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Review Article

# Parallel Robot

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***Abstract***

The need to high performance, stability, and dexterity robot is the main motivation to improve industrial robots, parallel robots are general-purpose industrial robots, that can give all previous needs with high accuracy. In this paper, a detailed review of parallel robotics is submitted, the paper depends on the latest researches and books related to different types of parallel robots. In the beginning, with an introduction regarding the advantages historical overview and various types of parallel manipulators. Then after the presentation, the categories of parallel robotic research fields are divided into ten categories and subcategories according to the methodology of the paper, the categories are kinematic analysis, dynamic analysis, robotic components, materials and manufacturing, modelling and simulation, artificial neural networks, control, experimental measurements and new devices, calibration, and validation, combined methods and article review.This review aims to give a clear view of parallel robotics' latest trends in different types and a comprehensive research methodology survey.

*Keywords:* Parallel robots, Parallel structure mechanisms, Robotic system, Kinematics, Dynamics, Modeling and Simulation, Calibration, Artificial Neural Networks, Control Robotic Components.

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## 1. Introduction

The first known parallel robots (PR) was invented by James E. Gwinnet and called spherical (PR) in 1928 [1], the improvements were applied after this invention and applied to different uses, in 1965, Stewart proposed a 6 DOF (PR) to use as an aircraft simulator, the development is continued to reach the current classifications of PR.

The (PR) can be used in different industries and purposes such as machine tools, 3D printing, medical rehabilitation, buildings, and other uses. The types of (PR) can be classified according to different factors like structure, kinematics, synthesis, links, degree of freedoms (DOF), number of links, components material, control, and other factors [2-5].

According to the PR's advantages, uses, and importance, this review is established to cover all (PR) research interests as much as possible, shown in Fig.1.

## 2. Robotic Components

The researchers studied the effect, design architecture, and geometry of different (PR) parts such as links, joints, cables, and platforms in the robotic components section.

A 3-SRU (spherical-revolute-universal) parallel platform was discussed in detail, including description, mobility analysis, translation, and Joints [6], A variable geometry trussed manipulator (VGT) was derived containing the design, architecture, motion kinematic, mechanical analysis, and control [7].

The flexible links robots were investigated numerically with a stiffness matrix, this model connects the PKM platform with these links [8], The optimal kinematic arrangements of 3 intersecting link extensions were studied to determine the wave energy converter's absorbing point in (PR) as one example [9], An efficient biomedical human lower-limb model was developed with a more accurate and simple design, the model was based on using a low-cost (PR) , it gives more control and adaption than other mechanisms[10].

Lee and Alandoli [11] classified in a critical review three types of manipulator links: fixed and rigid (FLMs & RLMs) and hybrid links manipulators, the used equations methods in this classification were finite elements, Lagrangian and Newtonian method respectively, Different types of 3 PUP (PR) linkage were suggested with different arrangements, this technique depended on linkage assembly configurations to solve the robot geometrical problems [12],The forces on the knee rehabilitation (PR) were calculated to be given as feedback to the dynamic control system, the system can adapt the model to increase the safety and effectiveness [13], A new parallel wire structure for serial links were designed and analyzed as a cable-driven parallel robot (CDPR), the wire used to control the movement of links and limiting the joints angles[14].

The translation (PR) with parallelogram and prismatic joints was designed and evaluated to ensure dexterity, free workspace, and high payload manners that nominate this kind of robot to various industrial applications [15], Sayapin [16] discussed the basics of adaptive robot design to increase the robot function capabilities, also solve the problem of Incomplete Certainty in Swarm systems.

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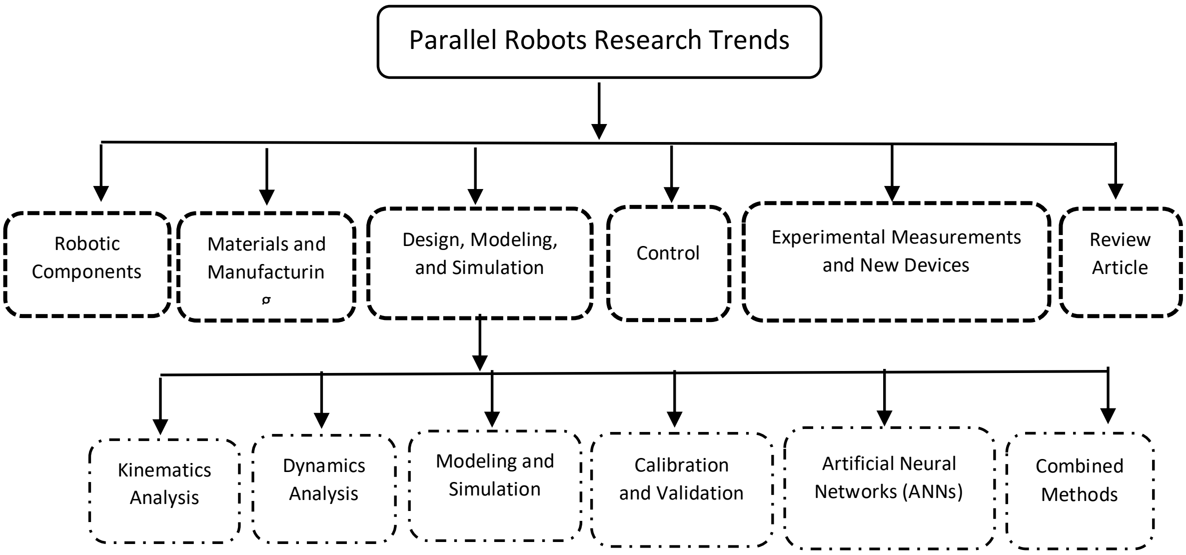

**Fig. 1.** Parallel Robots Research Trends

A new approach was determined using the cable-driven robot's remote center of motion (RCM) function to calculate the rope's tension. This calculation reduced the robot footprint and determined the minimum stiffness needed to select the suitable rope[17], Abdolshah and Rosati [18] controlled the tension in the cable of the cable-driven robot experimentally, the resulted tension was feedbacked to get high accuracy with minimum energy consumption.

The delta robot's trajectory path was designed, considering the effect of passive joints clearance by measuring torques. Then, optimization was applied to increase performance by (10-80)% [19], A comparative study between 3 and 4 RRR parallel mechanisms considering joint clearance, the comparison obtained by kinematic and dynamics factors, and kinematic analysis depended on the first derivation of the constraint equations, and dynamic analysis depended on the Newton-Euler method [20], A 3-PRRU (PR) with 3DoFs tool head Was studied according to joint clearance and structural stiffness, the practical and accurate approach was developed to reduce the error resulted from the joint clearance [21].

A new parametric model for the vibration of the (PR) was driven using Symmetric Gough-Stewart Platforms (SGSPs) in the joint space depended mainly on joint space, by comparing this method with the GSPs method, it gives better formulas by adding inertia and stiffness matrices to get a better system accuracy [22], A paired bearings support joint (PBS-joint) of the serial mechanism was modeled to describe the joint space solution, aiming to improve the topological structure and accuracy of the mechanism [23].

Wang and Kong [24] used the S joint to connect a single loop linkage to get a multi-loop mechanism, the resultant mechanism can get multiple modes in one position, the Lockable spherical joint was designed in different kinematic solutions, this joint allow with translation and rotation modes of the robot, which can get different modes [25]

The effect of joint clearance was studied using Finite element software and experimental vibration measurements, the results compared with other of no clearance and the effect compared to get better dynamic control of model mechanism [26], the resulting forces from the spherical joints were measured using forces/torque sensors, the sensors created a force map matrix, the results were verified with FEM and indicate that the sensor has a good accuracy [27].

