

A brief overview of parallel robots and parallel kinematic machines

M Ratiu¹ and D M Anton²

¹ Department of Mechanical Engineering and Automotive, University of Oradea, 410087 Oradea, Romania

² Department of Mechatronics, University of Oradea, 410087 Oradea, Romania

E-mail: mratiu@uoradea.ro

Abstract. In this paper, a brief overview is presented, resulting from a recent literature review of some representative books or papers regarding various research on different types of parallel robots, parallel kinematic machines, or hybrid parallel mechanisms. Starting from a short introduction regarding the motivation and necessity of the emergence of such parallel mechanisms, some basic terms are presented, in the context of founding the existence of several terminologies for certain specific expressions of this subject, as well as different definitions for them. Then, after a short presentation of the advantages and disadvantages of the parallel robots, compared to serial ones, and of the parallel kinematic mechanisms compared to the conventional machine tools, some publications related to kinematics, dynamics, modeling and simulation of these types of mechanisms are highlighted. This research is realized in order to identify a solution that will be the basis for the development of a prototype, both virtual and experimental, for such mechatronic system.

1. Introduction

In the last few decades, alongside the development of serial industrial robots, parallel robots attracted the attention of many industries and researchers. This because of their higher precisions, rigidity, dynamic performance and loading capacity, compared with the serial robots.

Also, in order to reduce or eliminate the disadvantages of the conventional machine tools, the modern machine tools, based on the parallel kinematic mechanisms were developed, that are faster, more accurate and less costly and offer higher dynamic performance and operational flexibility. Nowadays, parallel kinematic machines, also called parallel robotic machine tools or parallel robot-based machine tools, are developed and produced by many researchers and companies and used in a lot off applications.

The development in this field continued, and a new concept appeared, followed by the development of different variants of hybrid parallel kinematic machines, that are able to work both in robotics and machining applications.

After a substantial analysis, based on an extensive bibliography, consisting of 123 references, Merlet and Gosselin [1] stated in 2008 that, compared to the serial robots, the analysis of the parallel mechanisms and robots is far from being complete.

Their statement proved to be true, so in the years that followed, the interest of researchers and companies in this field has increased, so that at present, there are a large number of books, articles or

websites presenting papers, researches or information on this topic. For example, searching on Google "parallel robot", about 237,000 results were identified [2], and on Web of Science Core Collection [3], 2,314 results. Also, on the Robotic Industries Association (RIA) website [4], for the same search, a total of 5,679 results were identified, out of which 1085 referred to products, 308 were companies, 205 were services, and 384 were industry insights.

According to this general interest, and in the desire to develop such a mechatronic system, we conducted a literature review on the topic of parallel mechanisms, presented, briefly, in this paper.

2. Basic terminology

Consulting numerous books and scientific articles in this field, we found the existence of several terminologies for certain specific expressions of this subject, as well as different definitions for them. Of all these, we chose to take over and use the terminology provided by the ISO 8373 (1994), Manipulating industrial robots-Vocabulary, and the Parallel Mechanisms Information Center. According with these:

- Parallel Robot is "a robot whose arms (primary axes) have three concurrent prismatic joints".
- Parallel Kinematic Machine (PKM) is "a machine tool based on a parallel mechanism".
- Fully-parallel mechanism is "a parallel mechanism with an n -DOF (degree of freedom) end-effector connected to the base by n independent kinematic chains, each having a single actuated joint".
- Hybrid parallel mechanism is "a parallel mechanism with an n -DOF end-effector connected to the base by m ($m < n$) independent kinematic chains, each having one or more actuated joints".

Other definitions for the parallel robots, of some prestigious researchers in this field:

- "Parallel robots are closed-loop mechanisms presenting very good performances in terms of accuracy, rigidity, and ability to manipulate large loads" [5]. After few years, in the second edition of the book, [6], Merlet maintains his definition but adds that parallel robots are sometimes called hexapods or PKM, and notes that this field is in a quickly moving, becoming increasingly popular in the machine tool industry, and being addressed in an extensive bibliography.
- For Gogu [7], a parallel robot is "a robot in which the end-effector is connected in parallel to the reference link by $k \geq 2$ kinematic chains, called limbs or legs" For a fully-parallel robot, the number of limbs is equal with the robot mobility, $k=M \geq 2$, and in each limb exist just one actuator. For an hybrid serial-parallel robot, the end-effector is connected to reference link by just one complex kinematic chain, called complex limb or complex leg.
- Recently, Staicu, in [8], defines the parallel robots as "closed-loop mechanical structures whose mobile platforms are linked to the base by some independent kinematical chains, presenting very good potential in terms of accuracy, rigidity and ability to manipulate large loads with minimal positioning errors".

