IOSUD - Polytechnic University of Timisoara
Doctoral School of Engineering Studies

RESEARCH ON THE PERFORMANCE OF PLANAR PARALLEL ROBOTS USING KINEMATIC CHAINS WITH GEARED LINKAGES

Doctoral Thesis – Abstract

for obtaining the scientific title of doctor at
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The topic of the present thesis is situated within the current scientific concerns in the field of planar parallel robots. The main objective of the doctoral thesis is the research of the precision of planar parallel robots using kinematic chains with bars and gear wheels. Thus, the objectives of the doctoral thesis can be divided into the following steps:

A. Literature review of the current state of research on planar parallel robots

- Current state of serial industrial robots;
- Current state of planar parallel industrial robots;
- Evolution of planar parallel industrial robots;
- Presentation of different structures of planar parallel robots;
- Application areas of planar parallel robots.

B. Analysis of the structural analysis and direct and inverse cinematic analysis of parallel plan robots with linkage chains consisting of bars and gears with linear actuation

- Structural analysis of parallel plan robots that use linkage chains consisting of bars and gears with linear actuation 3-R(PRRGR)RR and 3-R(RPRGR)RR;
- Kinematic analysis of parallel plan robots that use linkage chains consisting of bars and gears with linear actuation, having the crank-piston kinematic chain as the base kinematic chain 3-R(PRRGR)RR;
- Kinematic analysis of parallel plan robots that use linkage chains consisting of bars and gears with linear actuation, having the oscillating slide kinematic chain as the base kinematic chain 3-R(RPRGR)RR.

C. Characterization of the performance of parallel plan robots with linkage chains consisting of bars and gears with linear actuation

- Analysis of the workspace of parallel plan robots having linkage chains consisting of bars and gears with linear actuation 3-R(PRRGR)RR and 3-R(RPRGR)RR;
- Analysis of the singularities of parallel plan robots having linkage chains consisting of bars and gears with linear actuation 3-R(PRRGR)RR and 3-R(RPRGR)RR;
- Analysis of performance indices of the parallel plan robot derived from mechanisms with bars and gears with linear actuation 3-R(RPRGR)RR;

- Analysis of performance indices of parallel plan robots having linkage chains consisting of bars and gears with linear actuation 3-R(PRRGR)RR and 3-R(RPRGR)RR;
- Comparison of global performance indices of parallel plan robots having linkage chains consisting of bars and gears with linear actuation 3-R(PRRGR)RR and 3-R(RPRGR)RR with the elementary parallel plan robot 3-RRR.

D. Creation of CAD models with linkage chains consisting of bars and gears with linear actuation, simulation of the mobile platform's positioning for various simple and combined movements within the workspace, as well as the design and realization of the parallel plan robot prototype.

- CAD design of the parallel plan robot 3-R(PRRGR)RR;
- Simulation of the mobile platform's movement for various motions: translations along the X and Y axes, rotation around the Z axis, and combined movement;
- Realization of the prototype of the parallel plan robot 3-R(PRRGR)RR.

E. Conducting experimental studies on the precision of trajectory realization for various operation modes, as well as the travel times and velocities of linear actuators.

- Study of the precision of simulated trajectory realization using the prototype of the parallel plan robot 3-R(PRRGR)RR;
- Experimental studies on the precision of simulated trajectory realization for various operation modes using the prototype of the parallel plan robot 3-R(PRRGR)RR;
- Experimental determinations of the travel times and velocities of actuators for simulated trajectories for various operation modes using the prototype of the parallel plan robot 3-R(PRRGR)RR.

F. Conclusions and personal contributions.

- Presentation of the main conclusions from theoretical and experimental research;
- Presentation of personal contributions;
- Research perspectives on parallel plan robots.

The doctoral thesis is structured into 7 chapters: 1 introductory chapter, 1 chapter on the current state of parallel manipulators, 2 theoretical contribution chapters, 1 chapter on the design and simulation of the CAD model of the manipulator, as well as the realization of the experimental prototype, 1 chapter on experimental studies, and 1 chapter of conclusions that synthesize the contributions of the thesis.