The Π joint design and manufacturing presented by proposing two different applications, the results showed the detailed advantages and disadvantages of Π joint [28], The Pa2 joint preliminary design was presented as a part of PM's kinematic chain [29], this study needs more advanced researchers to illustrate in detail restrictions and constitutes, A 2 DOF hemokinematic joint was used to propose several types of zero-torsion (PR) , these classes were structurally synthesis investigated [30]

CDPR end-effector was stiffened by adding springs to study the wrench-feasible workspace (WFW), different locations of spring effect were investigated without increasing cables or motors [31].

The Miniaturization of the (PR) was reviewed and declared the challenges of adaption size, the advantage of sensor used to improve the accuracy after resizing [32], Sinapius [33] represented the basics of adaptonic systems used in different robotics systems to give more adaptive technical features and multifunctions.

## 3. Materials and Manufacturing

The material of robot components is an effective factor, the researchers investigate the parameters affected with changing and applying new material, especially in CDPR, also the effect of using (PR) in material fabrication processes.

The creep behavior of polymer cable was described using CDPR during unloading and loading, the experimental data were compared with estimated formulas to identify the suggested parametric model utilization [34], A mathematical model of polymer CDPR cable was proposed, the model considers hysteresis effects, which depend mainly on the material parameters such as tension, frequency, and excitation amplitude [35], A new mathematical method was presented to solve slackness in tensions in the CDPR, the problem was solved using the control of damping assignment passivity method [36], The viscoelastic materials (UHMWPE Fiber) of CDPR have been tested using the Burger model, this test investigated the stress-strain dynamics, which helps in better evaluation of tension control and accuracy [37].

The effect of two low-cost different gripper materials utilized experimentally, statically, and dynamically also used gripper-characteristic-maps to evaluate the gripper adequacy according to changing the manipulated objects parameters, the parameter ware material, weight, and size [38], Allen and Trask [39] investigated the experimental study of Curved Layer Fused Filament Fabrication (CLFFF) using PR, the need for static vertical movement of the tool path was the primary purpose of using PR, The impact damage of foam sandwich panels by forming tool was Studied, the tool path was controlled using predesign hexapod (PR) [40].

## 4. Design, Modeling, and Simulation of Parallel Robots

### 4.1. Kinematics Analysis

In the kinematic analysis, as shown in Fig. 2 the researchers use different algorithms to calculate motion variables, plan trajectories, design a new model, compare many models, and optimize previous models using theoretical kinematic analysis to evaluate the efficiency, improve the real-time path, choose the better mechanism of PR and ensure the human safety.

Multi optimization method was used as Atlas and Particle Swarm Optimization (PSO) to get an excellent dimension design of the (PR) [41], a topological structure optimization method was proposed that depends on the coupling reduction of parallel mechanisms. The technique gives potential, kinematic solutions, and more real-time control [42], new parallel mechanisms that depend mainly on reconfigurable joints have been discussed in detail, geometrical constraints and mobility analysis included [43], A multi-objective method was discussed to plan the 6UPU (PR) trajectory. It depends on an improved immune clonal selection algorithm to solve the optimization problems [44].

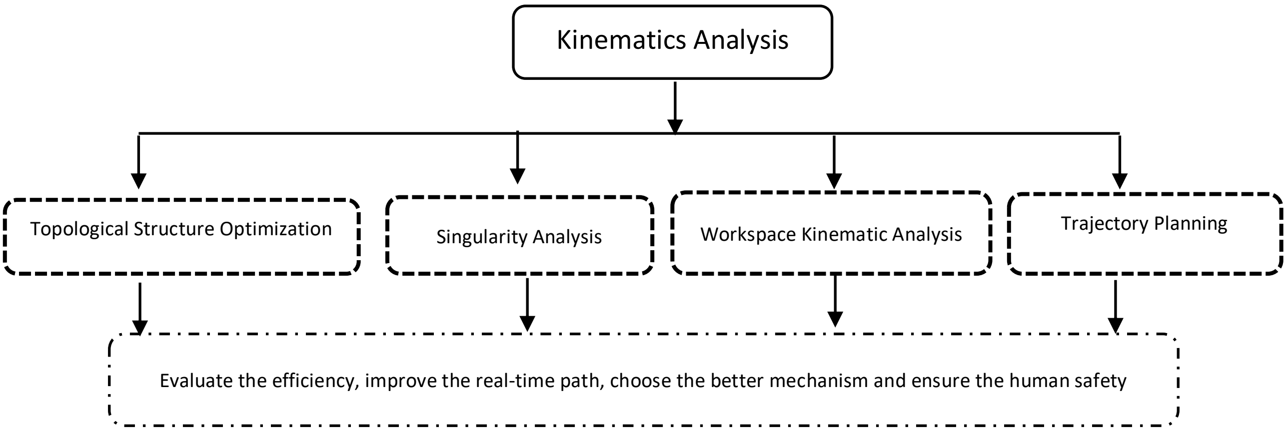

**Fig. 2.** Kinematics Analysis Methods and Aims.

Russo and Ceccarelli [45] presented the designed structure of the parallel mechanism for biped robots. The paper solves the small maintaining workspace problem and approaches a large payload compared to other robots, a 3 P^ur reconfigurable manipulator was kinematically analyzed, the workspace of different modes was discussed, this type of robot can adapt itself to achieve the required workspace due to movable base joints [46], The kinematics of a four-limb parallel Schönflies (PR) with rotational end-effector were analyzed, the dexterity of workspace and singularity were studied to evaluate the robot performance [47].

The parallel 3-PRRR mechanism used as a lower limb rehabilitation robot was kinematically to estimate workspace and rotation angles [48], The RAISE lower limb rehabilitation (PR) was numerically analyzed, the workspace of anatomic and active joints has also investigated the singularities were computed [49], Desai and Muthuswamy [50] investigated the inverse analysis method of 3RPS using nonlinear kinematic equations, the methodology applied to various combinations of limb and system dimensions, the obtained workspace is continuous and symmetrical.

A new method that identifies the workspace barriers via sampling was stated, clustering, and self-motion manifolds, reducing the inverse problem and applicable for a different (PR) type with collision problem[51], High-speed handling (PR) design was proposed with four limbs a 1.5 mobile platform, the kinematic, modeling, and workspace analysis have been investigated [52], A 2USP-U parallel mechanism workspace was studied and modeled, by increasing the trajectory workspace.

The kinematic problem solution was increased [53], PR platform can have a rotational workspace by adding gears to the end effector links, more than one model was suggested and studied [54], Kinematic analysis of a new four limb (PR) with rotational end-effector via gear was illustrated mathematically, also the workspace was simulated, and dexterity checked [55], Nadine and Guillaume [56] analyzed a new 7 DOF (PR) with the folded platform with actuator control, the kinematic and workspace analysis was applied to create a fabricated prototype.

A new dynamic model was investigated depending on Udwadia–Kalaba equation by dividing the system into several subsystems then merging them, the results compared with the hierarchical modeling approach and get high control design ability and friction compensation [57], Enferadi and Jafari [58] dynamically solve inverse kinematics problems using Kane's depending mainly on inverse velocity and inverse acceleration analysis. The results were verified and compared with Newton Euler and Lagrange methods, the first method is easier in solution with three linear equations.

A new delta robot type was kinematically presented to prove the efficiency, and this type is similar to the flywheel, it allows actuators to revolve in space around 360 degrees [59], 6 DOF (PR) forward kinematics problem was solved by a new algorithm, this method was compared with Newton method by applying the solution for 3 PUS and 8 UPS PR, the results give high efficiency [60].

A new (PR) test bench used to simulate impacts was investigated and designed, this model participates in human safety, particularly in automotive accidents [61], The virtual refine chain approach was used to improve the synthesis of the multi-mode mobile (PR) by removing and combining inactive joints, the proposed arrangements were simulated [62].

B´ezier curve was utilized to improve the real-time path design of the Delta PR. Moreover, experimental results were presented to verify the accuracy of the proposed design method [63].