3. Advantages and disadvantages

Reiterating the advantages of the parallel robots, compared to serial ones, Staicu presents the increased interest of the researchers in this field, as well as the wide spectrum of their use, going up to the non-traditional and innovative applications, such the surgical and rehabilitation robots. Regarding the hybrid industrial robots, they present the advantages of both serial and parallel robots, namely high dexterity, high stiffness, large workspace, and high force-to-weight ratio and minimized disadvantages.

Compared to the conventional machine tools, the parallel kinematic mechanisms offer higher stiffness, higher acceleration, potential higher accuracy, lower moving mass, mechanical simplicity, and reduced installation requirements, and so, they have the potential to be high precision machines, highly modular and reconfigurable, with high dexterity and multi-mode manufacturing capability, and also with a small footprint, thus changing the classical manufacturing technologies. [9]. By citing on Giddings and Lewis, Zhang shows that a Hexapod machine tool is a substantially improved machine tool in terms of speed (about 4 times), rigidity (about 5 times) and precision (about 7 times).

The Hexapod machine tool, which is a parallel kinematic machine with six legs, combines the speed and dexterity of a conventional robot with the stiffness and accuracy of a machine tool.

The Deltapod represents a combination between Delta robot and Hexapod machine tool, which is a less costly and very compact machine, powerful, and that can carry payloads exceeding four times its own mass [10].

An overview on the evolution of the parallel kinematics machine tools is conducted in [11], a survey of their development, performances and practical application compared with the serial machine tools.

In a comparison between Tricept hybrid PKM versus serial robots and traditional machine tools, in [12] is shown that, in terms of speed and flexibility, Tricept hybrid PKM is comparable to serial robots, and in terms of accuracy and stiffness, its performance is more close to the machine tools.

4. Kinematics

Direct kinematics, also known as direct kinematic problem or forward kinematics, consists in finding the generalized coordinates (the variables that describe the pose of the mobile platform) from the articular coordinates (the variables that describe the actuated joints), or, in other words, in determining the position and orientation (the pose) of the mobile platform for a given set of the articular coordinates. For the parallel robots, usually, the direct kinematics is much more complex than the inverse kinematics, but it is necessary for motion planning, control purposes and calibration of the robot.

Inverse kinematics, also called inverse kinematic problem, or reverse kinematics, consists in finding the articular coordinates from the generalized coordinates, or, in other words, in determining the vector of leg lengths for a given pose of the mobile platform, defined by the position vector and the rotation matrix. For the parallel robots, the inverse kinematics is usually uncomplicated and easy to do or understand.

A comparative study on the optimum kinematic designs of the parallel, serial and hybrid machine tools and robotics structures is presented in [13] and few strategies for kinematic designs of some parallel and hybrid mechanism are developed, discussed and analyzed.

For an experimental prototype of a new type of a 2RPU-2SPR parallel manipulator, presented in [14], the direct kinematics solution is calculated by applying an artificial intelligence method, namely the back propagation neural network (where the notation used for the kinematic pairs means: P - prismatic; R - revolute; U - universal or Hooke's or Cardan joint; S - spherical).

To solve the inverse kinematics for any kind of parallel robot used, generally, for drilling or milling, that require three translational and two rotational degrees of freedom, 3T2R, a general kinematics model is introduced in [15].

5. Dynamics

Dynamics of the parallel robots, usually more complicated because of their complexity, is based on the direct kinematics and requires the determination of the dynamic parameters, in order to obtain the dynamic model, which is important for its automatic control.

The most used approaches in the dynamics of the parallel robots are the classical methods that use the Lagrange formalism, Newton-Euler equations, Hamilton's principle, Kane method, and the screw theory and the principle of virtual work. An analogy between the principle of virtual work, and the formalism of Lagrange's equations is presented by Staicu, in [8].

The inverse and direct dynamics of a 3SPS-1S parallel robot is solved in [16] and two different control methods are presented, with some control examples for each method.

A new method for the dynamic modeling of the Stewart parallel mechanism, but which can be used also for other linear multibody systems is proposed in [17] and validated through a numerical study. It is based on the transfer matrix method and considers the mechanism as a flexible multibody system, with the platform rigid and the legs flexible.

By using the matrix method and the Lagrange equation, in [18] is obtained the solution of the inverse dynamics problem for a combined relative manipulation mechanism.

