KAMAL AZIZ

Development and Research of a Suspended Cable-Driven Parallel Robot

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ANNOTATION

Relevance of the Research Topic. Over the past several years, a trend has emerged toward the introduction of equipment based on parallel-structure mechanisms into the global market, characterized by improved technical and operational performance. In mechanisms with a parallel structure, the end-effector is connected to the base by several kinematic chains, each of which contains multiple actuators or imposes constraints on its motion. Unlike conventional mechanisms, these systems possess closed kinematic chains and perceive loads as spatial truss structures, which leads to increased accuracy, speed, and load-carrying capacity.

The research on suspended CDPRs presented in this dissertation is closely related to the work of researchers from Russia, Germany, Japan, and other countries, who conduct in-depth studies in areas such as integrated development of suspended CDPR configurations with improved characteristics using advanced analysis and synthesis methods; development and implementation of advanced controllers and actuators for higher performance and accurate trajectory tracking; improvement of stiffness and load-carrying capacity through structural synthesis; and application of reconfigurable and modular design approaches used in rigid-link parallel robots for the development of efficient suspended CDPRs. Owing to the advantages of suspended CDPRs, including low inertia and large workspace, the development and practical implementation of suspended CDPRs with new structural solutions and enhanced functional capabilities represent an important and relevant research objective and contribute significantly to the advancement of science in this field.

Objective of the Study. The objective of this work is the development and research of a suspended cable-driven parallel robot with the possibility of further practical application in various industries.

Object of Research. The object of research is a cable-driven parallel robot.

Subject of Research. The subject of research is the development and investigation of a suspended cable-driven parallel robot.

Research Objectives

- to review the current state of research on suspended cable-driven parallel robots worldwide;
- to perform structural synthesis of a suspended cable-driven parallel robot;
- to investigate the workspace of a suspended cable-driven parallel robot;
- to carry out kinematic analysis of a suspended cable-driven parallel robot;
- to develop mathematical models of the kinematics, statics, and dynamics of a suspended point cable-driven parallel robot;

- to develop a model of a suspended point cable-driven parallel robot using the SimulationX software package;
- to synthesize the control system of a suspended point cable-driven parallel robot;
- to develop and manufacture a suspended point cable-driven parallel robot;
- to conduct experimental studies of the prototype of a suspended point cable-driven parallel robot;

Research Methods. Theoretical studies were carried out using classical methods of the theory of mechanisms and machines (kinematics, force analysis, and dynamics), as well as methods of mathematical modeling of complex mechanical systems. The dynamic model of the cable-driven parallel robot was developed using the SimulationX software package. The control system synthesis problems for suspended cable-driven parallel robots were solved using the Maple analytical computation package and the Python programming language. Experimental studies were conducted using modern strain measurement methods with strain gauges.

Scientific Novelty. The scientific novelty of the work consists of the following:

- mathematical models of the kinematics, statics, and dynamics of a suspended point cable-driven parallel robot have been developed;
- a control system for a suspended point cable-driven parallel robot has been developed;
- a prototype of a suspended point cable-driven parallel robot has been designed and manufactured;
- a mine detection device based on a suspended point cable-driven parallel robot has been designed and manufactured.

Theoretical and Practical Significance. The results obtained in the dissertation have both theoretical and practical significance for the development of suspended point cable-driven parallel robots. The developed mathematical models of kinematics, statics, dynamics, and control systems make it possible to design various cable-driven parallel robots for solving practical tasks. The developed prototype of the suspended point cable-driven parallel robot can be further developed for commercial use, which is confirmed by a Eurasian patent for invention. Based on this patent, a mine detection device using a suspended point cable-driven parallel robot has been developed and manufactured. Laboratory tests of the mine detection device demonstrated high efficiency in mine detection.

Scientific Provisions Submitted for Defense:

- mathematical models of the kinematics, statics, and dynamics of a suspended point cable-driven parallel robot;
- a model of a suspended point cable-driven parallel robot developed in the SimulationX software package;
- the control system of a suspended point cable-driven parallel robot;
- the prototype of a suspended point cable-driven parallel robot;
- a mine detection device based on a suspended point cable-driven parallel robot.

Reliability and Validity of Scientific Results. The reliability and validity of the scientific provisions, conclusions, and results of the dissertation are confirmed by the application of proven methods of mechanics and the theory of mechanisms and machines, as well as by the use of verified software tools such as Maple, SimulationX, and the Python programming language. The reliability of the results is further confirmed by the development and manufacturing of a prototype of the suspended point cable-driven parallel robot, whose experimental results showed good agreement with theoretical results.