Nawratil and Rasoulzadeh [64] discussed a redundant octahedral motion platform's kinematic design with a movable base. Singularity avoidance was taken into consideration, Santamaría and Castaneda invented the Delta robot reconfiguration strategy as an extra actuator to improve the kinematics performance, the inverse displacement, velocity, and singularity analyses were performed to evaluate the accuracy [65].

A 4-CRU (cylindrical revolute universal joints) parallel mechanism used for 3D-printing building design was demonstrated using the algebraic approach, the design depended on operation modes definition [66], the reciprocal screw theory was used to perform kinematic analysis for limited-DOF PM, it depends on dividing any system into subsystems, then decomposition was applied to create the matrix, this method can give an excellent geometric reflection to any other limited-DOF PM [67].

A comparison was performed between the Stewart platform, and 6 UPS PM analyzed with a genetic algorithm, 6-PUS offered improved stiffness and rigidity [68], A new synthesis study of 2R1T parallel mechanisms was presented, depending on reducing kinematic joints to a minimum number, the results give an excellent guide to designing the (PR) with the more improved performance [69], A two PKM with 3 DOF micro motions were compared, one has a redundancy actuator and the other without, the results showed that actuators increased the stiffness [70].

The kinematic design of a (PR) System used to Lower Limb for ankle rehabilitation was studied [71], Newton-Raphson and homotopy, and Sylvester dialytic methods were used to perform kinematic analysis for PUS+RR (PR) used for ankle rehabilitation [72], Bionic synthesis of the (PR) was discussed with mention to the skeleton of animals, this approach aid in simplifying and proposition of walking robots [73].

The low-cost rehabilitation (PR) was investigated in detail of design, modeling, and manufacturing [74], high reconfigurability and large folding rate were the principal aims of designing the truss antenna mechanism, the model depended on the rearrangement of joints, more than one suggested deployable model was kinematically presented and compared to choose the better mechanism [75].

The inverse kinematic approach of a multi-body system was simplified using FEM and constrained optimization formula. The net result is an excellent example of reducing computational methods to another application, reducing the cost and time [76], an approach was proposed to be used in the advanced design of parallel kinematics machines (PKMs), it was deduced by proving between parametric model and finite instantaneous screws of 5 axes PKMs [77].

Lighting robotic arm design was presented in a section of ergonomics specifications and design, more than one industrial solution was suggested and compared, the best solution was dimensionally synthesis defined [78], A Griffis-Duffy Platforms was designed depending on synthesis means, the paper presented a new design approach using intuitive graphical methods geometrical theorems [79].

A new architecture of 4 DOF haptic robot devices designed based mainly on delta robot was proposed, the kinematic investigated mathematically, the model was verified with 3D printed prototype [80], A 3-DOF Reconfigurable Planar (PR) was modeled using Solidwork software, the motion trajectory and configuration design were analyzed to different robot arrangements [81].

The design of the Inspecting and scanning artwork CDPR was presented, and the geometrical optimization was applied to get a tilt angle near 70 degrees [82], a Cable-Driven parallel robots (CDPRs) was designed and investigated to create a feasibility map, the minimum planning path can be described after analysis of the map [83], CDPR model was represented using Euler-Lagrange (EL) and PortHamiltonian (PH) formalism, this modeling method gives a model with the easiest shape controllers [84].

Xu and Park [85] discussed a solution for the collision of CDPR trajectory planning using the artificial potential field (APF) approach, three types of stimulation were applied to evaluate the algorithm, Two different syntheses of CDPR were compared to ensure operational performance and safety, this robot was used in fusion reactor maintenance and handling [86].

Problems of the vibration component on the ships were solved by fixing the top Stewart platform and floating the lower one, the links absorb the movement and vibration, kinematics analysis was performed to evaluate the motion compensation [87].

### 4.2. Dynamics Analysis of Parallel Robots

In the dynamic analysis, the research analyzes the dynamic parameters, calculates the stiffness, and checks the system accuracy using different mathematical approaches as shown in Fig 3.

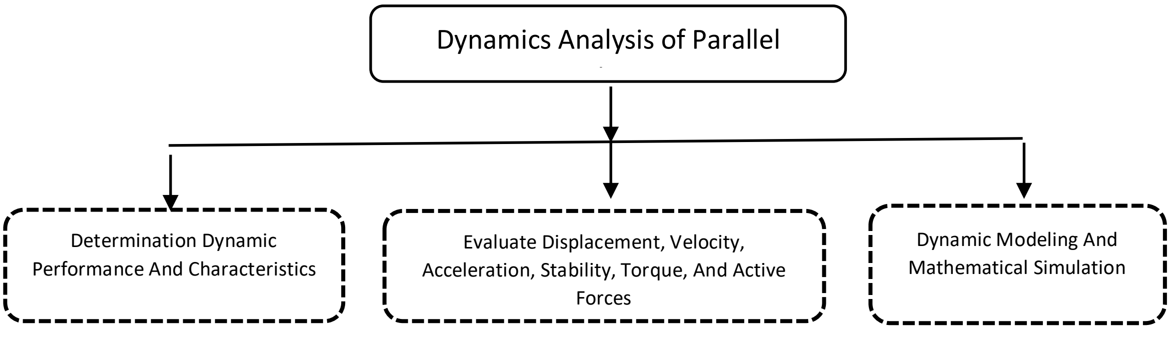

**Fig. 3.** Dynamics Analysis of Parallel Robots Research Directions

The dynamic performance of 6 DOF CDPR using Lagrange formulation was investigated, the dynamic performance concentrated to the advantage preloading of the robot cables on the performance, the used material was steel, the results showed that soft cables material have higher stiffness and natural modal frequencies [88], Dynamic characteristics of the serial and (PR) were predicted using Lagrange principle and Hamilton equation of motion as real-time control, the approach investigated the joints velocity and forces, the results were compared with experimental error measurements, the values were not closer, but the approach results have better universality and algorithm efficiency [89]. A motoBOTTE is an ankle therapy PR, the trajectory torque was estimated by using Euler-Lagrange modeling to optimize the control of the model as a closed-loop kinematic chain [90], Khosravi and Taghirad analyzed CDPR dynamically using the Euler-Lagrange approach, the cable was considered in modeling as linear axial springs, a control algorithm was proposed to test the cable length. The stability of the modeled was examined with Lyapunov second method, the analysis and control methods performance verified with simulation [91], for the same case, another composite controller was proposed, the controller consisted of a rigid model of the system, damping, and tensions in cables [92].

The FEM theory and Lagrange methods were used to perform the dynamic modeling of 5-PSS/UPU PR, the kinematic coupling between each robot component was determined, the natural frequency was considered as the main factor to determine the robot accuracy [93], A 5 DOF UPS/PRPU was optimized by adding a drive to the middle of the robot, the system was modeled dynamically using the Lagrange method, the proposed modification gave a high bear to cutting forces, the simulation results with Adams software showed the optimization performance and the stability [94], The dynamic parameters of the flight simulator platform were obtained and compared from theoretical and experimental methods, the theoretical method can be determined by transforming Lagrange dynamic model into a linear equation [95].

A lower mobility parallel mechanism (LMPM) was analyzed in terms of the reaction of kinematics joints and limb stiffness considering the links elastic deformations, the results were verified using Adams software [96], A new mathematical method was applied to inverse dynamic and joint analysis of PR. Depending on the Newton–Euler and the constraint transfer matrix (CTM) formulation with analysis using screw theory, the results were verified using a software package and previous work [97].

A new approach was proposed for stiffness enhancement of heavy-load (PR) s, the A3 head and the Tricep type were compared to illustrate the practicability of the stiffness improvement [98], A 5 DOF (PR) was modeled dynamically using subtracting and reduction method, depending on reducing and converting robot elements into mass and stiffness, the results compared with FEM and showing high rigidity and lower natural frequencies [99].