The dynamics formulation for a 5-DOF 2RPU-2SPR parallel manipulator is realized in [19] by using the principle of virtual work, and linear parameterization with the regression matrix form.

The general principle of virtual work is used, also, in [20], for solving the inverse dynamics problem for a 5-DOF modular parallel robot and the achieved results are compared with the Siemens NX dynamic simulations.

For a new and innovative structure of a 6-DOF 6-PGK spatial parallel robot, an inverse dynamic model based on an artificial neural network is performed in [21] and a dynamic numerical simulation is presented in [22].

6. Modelling and simulation

A finite and instantaneous screw based method is used in [23] for dynamic modeling and analysis of a Helix robot, a 2-DOF parallel robot with changeable rotational axes. After the validation of the dynamic model in ADAMS and MATLAB software, the method is declared suitable for the integrated design of different parallel robots.

In the paper [24] is presented a virtual prototyping environment, developed in ADAMS, for the analysis and design of a 3-DOF PKM, but which can be applied to any PKM modeled by rigid bodies.

After the study on the kinematics of a 3-DOF parallel robot, mathematical modeling, and simulation is developed by using the MATLAB software and Optimization Toolbox package in [25] and a prototype of the robot is developed.

In the paper [26], on the research object, which is a 5-DOF 4-SPRR-SPR parallel mechanism, an inverse kinematic position analysis is carried out and solved by using MATLAB and then verified in a virtual simulation, in ADAMS.

Through the paper [27] a novel 5-DOF 4-UPS-RPS spatial parallel mechanism is introduced and its rigid dynamic model is established and analyzed, model that is then verified by numerical calculation in MATLAB and virtual simulation in ADAMS.

A modeling and simulation process in SolidWorks for a 6-DOF 6-SPS parallel robot is used in [28] for the analysis the variations of different motion parameters.

In [29], on the base of a detailed study on the mechanical structure, the kinematics, dynamics, and the control system of a new type of 5-DOF 3T 2R hybrid robot manipulator (composes by a 3-DOF 3T parallel module and a 2-DOF 2R serial module) and a virtual kinematics co-simulation conducted both in ADAMS and MATLAB, a physical prototype and a specially designed control system are developed, followed by few tests for repeatability and accuracy.

Another dynamic modeling of a new type of a 5-DOF gantry hybrid machine tool, in fact, a 2-RPU+2-UPS parallel mechanism connected to the linear guides by two sliding pairs P5, is developed in [30], by using the virtual modeling and simulation, also, in MATLAB and ADAMS.

In a recent paper, [31], a type of 5-DOF 2UPR-RPS-RR hybrid robot is analyzed and is proposed a multi-objective optimization model taking into consideration that objectives which better reflect the motion range (the higher priority), the stiffness and the kinematics performance of the robot.

For a 6-DOF 3-PRUS parallel kinematic machine, a comparative study of the dynamic analytical model, realized through the numerical and ADAMS-based simulation, and, also, a dual experimental prototype are presented in [32].

7. Conclusion

The purpose of this article is to present a brief overview, resulting from a recent literature review on different types of parallel mechanisms, which is realized in order to identify a solution that will be the basis for the development of a prototype, both virtual and experimental, for such a mechatronic system.

References

- [1] Merlet J P and Gosselin C 2008 Parallel mechanisms and robots *Springer Handbook of Robotics*
- [2] <https://www.google.com> Accessed in 02.04.2020
- [3] <https://clarivate.com/webofsciencegroup> Web of Science Core Collection Accessed in 02.04.2020
- [4] <https://www.robotics.org> Robotic Industries Association Accessed in 02.04.2020
- [5] Merlet J P 2000 Parallel robots, *Solid mechanics and its applications*, Kluwer Academic