Relation of the Dissertation to Other Research Works. This dissertation research was carried out within the framework of a scientific project funded under the grant program for fundamental and applied scientific research for scientific and (or) scientific-technical projects for 2021–2023 of the Ministry of Science and Higher Education of the Republic of Kazakhstan, entitled "Development of Modeling and Control Methods for Cable-Driven Parallel Robots" (State Registration No. 0121RK00443, Project IRN: AP092259339).

Approbation of the Work. The main results and provisions of the dissertation were presented and discussed at the following scientific events:

- the 12th International Scientific Conference "Chaos and Structures in Nonlinear Systems: Theory and Experiment", Pavlodar, 2022;
- the International Scientific and Practical Conference dedicated to the 115th anniversary of Corresponding Member of the Academy of Sciences of the Kazakh SSR A.Zh. Mashanov and the 100th anniversary of Academician of the Academy of Sciences of the Kazakh SSR Zh.S. Erzhanov, Almaty, 2022;
- the VIII International Conference "Problems of Mechanics of Modern Machines" dedicated to the 60th anniversary of ESSUTM, Ulan-Ude, 2022;
- the International Congress "The 16th IFToMM World Congress" (2023, Tokyo, Japan);

Publications. A total of 11 scientific works have been published by the author on the topic of the dissertation. Among them, 2 publications were published in scientific journals recommended by the Committee for Quality Assurance in Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan for publishing the main results of scientific activity [1,2]; 3 publications were published in foreign scientific journals indexed in the Scopus database [3-5]; and 3 publications were published in the proceedings of international and national scientific conferences [4, p. 53-62; 6-8]. In addition, 1 patent of the Republic of Kazakhstan for an invention [9] and 1 Eurasian patent for an invention [10] were obtained.

Personal contribution of the author. The main scientific results and conclusions presented in the dissertation were obtained by the author independently. In the co-authored publications [1, pp. 202-209; 2, pp. 174-183], the applicant conducted a review of theoretical and experimental studies on cable-driven parallel robots. In publications [3, pp. 67-74; 4, pp. 53-62; 5, pp. 1-9], the applicant contributed to the development of the control system for the cable-driven parallel robot. In publications [4, pp. 53-62; 6, pp. 633-638; 7, pp. 454-463; 8, pp. 132-137], the applicant participated in the development of structural schemes of suspended

cable-driven parallel robots. In publication [9], the applicant participated in the development of the structural scheme of a cable-driven parallel robot for mine detection and neutralization. In publication [10, pp. 1-2], the applicant developed the block diagram of the earthquake simulator control system.

Structure and Scope of the Dissertation. The dissertation consists of a title page, table of contents, list of symbols and abbreviations, introduction, six chapters, conclusion, list of references, and appendices. The total volume of the dissertation is 93 pages, including 78 figures and 7 tables.

Main Content of the Dissertation. The introduction presents the relevance of the research topic, defines the research problem, and outlines the stages of its solution.

The first chapter is devoted to the current state of research on suspended cable-driven parallel robots worldwide. A review of methods for kinematic, static, dynamic, and control analysis of suspended cable-driven parallel robots is presented.

The second chapter considers the method of structural synthesis of suspended cable-driven parallel robots. The classification of suspended cable-driven parallel robots is presented, and their structural schemes are described.

The third chapter presents a study of the workspace of a suspended cable-driven parallel robot. Various types of workspaces are described, and typical workspace models arranged in order of increasing complexity are presented.

The fourth chapter examines methods of kinematic and static analysis of suspended cable-driven parallel robots. Solutions to the forward and inverse kinematics problems are presented.

The fifth chapter presents mathematical modeling of the kinematics, dynamics, and control systems of a suspended point cable-driven parallel robot. Solutions to forward and inverse kinematics problems are provided, and static analysis is carried out. Dynamic and mathematical models are developed, a model of the suspended point cable-driven parallel robot is created in the SimulationX software environment, and the control system synthesis is performed.

The sixth chapter describes the development of a prototype of a suspended point cable-driven parallel robot. A 3D model of the prototype is developed, and design documentation is prepared based on this model. The prototype is manufactured and experimentally tested.

The seventh chapter presents the development and experimental investigation of a mine detection device based on a suspended point cable-driven parallel robot. A review of existing robots for mine detection is provided, the design of the mine detector is developed, and experimental studies are carried out.