A serial-parallel bionic shoulder joint mechanism was proposed. The system was actuated using pneumatic actuators. The model was optimized with PSO, normalization, and adaptive-weight method in terms of medical and dynamic factors, the normalization method gives better results [100]. A new novel consisting of Stewart platform, 6DOF, and X Shape structure were investigated. The results showed high zero, positive and negative stiffness, high vibration isolation, and the low resonance frequency of the proposed model [101].

The cable pulley system was modeled and simulated mathematically, the model included all pullies and winches, the results were approved with actual conditions of the system [102]. A (PR) used to the assembly of vacuum vessel (VV) used in the nuclear reactor was investigated with kinematics and dynamics equations, the purpose of the study was to approve the design free from singularities and feed the controller with control signals to achieve the required trajectory [103].

The energy efficiency of (PR) was evaluated via transmitted power and energy, this method is very helpful in designing high-efficiency machines and optimizing machining parameters [104], A 4 DOF (PR) design was presented, the robot is suitable for Pick-and-Place missions due to rectangle trajectory, the dynamic analysis was performed to ensure from kinematic trajectory dexterity, the results were correlated with Adams software [105].

KNTU CDRPM was analyzed using theoretically dynamical equations, the model simulated to verify the accuracy and integrity of dynamic analysis [106], Delta (PR) was dynamically modeled and analyzed with a simple approach. Also, links mass distribution was checked, which helps improve the accuracy [107], a climbing robot novel with tri-planar limbs was proposed, the kinematic and dynamic models were illustrated to determine displacement, velocity, acceleration, and active forces, singularities were not included, the simulation was utilized to verify the modeling results [108].

A 3-RRR spherical (PR) was illustrated using dynamic analysis, the analysis was performed using the D'Alembert's principle and Kane method, the study was aimed to show the effect of force and torque on the platform, then optimization can be applied later [109], A 3 leg 6 DOF (PR) coordinate dynamics were solved using derived unified dynamic formulae, the model moment of inertia, displacement, velocity, and acceleration were used as input to determine the active forces on the finger, the simulation was verified the approach results, the proposed method can be applied to other types of (PR) [110], a novel of 5 DoFs central rotational actuators (PR) was presented, the dynamics parameters were solved by modeling velocity mapped matrix, dynamic active torque and velocities of legs, the approach was verified by simulation, it provided a structural optimization, fabrication, control guide [111].

Vey [112] discussed a coordinate-free dynamic model of CDPR using Appell's Function and constitutive laws, the purpose of the research is to consider the dynamic model with a control problem, CDPR failure was investigated using real-time computation of braking force and cable tensions, the force obstacle the end-effector to reach the required position [113].

The elasticity of Large Adaptive Reflector (LAR) cables was modeled with nonlinear dynamic formulas using Newton-Euler formulation, this manipulator is considered as CDPR, the study gave a helpful formulation in controlling the system, increasing the frequencies, and bearing high forces [114], A flying CDPR was analyzed dynamically, due to wind, the cables were vibrated, the tension of cables was changed that affected on the accuracy of the robot, using FEM and assuming wind was steady-state, and four-rotor was stable, the system was modeled, the changing in tension was up to 12% [115].

### 4.3. Modeling and Simulation of Parallel Robots:

The research in modeling takes multi-direction as shown in Fig.4, such as geometrical modeling using CAD such as works, and Catia was performed, programing a (PR) design software using different programming languages, using FEM software as Ansys and Adams. The main purposes of using modeling are to improve the design, study the performance and check accuracy.

A geometrical approach called the triangle to triangle test was present to get a free collision workspace, the method reduced the computational time by 23% on average 0.049 µs [116], A rehabilitation parallels robotic kinematic and dynamic simulation was developed using MATLAB and NX software to achieve model correction and getting overlapping data [117], Pisantia [118] used MATLAB software to simulate tracking solar system robots and compute the energy spent to move the platform. C++ programming language framework was developed for CDPR, the framework called XDE, allowed to simulate the elements of the robot such as cable, pullies, platforms, and winches, XDE has been connected with MATLAB/Simulink to control the modeled robot [119].

Guanglei [120] used Solidworks software to simulate six-axis (PR) after the structural simplification, the simulation showed that the robot acceleration was 100G maximumly after modifications, A limb exercises device was simulated using Solidworks software to verify the same model experimental results[121], the Solidworks CAD software was combined with a python programming language to create HSMWorks CAM analysis tool, the resulted NC code was exported to MATLAB software in order to simulate the movement of the (PR) machining machine [122], The reaction forces resulting in Parallel Topology Robots' spherical joints have been determined using SolidWorks software, the results give the flexibility to apply modifications [123].

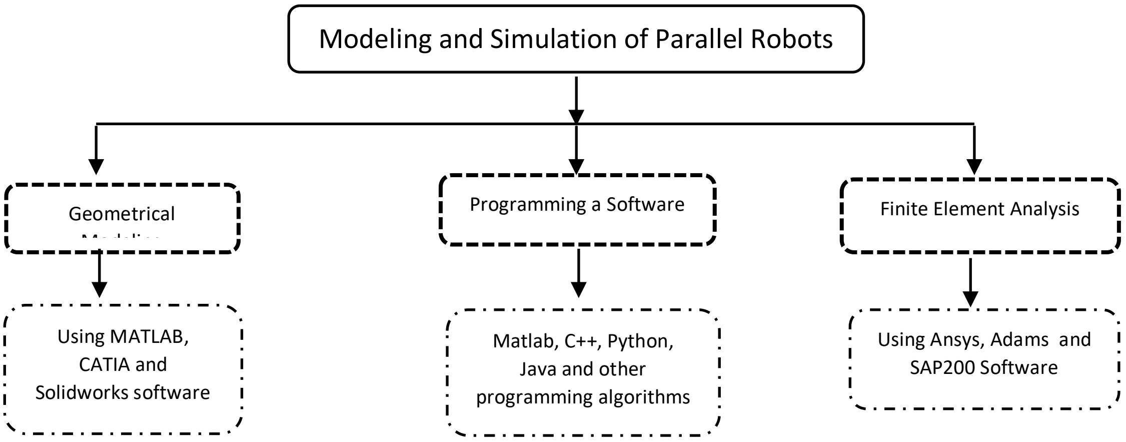

**Fig. 4.** Modeling and Simulation of Parallel Robots Research Directions

CATIA software was utilized to perform a workspace analysis of the Delta robot, the resultant workspaces were restimulated after improvement to check optimization effectiveness [124], Forward kinematic problem (FKP) of (PR) was presented using CATIA CAD software, the simulation gives a clear approach to 3D workspace, singularities, and assembly modes [125].

The rotational mechanism's workspace was simulated to evaluate the robot's homogeneity or dexterity and performance [126], the 2RPR-PR kinematics and dynamic control can be simulated using an educational virtual simulation tool [127], a new deep simulation novel was presented to obtain the performance policy for robot batching, it depends on the tabula rasa approach [128], A medical robot with 5 DOF used a virtual simulator to plan the needle's trajectory, this robot was used in Brachytherapy as a cancer treatment innovation [129].

A virtual simulator software of (PR) was created using Java programming language, it is beneficial, especially to the student, to understand parameters affecting (PR) singularities [130], The design of 6 DOF haptic manipulators was tested using CAD to make insurance and verification of performance before manufacturing [131], A 3RPR planar (PR) trajectory was designed using a simulation tool, this tool gives the trajectory, ability to change different parameters and showing singularity locus [132].

Tarokh [133] simulated the hybrid rolling-walking robot model resulting from the analytical design to ensure the path, robot motion, and satisfactory performance, The CAD from Zeiss Prismo 7 CMM (PR) was used to measure the turbine blade's planned path to draw the error map [134].