- [6] Merlet J P 2006 Parallel robots (Second edition), *Solid mechanics and its applications*, Springer
- [7] Gogu G 2010 *Structural Synthesis of parallel robots: part 3: Topologies with planar motion of the moving platform* (Springer)
- [8] Staicu S 2019 Dynamics of Parallel Robots *Parallel robots: Theory and applications* (Springer, Cham) Chapter 1 pp 1-12, Chapter 9 pp 191-243 and Chapter 12 pp 309-326
- [9] Zhang D 2010 *Parallel robotic machine tools* (Springer US)
- [10] Soetebier S, Kock S and Legeleux F 2007 The Deltapod: a new parallel robot for flexible fixturing applications. www.parallelemic.org
- [11] Pandilov Z and Dukovski V 2012 Parallel kinematics machine tools: overview- from history to the future *Annals of Faculty Engineering Hunedoara – Int. J. of Engineering* **X**(2) pp 111-124
- [12] <http://www.pkmtricept.com>
- [13] Harib K H et al. 2012 Parallel, serial and hybrid machine tools and robotics structures: comparative study on optimum kinematic designs <http://www.intechopen.com>
- [14] Zhang H, Fang H, Zhang D, Luo X and Zou Q 2019 Forward kinematics and workspace determination of a novel redundantly actuated parallel manipulator *Complexity* **2019**
- [15] Schappler M, Tappe S and Ortmaier T 2019 Modeling parallel robot kinematics for 3T2R and 3T3R tasks using reciprocal sets of Euler angles *Robotics* 2019 **8**(3) 68
- [16] Chaparro-Altamirano D, Zavala-Yoe R and Ramirez-Mendoza R 2014 Dynamics and control of a 3SPS-1S parallel robot used in security *21st Int. Symp. MTNS*, Groningen, The Netherlands
- [17] Gangli C et al. 2018 A novel method for the dynamic modeling of Stewart parallel mechanism *Mechanism and Machine Theory* **126** pp 397-412
- [18] Pashchenko V et al. 2020 Inverse dynamics problem solution for the combined relative manipulation mechanism with five DoF *Proc. Int. Conf. ER(ZR)* (Springer) **154** pp 253-263
- [19] Zhang H, Fang H, Zou Q and Zhang D 2020 Dynamic modeling and adaptive robust synchronous control of parallel robotic manipulator for industrial application *Complexity* **2020** (Hindawi)
- [20] Plitea N et al. 2016 Inverse dynamics and simulation of a 5-DOF modular parallel robot used in brachytherapy *Proceeding of the Romanian Academy* **17** (1) pp 67–75
- [21] Moldovan L, Grif H S and Gligor A 2016 ANN based inverse dynamic model of the 6-PGK parallel robot manipulator *Int. J. of Computers Communication&Control* **11** (1) pp 90-104
- [22] Moldovan L, Gligor A, Grif H S and Moldovan F 2019 Dynamic numerical simulation of the 6-PGK parallel robot manipulator *Proceedings of the Romanian Academy* **20** (1) pp 67–75
- [23] Shao P, Wang Z, Yang S and Liu Z 2019 Dynamic modeling of a two-DoF rotational parallel robot with changeable rotational axes *Mechanism and Machine Theory* **131** pp 318-335
- [24] Bianchi G, Fassi I, Molinari Tosatti L and Catelani D 2000 A virtual prototyping environment for parallel kinematic machine analysis and design *Proc.PKM int. conf.* (Ann Arbor, USA)
- [25] Artemov D V, Masyuk V M, Yu Orehov S and Pchelkina I V 2019 3DoF Parallel robot analysis *IOP Conference Series: Materials Science and Engineering* **489** 012052
- [26] Yu H, Guo Q and Cui G 2019 Kinematics simulation of 5-DOF parallel mechanisms *Proc. of the 2019 Int. Conf. on Robotics, Intelligent Control and Artificial Intelligence* pp 712-717
- [27] Chen X, LiangX, Deng Y and Wang Q 2015 Rigid Dynamic Model and Analysis of 5-DOF Parallel Mechanism *International Journal of Advanced Robotic Systems* **12**:108
- [28] Miclosina C O, Cojocaru V and Korka Z I 2020 Analysis of a 6-DOF parallel robot motion simulation *Journal of Physics Conference Series* **1426**
- [29] Guo W, Li R, Cao C and Gao Y 2016 Kinematics, dynamics, and control system of a new 5-degree-of-freedom hybrid robot manipulator *Advances in Mechanical Engineering* **8** (11)
- [30] Li R, Wang S, Fan D, Du Y and Bai S 2017 Dynamic modeling of a 2-RPU+2-UPS hybrid manipulator for machining application *Modeling, Identification and Control* **38**(4) pp 169-184
- [31] Li J, Ye F, Shen N Y, Wang Z R and Geng L 2020 Dimensional synthesis of a 5-DOF hybrid robot *Mechanism and Machine Theory* **150**:103865
- [32] Thomas M J, Joy M L and Sudheer A P 2020 Kinematic and dynamic analysis of a 3-PRUS spatial parallel manipulator *Chinese Journal of Mechanical Engineering* (2020) **33**:13