Chapter 1 presents a brief introduction and the structure of the doctoral thesis.

Chapter 2 presents the current state and evolution of industrial robots with serial structures in general, and, in particular, those of parallel robots. Different structures of industrial robots are discussed, along with their general characteristics and application areas. Similarly, parallel robots are analyzed, with a focus on planar parallel robots, highlighting their structures, actuation systems, and characteristics. The classification of parallel robots is carried out based on their advantages and limitations, as well as their degrees of freedom and kinematic structure. The most well-known models from industry manufacturers are presented, along with their industrial applications and experimental models developed by various researchers.

Based on the current state of research in the field of parallel robots, the doctoral thesis aims to study a constructive solution of a planar parallel robot that uses kinematic linkage chains between the fixed and mobile platforms, consisting of bars and gears with linear actuation. The study proposes to perform a direct and inverse kinematic and positional analysis for the proposed kinematic chains and to simulate the movement of the characteristic point along various trajectories. Additionally, the characterization of these

planar parallel manipulators is carried out from the perspective of the workspace, first and second-order singularities, maneuverability index, uniformity of maneuverability index, condition number of the Jacobian matrix, stiffness index, and transmission index. To validate the theoretical studies, a prototype was developed, and experimental research was conducted. The results of the mathematical model were interpreted and compared with the experimental results to verify the outcomes, and the positioning errors along trajectories for various operating modes, as well as the travel times and velocities of the actuators of the planar parallel robot, were determined.

Chapter concludes by establishing the objectives of the doctoral thesis resulting from the conducted bibliographic analysis.

Chapter 3 presents a structural synthesis of planar parallel robots with kinematic linkage chains of the kinematic group type. Additionally, the structures of planar parallel robots with kinematic linkage chains consisting of bars and gears are synthesized. Structures that accept a maximum number of motor translation joints equal to 1 are presented. In addition to solutions for planar parallel robots with kinematic chains containing second-class second-order kinematic groups, structures of planar parallel robots with kinematic chains formed from fourth-class second-order kinematic groups are also presented.

For the structural synthesis of planar parallel robots, the degree of mobility of the mobile platform in the plane was set equal to 3, meaning a non-redundant planar parallel robot. The structures of planar parallel robots resulting from the structural synthesis, which accepted a maximum number of motor translation joints equal to 1, amounted to 12 useful structures out of 15 possible structures, along with other derived structures.

Thus, five kinematic chains with second-class second-order kinematic groups were obtained: RRR, RRP, RPR, PRP, and RPP. Among these, only three structures provide suitable solutions, utilizing kinematic chains RRR, RPR, and PRR. Additionally, there is a derived solution that employs kinematic chains with lower-order kinematic joints of wrapping (RIR).

In addition to these solutions for planar parallel robots with kinematic chains containing second-class second-order kinematic groups, structures of planar parallel robots with kinematic chains formed from fourth-class second-order kinematic groups were also presented. The number of possible structures for planar parallel robots is 3, using the kinematic chains: R(RR RR)R, P(RR RR)R, and P(RR RR)P. Among these, only two structures—those utilizing the kinematic chains R(RR RR)R and P(RR RR)R—provide suitable solutions.

In addition, structures of planar parallel robots containing kinematic chains with bars and gears were synthesized. Thus, for the case of kinematic chains with bars and gears having 3 elements, three solutions for planar parallel robots were obtained: 3-R(RRGR)R, 3-P(RRGR)R, and 3-R(PRGR)R. Furthermore, two alternative structures were also derived, which include belt transmissions instead of gear transmissions: 3-R(RPcR)R and 3-T(RPcR)R.

For the case of kinematic chains with bars and gears having 5 elements, four suitable structures were obtained, containing the following kinematic chains: R(RRGR)R, P(RRGR)R, R(RPRGR)R, and R(PRRRGR)R.