The inverse kinematic problem of (PR) was simulated using PAROLA web-based tool, also singularities problems and path planning can be studied [135], ADEFID is software for delta robot modeling and estimations, it was used to evaluate the performance, analyze direct and inverse kinematics and visualize this type of robot [136], m-PaRoLa is a virtual simulation laboratory tool, was created with a JavaScript programming language, it was used to study the kinematics problem and singularities of five bar and 3RRR planar (PR) s [137].

CAD software called ARACHNIS was used to model, design, and analysis the CDPRs, also to describe the performance, loads, and workspace [138], the Gazebo and ROS were simulated the CDPRs as real-time simulations, the dynamic controller can be added to simplify and get real efficient control [139], A 5 DOF (PR) synthesis was designed using CAD software with an established limb database, the structure characteristics and force or couple could be presented from the software [140].

A CAD-based graphical programming tool was used to simulate several architectures of 3DOF PPRMs, the tool helps the designer enhance the (PR) problems and improve the model [141], Motion cueing generation parallel mechanism in vehicle simulators was simulated depending on the Laplacian polynomial transfer function models, the results obtained with means of AM-FM bi-modulated signals [142].

Ansys software was utilized to simulate the deformation and displacement of 3DOF compliant (PR) joints and units, the FEM analysis identifies that curved unit gives better performance [143], Modular Reconfigurable Parallel (MRP) robot was dynamically studied using Ansys software, the results of frequencies and deformation were applied to improve the structure of the robot [144], ANSYS Workbench software was used to analyze Eight-axis Industrial Painting Robot, the results depended on six mode shapes, the suggested modification was stiffening the joints, structure and changing the materials of some components [145].

A combination of the virtual joint method with an FEA stiffness model has been applied to Delta (PR), and compared with experimental data, the comparison showed the high accuracy in early design [146], The high stiffness of (PR) with Scara motion was obtained by comparing FEM with the analytical method (Castigliano’s second theorem).

FEM analysis is a helpful method to describe the mechanism's ability and deformation under external loads [147], more than one CDPR model Vibration analysis has been performed by two analytical methods (FEM and modified analytical method) to get the natural frequencies, the results compared with FEM software to verify and improve the models [148], Cargo container truck motion system was structurally simulated using FEM software, the analysis results increase the design durability and safety [149].

FEM was used to get the effective frequency of moving CDPR, the result was compared with experimental works to complete and verify the vibration analysis [150], A planar 3 DOF CDPR was simulated, including cables' dynamics, the rigid FEM method was used to present a pre-simulation model [151], A circular-orbit CDPR was analyzed using FEM to verify the dynamics and kinematic of the model, the results were used to enhance and improve the model [152].

Dionis is a medical (PR) used for endoscope positioning, this type of robot was designed and simulated with FEM software, the results showed the high stiffness with the small weight and size [153], A 3RRR PM was analyzed using the theoretical FEM approach, the numerical test used to evaluate the system behavior and validate the beam's plastic deformations [154], Gao and Zhang analyzed a compliant parallel mechanism (CPM) using FEM, the simulation ensures the feasibility of design considering sensitivity and compliance [155].

Chanhun used FEM software to analyze a high-speed (PR) design, the results of vibration and stress can be used to increase the robot's performance [156], Cammarata and Sinatra [157] studied the electrostatics of spherical parallel machines with curved links (called Agile Eye robot) with FEM and Timoshenko beam theory, the position error resulting from the static force is the aim of the study, the results were compared and give a limited discrepancy due to assumptions of a mathematical approach.

Nguyen-Van and Gwak [158] investigated the force in cables and natural frequencies of CDPR using FEM method, the results were validated using SAP200 software, the system was optimized to reduce the actuator's size and cable tensions, CDPR dynamic behavior was investigated using FEM mathematical model based on the multi-body approach, the results were validated with experimental measurements, the approach facilitates the accurate design of geometrical and physical properties [159].

Simulation and hardware tests were applied to the CDPR as a novel dual interface, this method helped to increase the time efficiency and accuracy [160], a 5 DOF 3T2R parallel mechanism workspace and orientations were described using the simulation method, this approach simplifies the computation and optimization of the robot structure [161].

## 4.4. Calibration and Validation of Parallel Robots

The researchers use different algorithms to check the singularities, validate models, test the accuracy, calibrate, and evaluate PR's behavior.

A singularity optimization was applied to 3SPS+1PS parallel mechanism vis simulation, the obtained results were applied to the practical model, then the performance improved with no singularity [162], a robust mathematical method was investigated to avoid the singularity in PR, the method depended on examining the center of robot rotations when actuators locked, then the radius of rotation was optimized, the results of the new approach have more efficiency than Jacobian-based methods [163], Rasoulzadeh and Nawratil reduced pentapods robot singularities by pedal points reduction and geometrical optimization [164].

A parallel medical robot used for skull surgery was tested to evaluate the position accuracy, the Monte-Carlo simulation method is the first testing method, also experimental measurements using a coordinate measure machine were applied, the results helped in the optimization of the robot [165], Offline and online approaches were investigated to measure, calibrate and improve the pose error of Stewart platform, an online correction technique and optimization-based kinematic calibration method were applied and compared with the indoor-GPS reference method [166].

Pose error of the positioning mechanism was calculated using screw theory and Lie-group theory under different conditions, after evaluating the performance, the model was optimized to increase the actuation-redundant mechanism accuracy [167], A sensitivity analysis of a 3-DOF (PR) was performed with two steps, firstly each platform error source was separated and illustrated separately, then all errors were collected to platform map to indicate the influence in the global range, the method was considered as a robot design basics optimizer theory [168].

Mathematical equations were stated to perform a full singularity analysis to brachytherapy medical robot and modify its behavior, the approach was compared with experimental data results [169], A parallel/hybrid was analyzed space error with closed-form calculations, also the error source was defined by Baker–Campbell– Hausdorff formula, the experimental cases were proposed to evaluate the performance of the algorithm methods [170].

A feasible kinematic sensitivity approach was proposed, the method was dependent on merging kinematic sensitivity and namely feasible workspace as kinematic properties, a controllable was programmed with this theory, the experiment was performed to CDPR attached with the controller [171], The position of a 3 DOF CDPR was optimized using radial basis functions (RBFs), the experimental work was applied to the model with optimized results [172].

Rasoulzadeh and Nawratil [173] discussed the rotational parameters of linear pentapod singularity, the results compared with maximum free-sphere singularity, in order to avoid the singularities of PR, a geometrical method was proposed depending on the properties of the rotation center, this approach solved the problems of singularity analysis traditional method based on of the Jacobian matrix indexes [174].

The Delta robot's joints singularities were illustrated and calculated using SIROPA library and Gröbner bases [175], A 3-UPU (PR) was kinematically analyzed to detect the robot performance, the workspace, singularities, and dexterity analysis were performed, the method is beneficial to optimize the robot design [176].

A hexapod (PR) used for the machining process was tested to evaluate positional repeatability and accuracy, this type of robot was used to reduce the high cost of huge industries [177], The trajectory planning of machining (PR) was enhanced by joining Non-uniform rational basis spline (NURBS) curves constants with time-dependent, the Catia simulation results verified the accuracy of the theoretical calculations method [178], A triaxial loading device (TLD) was invented to simulate the real machining forces on 3 DOF (PR) machine tool spindle, TLD was controlled using fuzzy PI controller, the controller allowed to test the robot with time-variant and controlled feedforward force, the experimental work proved the validity of TLD with acceptable errors [179].

A 3 DOF Delta robot was analyzed using two algorithm methods to evaluate the kinematic accuracy, the results of the geometric error model method are more accurate in determining the exact position than the Jacobian error model [180], The hexapod table machine tool motion error was determined using a comprehensive algorithm, the method described the non-linear motion error with the help of C#.Net programming, the results derived that error increase with the increase of feed rate [181].

