-related coordinate systems, which use the Denavit-Hartenberg and Newton-Euler methods.

– The following regularities of dynamic load distribution are established: two distributed transverse dynamic loads lying in mutually perpendicular planes coinciding with the main axes of the cross-sections of the links and with the longitudinal axis of the links; longitudinal distributed dynamic loads acting along the axis of the links and distributed torques arising from the own masses of links with constant cross-sections during their movements in space.

– An algorithm and program code are developed, that creates visual plots of the above dynamic loads along the link axes, interactive three-dimensional models of manipulators.

Reliability and validity of scientific statements, conclusions and results of the dissertation. The main computational equations used in the dissertation work are obtained with correct use of the main provisions of theoretical mechanics, mathematical analysis, higher algebra, differential equations, fundamentals of robotics, theory of machines and mechanisms, and deformable solid mechanics.

The reliability of theoretical results is confirmed by the rigor of mathematical models and the correctness of the results obtained for solving the tasks set.

The spatial position and directions of the RRRRT manipulator links can be seen in a visualized 3D computer model created using the developed algorithm and program code in the Maple environment. Verification is performed by comparing the positions and directions of these models with the extracted numerical values. The kinematic parameters of the manipulator necessary for determining dynamic loads were calculated using recurrent Newton-Euler formulas and checked using homogeneous transformation matrices. Diagrams of dynamic loads along links correspond to the laws of distribution of the found loads.

Connection of the dissertation work with another research works. This dissertation work was carried out within the framework of the scientific project of grant funding of the Ministry of Education and Science of the Republic of Kazakhstan "Zhas Galym" on the topic " Development of an analytical methodology for determining dynamic loads of spatial manipulators "(20-2424-2026 - 2026, AR22686476).

Testing the work. The main provisions and results of the dissertation work were reported and discussed at the following scientific events:

- International scientific and practical conference **"** The priorities of mechanics and theory of automatic control in the development of space technic and technology**"** dedicated to the 75th anniversary of Professor, Academician of the National Academy of Sciences of the Republic of Kazakhstan and NIA of the Republic of Kazakhstan Moldabekov Meyrbek (Almaty, September 14, 2022);
- International Scientific Conference "IFToMM Asian Asian Mechanisms and Machine Science Conference 2024 (Almaty, August 28-30, 2024);
- International Scientific Conference European Meeting on Applied Science and Engineering on the theme: "Transforming Innovations into Reality for a Better Future in Science and Engineering "(Berlin, Germany, April 14-15, 2025);
- scientific seminars of the Department of Mechanics of Al-Farabi Kazakh National University.

Publications. The author published 7 papers on the topic of the dissertation, including 1 publication in scientific journals and proceedings of international conferences indexed by the Scopus and Web of Science databases:

- Utenov, M.; Sobh, T.; Temirbekov, Y.; Zhilkibayeva, S.; Patel, S.; Baltabay, D.; Zhumasheva, Z. Analysis of Distributed Dynamic Loads Induced by the Own Mass of Manipulator Links and Their Visualization on Interactive 3D Computer Models. *Robotics***2025**,*14*, 46.(quartile Q1, 84%)
  https://doi.org/10.3390/robotics14040046

2 publications in scientific publications recommended by the Committee for Control in the Field of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan for publishing the main results of scientific activity:

- Utenov M. U., Baltabay D. K. Direct positional kinematics problem of the RRRRT manipulator in the maple software environment// Bulletin of the National Engineering Academy of the Republic of Kazakhstan. Category Information and communication technologies. - Almaty, 2023. - №4 (90). – P. 138-147-147. https://doi.org/10.47533/2023.1606-146X.41
- Utenov M. U., Baltabay D. K., Batyrbek S. J. Computer 3D modeling of manipulators in the Maple software environment . Bulletin of the National Engineering Academy of the Republic of Kazakhstan. Category Information and communication technologies. - Almaty, 2022. - №4 (86). – P. 109-115-115. https://doi.org/10.47533/2020.1606-146X.201

2 publications in collections of international conferences indexed by the Scopus database(4-quartile, 15%).

2 publications in collections of international domestic conferences.

The author's personal contribution consists of:

- participation at all stages of the process of developing methods and algorithms for modeling, analyzing distributed dynamic loads acting on the links of spatial manipulators caused by their own mass, and visualizing dynamic loads in interactive 3D computer models of specific manipulators controlled by generalized coordinates;
- direct participation of the applicant in the review of modern theoretical and applied research on the creation of interactive 3D models and analysis of kinematics, distributed dynamic loads of spatial manipulators, development of algorithms and programs that allow the production of interactive 3D models of spatial manipulators, as well as determining kinematic characteristics, speeds and accelerations of manipulator links and with automatic plotting on the links of plots distributed dynamic loads;
- personal participation in testing the results of the study.
- preparation of the main publications on the completed work.

Structure and scope of the dissertation. The dissertation includes a title page, content, introduction, four sections, conclusion and a list of sources used, consisting of 108 titles. The total volume of the dissertation is 79 pages, including 37 illustrations, 2 tables.

The main content of the dissertation. The introduction includes an analysis of the current state of the problem under study with an overview of existing works, justification of the relevance of the topic of dissertation research, the purpose of the work, object, subject, research objectives, scientific novelty, theoretical and practical significance, the main provisions submitted for defense, information about published works on the topic of the dissertation and the degree of its development.

The first section of the dissertation is devoted to the modern presentation and research approaches to the creation of interactive 3D models, the analysis of kinematics, distributed dynamic loads of spatial manipulators**.**

The second section of the dissertation is devoted to the algorithm for 3D modeling of spatial manipulators. An algorithm and a program are developed that

creates interactive 3D models of spatial manipulators in the Maple software environment

The third section of the dissertation is devoted to kinematic analysis of spatial manipulators. An algorithm and program code for determining the kinematic parameters of spatial manipulators are developed. The results of kinematic analysis of the investigated spatial manipulator are presented in the form of 3D graphs.

In the fourth section of the dissertation, the law of distribution of dynamic loads on the links of spatial manipulators is defined. An algorithm and computer programs have been developed that make it possible to automatically plot plots of longitudinal and transverse distributed dynamic loads and bending moments on the links of spatial manipulators.

In conclusion, the main results and conclusions of the dissertation research are presented, an assessment of the completeness of solving the tasks set, recommendations and initial data on the specific use of the results, an assessment of the technical and economic efficiency of implementation, an assessment of the scientific level of the work performed in comparison with the best achievements in this field.