Theoretical studies within the doctoral thesis will continue to focus on the cinematic characterization of the three solutions of planar parallel robots with kinematic chains composed of bars and gears, having five elements, and using linear actuators.

Chapter 4 performs a structural and kinematic analysis of the 3-RRR planar parallel robots, as well as of planar parallel robots that use kinematic chains derived from bar and gear mechanisms with linear actuation: 3-R(RPRGR)RR, which has a rocking slider mechanism as its base mechanism, and 3-R(PRRGR)RR,

which has a crank-piston mechanism as its base mechanism. For each of these robots, the structure of the mechanisms and the direct and inverse position kinematic analysis are presented.

Initially, the kinematic analysis of the 3-RRR structure was presented because the two structures of planar parallel robots with kinematic chains composed of bars and gears, featuring linear actuation, are derived from the structure of a 3-RRR planar parallel robot through parallel linkage of kinematic chains RRR with kinematic chains composed of bars and gears. The kinematic position analysis was presented using the direct and inverse kinematic models, along with the calculation relationships specific to kinematic chains involving bars and gears.

Due to the fact that the structure of the planar parallel robot 3-P(RRRGR)R contains kinematic chains with bars and gears connected in parallel as passive kinematic chains, this planar parallel robot has not been considered anymore.

Chapter 5 carries out a characterization of planar parallel robots that use kinematic chains derived from linear actuated bar and gear mechanisms through the analysis of the workspace, singularities, and performance indices. Thus, they are analyzed and represented through level graphs:

- Workspace;
- Jacobian Matrix;
- First-order singularities;
- Second-order singularities;
- Maneuverability;
- Condition number;
- Stiffness;
- Indices of motion and force transmission.

Case studies are presented for each of the performance indices with the constructive parameters established at the beginning of the chapter. The chapter concludes with the comparison of performance indices of the planar parallel robots 3-R(PRRGR)RR and 3-RRR.

Chapter 6 presents the CAD model design of the planar parallel robot 3-R(PRRGR)RR. Thus, the mechanical design and engineering of the planar parallel robot 3-R(PRRGR)RR are presented in the CAD model variant. The mechanical system, actuation, and control system components of the planar parallel robot are described. In this chapter, CAD simulations are carried out. These simulations are performed for various movements executed by the robot, including translation along the X and Y axes, rotation around the Z axis, as well as combined movements.

Chapter 7 presents the experimental studies conducted using the prototype of the planar parallel robot 3-R(PRRGR)RR. Thus, by equipping the robot with angular position sensors, the trajectory of the characteristic point is experimentally determined, and the results are compared with the theoretical simulations carried out through CAD modeling. These experimental determinations are performed for all four theoretically simulated movements, and positioning errors on the trajectory are assessed for various operating regimes, actuator strokes, and speeds. At the end of the chapter, conclusions related to the experimental prototype of the planar parallel robot are discussed.

Chapter 8 is dedicated to conclusions and personal contributions, where the main conclusions, personal contributions, and identified future research perspectives are presented. Within the doctoral thesis, part of the obtained results have been published and are currently under publication. Eight scientific works have been published so far, including two articles published in ISI-indexed journals, one as the first author, three

scientific works published in volumes of ISI-indexed scientific events as a co-author, and three scientific works published in volumes of BDI-indexed scientific events (Scopus), two as the first author.

The research results have been disseminated at various national and international scientific conferences: European Conference on Mechanism Science (EuCoMeS), 2020; International Conference on Mechanisms and Mechanical Transmissions (MTM & Robotics), 2020; International Conference on Mechanical Engineering, Design and Manufacturing (MEDER), 2021; Innovation for Sustainable Development Goals Conference (I4SDG), 2021; IFToMM Italy Conference on Mechanism Science, 2022; *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 2022; and *Robotica*, 2023. Additionally, the results have been included in *New Advances in Mechanisms, Transmissions and Applications*, 2025.