The dynamic performance of 2RPU-2SPR (PR) was tested using a different algorithm, the velocity, acceleration, and the parameters between joint and platform were determined, the dynamic characteristics, driving forces, and dexterity were evaluated [182], A crossbar parallel machine tool was optimized using analysis of dexterity and workspace with new Jacobian matrix, the global dexterity index (GDI) and workspace volume index (WVI) were studied and improved using the proposed algorithm, the modification results was enhanced with 0.43 and 0.34 times [183], A 6-UPS Stewart Platform was calibrated using kinematic analysis using the interior-point algorithm, the method performed to compensate radius and six angles of the platform, a simulation was applied to verify the calibration results [184].

The motion error of 6 DOF (PR) with coaxial actuated arms was determined by studying the inverse kinematics and dynamics of the system, the results of errors were also obtained by image processing test [185], Using analytical methods, a 3 UPU (universal-prismatic-universal) parallel manipulator errors consider joint clearance and link deformations [186], Castigliano's 2nd theorem was used to evaluate 3 PRUP (PR) s' accuracy errors, and this method increases the ability to obtain the flexible joints compliance errors [187], Online kinematic calibration was performed to 3RRR PR, the method depended on merging camera as vision or sensor component with the system, the camera was connected with image processor and controller, the system can be directly adapted to compensate the geometric model, the position error of the system was changed from 0.12 to 0.04 mm [188], Verma and Chauhan [189] reviewed different calibration methods such as offline programming and online programming methods, the review declared that online methods are more accurate with no disturbance.

Sobol's statistical sensitivity analysis method was applied to the 3-RPR (PR) and Gough–Stewart platform, the method considered geometrical features, kinematic analysis, and weight matrix were calculated to estimate the sensitivity, this approach considered uncertainties of active joint only [190], Ayari and Bouamama [191] the path planning problem using D2PSO with better results than dPSO, the static deal only with static obstacles, The (PR) was used to simulate the motion of the human knee model, the resultant motion was measured to study the biomechanics of the ovine stifle joint as a preclinical model [192].

A 3-PRRU (PR) performance analysis was presented after modeling the dynamic model with Newton– Euler formulation, the system's equations of motion (EOM), equations of reaction (EOR), and dynamic manipulability ellipsoid (DME) were used to improve and optimize the performance of the model [193], Zhang and Wei [194] studied the performance of 3-DOF PR, the kinematic and Jacobian analysis was illustrated, the stiffness values were also determined to perform the optimization, the correlation of traditional stiffness model (TSM), kinetostatic compliance model (KCM), dexterous stiffness model (DSM) was applied.

Caro and Merlet studied the behavior of CDPR and failure analysis reasons to ensure human operators' safety [195], A type of CDPR called CAROCA was used to test the sensitivity analysis of the elasto-geometrical, the cables hysteresis effect was studied to enhance the behavior without measuring cable tensions [196], Gosselin and Foucault [197] measured the 3D trajectory error of 3 DOF CDPR using VICON system after the abbreviation of kinematic and dynamic of the system.

A trajectory solver was applied to suspended CDPR to monitor and track in real-time, CPR solver defined the position, velocity, and orientation quickly, Ideal CPR was used to test the current robot CPR [198], Advanced Robotics and Automated System (ARAS) CAM robot are one of CDPR types, the ARAS-CAM was calibrated using force sensors, Encoders, and IR tracker, the forced applied to the robot by attaching a weight to the end effector, the results were validated with simulation [199], A new automatic calibration method to CDPR was investigated, the method relied on measuring the length of cables by fixing encoder at servo motor, the maximum error didn't exceed 10-12 mm [200].

### 4.5. Artificial Neural Networks (ANNs) of Parallel Robots

ANNs method is a computing method that simulates the analysis process of the human brain, it consists of a node layer that comprises hidden, input, and output layers. In (PR) research, different types of ANNS methods are used to solve controlling problems, optimize the structure, and increase robot accuracy.

The structural adaption was investigated by applying a fuzzy type-2 neural network of PSP robots, high trajectory accuracy, and the low-cost computational cost was obtained [201], The delta PR's trajectory tracking accuracy was increased using the fuzzy type-2 neural network applied to the PD controller, and optimized structure [202], Prediction of end effector Planar Parallel Manipulator end effector was performed using deep learning, the method depended on direct and inverse kinematic computation and creating Neuro-Fuzzy Inference model for this system [203]

The CDPR trajectory control problem's solution was investigated, the multi-layer neural network method was applied to compensate the controller uncertainties for actuators coupled with a gearbox [204], the adaptive neural network was involved in designing 4 CDPR controllers to achieve the desired trajectory's stability [205].

Direct Kinematic Problem (DKP) for Real-Time control of (PR) was investigated using Newton–Raphson algorithm. The ANN method was proposed to get high accuracy results with low cost and to be compared with the NR method [206].

Delta (PR) trajectory position and force were controlled using a new adaptive and stable neural network scheme to achieve safety and stabilization [207], delta (PR) performance was improved by using the B-spline neural network method to design a PID controller. The trajectory tracking problem was also one aimed [208], the spherical prismatic spherical parallel (PSP) robot's trajectory tracking control was improved with less effort using the emotional neural network method compared with fuzzy and neural methods [209], The inverse kinematic problem of 6 DOF surgical robot arm controllers was solved using ANNs was presented [210].

PR end-effector manipulator accuracy and celerity were improved by applying BP neural network technique to achieve safety and avoid shortage in traditional methods [211], Mojtaba and Javad [212] presented a new Meta-heuristic algorithms method to enhance and evaluate parallel machines' performance by considering other factors such as machine eligibility, setup time, and precedence constraints.

Different case studies were performed to evaluate a parallel kinematic manipulator's control system, and this evaluation was performed by using the Associative Memory Neural Network (AMNN) to compare different types of controllers [213],The inverse kinematic problem of the industrial (PR) was solved using the deep learning method and closed analytical form. The two method accuracy was compared and validated with the kinematic model [214].

### 4.6. Combined Methods

Many research merges more than one method from previously listed to increase the (PR) ability, performance, and accuracy. CARR is a compliant ankle rehabilitation robot, the design, kinematics, dynamics, optimization, and experimental study were performed [215], the medical robot for needle insertion into the prostate was designed kinematically, the results were correlated with the experimental model and aid to propose optimization suggestions [216].

Kinematics, dynamics, workspace optimization, and experimental study were presented for a 3 DOF Parallel portable CNC with decoupled manipulator [217], Kaewkorn and Joochim [218] presented a detailed design of a 3-DOF pick and place delta robot, the inverse kinematics, mechanical design, and control were investigated.

A 6 legged (PR) was improved by adaptive gait, the approach depended on observing the walking of a human inflate al obstacle road to adapt the robot legs to move like him, the kinematic firstly computed to compensate the absence of force sensors [219], A new parallel leg wheeled robot was presented, the robot was used for moving with high performance on obstacle terrain, the kinematics, dynamics, and simulation was derived and verified the model [220].

Flexible (PR) gives a high adaptation to the end-effector, the kinematics design, simulation, and numerical solution using FEM method was investigated, the deformation measurement was applied to verify the design [221], A brachytherapy purpose medical (PR) was presented, the kinematics modeling was illustrated using algebraic constraint and the Study parametrization of the displacement, also singularities analysis using Jacobi matrices, the experimental model was performed and calibrated [222].

A new novel of the machine tool with walking six legs was demonstrated, the design, kinematic model, workspace analysis, and control were investigated, the robot motion was divided to leg, body, and head motion, comprehensive experiments were performed to test the accuracy, head motion repeatability, of the robot [223], Ghafoori and Khalaji [224] investigated six links parallel continuum robot, this type gives high flexibility, versatility, and multi-DOF, the kinematic model was designed using Cosserat theory, the experimental results showed the error average of the robot was 12%.

A free hex portable machine tool was presented, this type of robot can be attached to different types of surfaces, the kinematic, dynamics, and simulation analysis were studied, the results of the theoretical design were compared with experimental and simulation results, the error ranged between 3.7:5.1% [225], A 6 DOF gantry machine tool was investigated in detail of kinematic and dynamics, the acceleration, velocity, position, and workspace analysis were performed, also torque, power, and energy consumption were determined [226].

The proposed programming algorithm described a hexapod table machine tool motion, the tool was programmed with C#.Net to check the nonlinear errors, Simulation with Catia was performed to validate the results, the error was about 0.01 mm, experiments showed the real effect of the joint on the results of the free form motion when varied from 0.274 to 0.324 according to curvature level [227], Shape memory alloy (SMA) PM was stated mathematically in the section of platform and actuators, the design was also verified statically and dynamically with the aid of a control system to declare the model reliability [228].

The Stewart platform was used in a new invention as rehabilitation hippotherapy for the children with special needs, the model design, material, and experiment were presented, the percentage of Error did not exceed 10% [229], Tunc & Shaw [230] studied the stability of the Stewart platform hexapod robot, the platform was used as a milling machine, the results showed the relation between the stability and spindle speed, tool diameter, and depth of cut, A (PR) machine tool with 4 DOF was investigated, the machine was allowed to rotate around an axis parallel to the machined surface with no singularity and self-adapting [231], Hyperid machine was presented by combining helical milling and PR, the cutting forces and chatter were studied for5 DOF hybrid PKM.

A new novel of hybrid CNC robot was investigated for polishing the free surface, the program was designed according to the path details, the machine was feeded with the program to perform the required surface, the test was performed for the stainless steel, and surface results have been low roughness and high accuracy [232], The dynamic model prosed and analyzed using Euler's method approach, experimental results of machining speed changing [233].

A medical (PR) was invented to simulate the motion trajectory of chewing patterns, and as a rehabilitation robot, the robot motion was driven by a surface electromyography signals (sEMG) and central pattern generator (CPG), the material, methods, model architecture, control, and experimental results were presented [234, 235], Theoretical analysis, simulation, and experimental works were presented for delta PR, these method results were applicable in the optimization process [236], A CDRP workspace was analyzed to investigate FKP solution and uniqueness, two methods were applied to solve FKP problem, LoLiMoT neural network as a data collector from the simulation and gyro sensors data to reduce equations to linear type [237].

Enhancing methods to machine tools were applied to a 4 DOF parallel machine tool, the machine was modeled with Solidworks and exported to FEM software to perform modal analysis, the vibration measurements were applied using ME 'Scope modal analysis software, the results were verified, the suggested improvement was increasing the height of the table to reduce the natural frequency and increase the model stiffness [238].

Limb rehabilitation new device “CUBE” was invented depending on CDPR design, the model was investigated kinematically and dynamically, control algorithm was proposed to give efficiency and comfortability in design, the model was fabricated using 3D printers and results was validated the design and control theories [239], In this paper [240], a new CDPR called FASTKIT was used in logistic solution as goods pick and place robot was presented, simulation, control, and performance evaluation was applied.

A medical rehabilitation CDPR was investigated, the robot allowed the patient to rotate with large degrees around the on-axis by using a potentiometer, drum, and guides, the experiment was performed with an immersive virtual environment [241], A modern CDPR was proposed for high-speed pick and place, a robot consisted of a free frame, extensible limb, pullies, and actuation units, the system was tested and optimized using numerical simulation, the physical prototype was performed with the optimized results [242].

Two methods were discussed to solve the inclusion of CDPR and improve the design, two pully methods and end-effector wrapping method were modeled and tested experimentally [243], A large-scale CDPR used as 3D printing was discussed, this type can be used for building industry, and additive manufacturing, the components, mounting and experimental work were presented [244].

## 5. Control of Parallel Robots

Practical controller and controlling algorithms are used widely in different (PR) researches to control the path, enhance the position, increase the accuracy.

Adaptive control was mathematically applied to 2–DOF RPR and 3–DOF redundant CDPR with kinematics and dynamics uncertainties, the results were verified and improved using simulations [245], A new control method based on high authority strategy of torque required for move end-effector, and a low authority strategy of joint space control, a 3RRR PKM, was experimentally used to evaluate the approach's performance [246], A new time-varying feedback RISE control law was proposed to use in PR, this approach allowed to adjust nonlinear feedback with inline system state, the approach enhances the performance of the robot [247], SEMS algorithm method was applied to control Parallel Mechanism with Complex Robotic System, the results ensure the high accuracy of this method of the position error elimination [248].

Parallel manipulator was controlled using a finite-time adaptive fuzzy tracking control approach, Lyapunov theory method also used to validate the control method, the results declared the high response, precision and nonsingular [249], The force produced in the grinding machine was controlled with a new fuzzy control approach, it depended on controlling the force produced on the tool to prevent tool deflection compensation (TDC) in real-time, increase the accuracy and control the grinding force [250].

A zeroing neural-dynamics (ZND) approach was proposed to solve the (PR) problem of real-time control, the method can be modified by considering appropriate activation function [251], A 3-RPS (PR) was controlled using a forward kinematic algorithm, the approach depended on the geometric conditions, coordinates of spherical joints, and origin of the moving system, the accuracy results were very high with error did not exceed 10-6 [252].

Different types of PKMs PD controllers were compared using numerical simulation, the results were verified and enhancing the performance of the controller by proposing a dynamic control model [253], A new controller method using PID controller and a neural adaptively feed-forward controller was applied to SCARA PR, this approach is more effective in joint angle position control, the performance was verified by experimental tests [254].

An ankle rehabilitation robot (CARR) end-effector was controlled to adjust the link length, the controller used the control feedback and inverse kinematics [255],A 6 DOF medical (PR) was controlled by joining vision-based control with open-loop control, the control unit was stacked to the platform, the high accuracy result reached the error to 0.09 mm and 0.15o [256].

The Delta robot was controlled with a three control based design, and visual servoing was applied to leg-based, line-based, and image moment, each controller alert with the error at each component, the controller collects the alarms to adapt the optimal robot geometry and correct the position and avoid any singularities may be occurred [257], A 4 DOF (PR) was controlled using control hardware based on a PC control system with data acquisition, the control system gave high flexibility, low cost, and evaluation of robot velocity estimation [258].

A five-axis machine tool problem is a cumulative trajectory error, a new postprocessor was proposed to convert th data from CAM system to CNC depending mainly on the algorithm approach, the proposed modification gave a high tool adaption flexibility to machining straight and curved path [259], In this paper [260], a control system was presented to PARA-BRACHYROB modular structure, the purpose of this control was to improve the needle insertion process and to reach difficult targets with high accuracy.

CDPR was controlled using a fast terminal sliding mode (FTSM) controller extended with adaptive control, the results showed high tracking performance [261], the vibration of CDPR was reduced using a proposed controller based on the Linear quadratic regulation (LQR) and Pole placement linear method, the method increases vibration control [262], CDPR vibration was studied using the system's modeling in modal space, the stiffness and dynamic parameters were computed, the modal space used in designing SISO controller to convert the signals to motor position, the results were verified with simulation and experimental model [263].

Adaptive Super-Twisting Sliding-Mode (ASTC) Controller was applied to 6 DOF CDPR to improve the trajectory tracking accuracy, the performance of tracking the disturbance was raised to 400%, but there are a need to study the chatter effects [264], Khosravi and Taghirad [265] designed a PID controller using the PID algorithm and Jacobian transpose, the controller solved the problem of tension-changing feedback in CDPR, high performance was obtained with the proposed controller experiments.

Hui and Mingzhe [266] investigated the control of CDPR, which is used to star and astronomical tracking, the results were compared with robots have the same manner, then some improvements were applied, Merlet [267] proposed a control system to measure the length of CDPR cables the Vernier principle, the method depended on using sensors to detect the marks printed on the cables, the method was more valuable to estimate the cable length and control the system.

The energy and power consumption of CDPR were improved by using the Dynamic Minimum Tension Control (DMTC) approach, the method depends on changing the value of cable tension according to robot dynamics, the result was compared with the fixed tension method to show the high accuracy obtained [268], The CDPR was controlled using disturbance observer (DOB)-based control, this method helps the end-effector reach the required position without disturbance, the effectiveness of the control approach was validated with experiments [269], Large scale CDPR was controlled using a vision-based method, multi-camera with force sensor were fixed on the robot to give feedback to servo motors, the kinematics and system control were presented [270].

## 6. Experimental Measurements and New Devices of Parallel Robots

Different experiments are performed to evaluate the dynamic performance of (PR). Track the trajectories, check the accuracy, and vibration measurements are also used to correlate and identify the robot's dynamic characteristics, the vibration measurements methods weren't used widely, and different techniques can be used to improve the (PR) performance.

Novint Falcon haptic device dynamic identification was investigated using an experimental feed-forward control system, also the model kinematic and dynamics were studied by the Newton-Euler approach, the paper's authors did not use 3-DOF force sensor due to high price, but the resultant accuracy was more accurate [271], The linear PKM dynamic performance was evaluated using experimental measurements, the sensors were located on the joints and end-effector, the acceleration and velocity were measured in various speed conditions [272].

A 4 DOF delta robot with linear actuation was experimentally analyzed, the two experiments were applied to measure the static analysis for transmitted force prediction and singularities as an educational model [273], Borchert and Raatz [274] proposed a new method for joining rotation devices with a handling system, the system is like a pendulum attached to Delta PR, the results of structure stress are validated using simulation and experimental works.

A parallel hip joint manipulator PHJM was analyzed in terms of natural frequency, the vibration measurement test was performed to correlate the rigid and flexible FEM method or called rigid-flexible coupling theory [275], the dynamic performance of 2 DOF (PR) was evaluated, the frequency spectrum and vibration acceleration response of actuators were measured with a designed control system [276].

PR for medical purposes was used to measure the mechanical properties of bone-anchored in four different conditions, the pullout strength and spring constant were measured for the anchor, the (PR) gave an excellent simulation tool for this medical process [277], to test the mechanical properties, a hexapod (PR) was used to perform a simple shear and uniaxial compression to cellular materials like polymeric foams [278].

The position of rehabilitation CDPR Joints was measured using an optical tracking system, the robots were designed using a Korean database [279], Experimental measurements were applied to 4 DOF CDPR to evaluate the stability at multi-position, the force applied with a wrench, the deflection was very small compared to robot size [280], A new test rig was investigated to evaluate the human knee's dynamic behavior. The system depended on CDPR. The load was simulated using pneumatic links, and the natural response of joints was measured [281], CDPR was used as a construction robot for designing granular material architecture, in this paper [282] this type of (PR) was investigated.

The ankle stiffness and orientation can be measured for a single DOF, a new effective device was proposed to measure multi-DOF by using a position sensor and the multi-axis load cell [283].

The carbon nanotubes were fabricated using Delta 3D printer with extrusion hydrogel nanocomposite technique, the resultant product gave high impact mechanical properties [284].

## 7. Article Review

Different review articles studied the latest research on (PR) in general or particularly about one type.

Comparative research of serial and (PR) machine tools was presented, it concluded the kinematic and optimum design of a 3-DOF parallel kinematic and 2-DOF planner mechanism as examples [285], Stewart platform was presented in detail as 6 DOF (PR) , singularities, kinematics, dynamic, FEM analysis, and control were reviewed [286], The different types, design, modeling methods, kinematics, dynamics, performance and optimization, controlling, and trajectory planning of CDPR were investigated in detail [287].

A detailed article about redundant parallel kinematic mechanisms was reviewed, it presented the different methodologies to design, benefits, challenges in the design process, and other topics [288], A 6-DOFs (PR) was itemized presented its advantages, kinematics, dynamics, redundancy, design problems, and workspace volume [289].

Serial and parallel hybrid robots investigated in this survey [290], presented different applications, design aspects, kinematic, dynamics, and modeling challenges, Kampkera [291] reviewed the latest types of additive manufacturing machines, including industrial robots, he compared each machine according to structural weakness and strength.

The latest technologies of spherical parallel manipulators (SPM) or motors were declared to get a spherical motion generation (SMG), it presented the kinematics, performance, design dynamic and control of SPM, also spherical motors and recent developments of SMG [292], Ratiu and Anton [293] presented a brief survey about (PR) from recent researches, it concluded basic terminology, advantage, and disadvantage, kinematics, dynamics, modeling, and simulation of different (PR) types.

The latest researches were outlined updates of dynamic controllers design of micro-manipulators using dynamic decoupling, it was reviewed with both modeling and controller processes [294], different types of mobile-robot have been presented with details of the differences between them according to structural stiffness and accuracy of motion [295].

Nosova [296] presented a development of kinematic decoupling in parallel structure mechanisms, it showed the type of kinematic decoupling, an example of 6 DOF (PR) and Orthoglide robot development.

## 8. Conclusion and Future Work.

This paper concludes and classifies the recent parallel robot research trends, also gives the different methodology and steps used in all categories.

The researchers investigated several trends using different degrees of freedom parallel robot, the selection of degrees of freedom was mainly according to the purpose of the using robot, the higher degrees of freedom parallel robot gives more stiff robot, wide and controller workspace, in most cases the lower degrees of freedom parallel robot gives lower weight, links, joints, and workspace.

Future research will treat the lack of some points, such as using widely vibration analysis, artificial neural network, changing the materials of robot components, enhancing the dynamic characteristics, and combining the previous trends with a comprehensive study.

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## List of Abbreviations

AMNN - Associative Memory Neural Network
ANNs - Artificial Neural Networks
APF - Artificial Potential Field
ASTC - Adaptive Super-Twisting Sliding-Mode
CAD - Computer Aided Design
CAM - Computer Aided Manufacturing
CARR - Ankle Rehabilitation Robot
CDPR - Cable Driven Parallel Robot
CLFFF - Curved Layer Fused Filament Fabrication
CTM - Constraint Transfer Matrix
DKP - Direct Kinematic Problem
DME - Dynamic Manipulability Ellipsoid
DMTC - Dynamic Minimum Tension Control
DOF - Degrees of Freedom
DSM - Dexterous Stiffness Model
EOM - Equations Of Motion
EOR - Equations Of Reaction
FEM - Finite Element
FKP - Forward Kinematic Problem
FLMs - Fixed Links Manipulators
GDI - Global Dexterity Index
KCM - Kinetostatic Compliance Model
LAR - Large Adaptive Reflector
LMPM - Lower Mobility Parallel Mechanism
MRP - Modular Reconfigurable Parallel
PHJM - Parallel Hip Joint Manipulator
PKMs - Parallel Kinematics Machines
PR - Parllel Robot(s)
PSO - Particle Swarm Optimization
RLMs - Rigid Links Manipulators
SMA - Shape Memory Alloy
TLD - Triaxial Loading Device
TSM - Traditional Stiffness Model
RBFs - Radial Basis Functions
SGSPs - Symmetric Gough-Stewart Platforms
VGT - Variable Geometry Trussed Manipulator
WFW - Wrench-Feasible Workspace
WVI - Workspace Volume Index
P - Prismatic Joint
R - Revolute Joint
S - Sliding Joint
U - Universal Joint
UPU - Universal Prismatic Universal