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# Advancements in Design, Kinematics, and Control: A Comprehensive Review of Delta Robot Research

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**ABSTRACT**

A delta robot is a type of parallel robot that consists of three arms connected to universal joints at the base. Delta Robot is designed for high-speed, precision tasks, typically used in applications like pick-and-place operations, assembly, and packaging. This paper conducts the evolution, design, kinematics, and control systems of Delta robots, highlighting their advancements and industrial applications. Starting with their inception in the 1980s, the paper examines the pioneering design by Raymond Clavel, which revolutionized high-speed, precise pick-and-place operations through a unique parallel mechanism. Subsequent iterations of Delta robots are discussed, including innovations such as inverted configurations, linear Delta robots, modular designs, and miniaturized versions for microscale applications. The review delves into various control strategies ranging from traditional PID and sliding mode control to advanced neural network-based systems addressing challenges like singularities, workspace optimization, and energy efficiency. Applications in fields such as food packaging, pharmaceuticals, and high-precision assembly underscore the robot's versatility. The study concludes with insights into emerging trends, such as adaptive reconfigurable designs and enhanced motion planning, paving the way for future innovations in robotic automation.

## 1. Introduction

The Delta robot's influence extends far beyond its original scope, becoming a cornerstone in the field of parallel robotics. Its unique design leverages three lightweight arms connected to a common base, driven by actuators that work in unison to position an end-effector with remarkable speed and accuracy. This parallel kinematic structure minimizes inertia, making it ideal for tasks requiring quick and precise movements. One of its most notable advantages is its ability to maintain consistent performance even under demanding conditions. Over the years, advancements in servo motors, sensors, and real-time control algorithms have enhanced the Delta robot's ability to perform complex tasks with minimal error margins. These improvements have significantly expanded its applications, from high-speed sorting in logistics to delicate assembly processes in microelectronics. The Delta robot's adaptability has been further enhanced through the integration of advanced technologies such as machine vision and artificial intelligence. These technologies allow the robot to identify, track, and manipulate objects with a level of intelligence that was once unimaginable. For example, in food packaging, the Delta robot can now differentiate between products of varying shapes and sizes, optimizing efficiency and reducing waste. Additionally, research into optimizing the Delta robot’s workspace has led to the development of hybrid configurations that combine the benefits of both parallel and serial kinematics. These innovations have not only increased the robot’s reach and flexibility but also enabled it to handle a broader range of payloads without compromising speed or precision [1],[2]. The use of advanced materials, such as carbon fiber composites and lightweight alloys, has further refined the Delta robot's performance. These materials reduce overall weight, allowing for faster accelerations and decelerations while maintaining structural integrity. This has been particularly beneficial in applications that demand repeated cycles over extended periods, ensuring durability and long-term reliability [3]. In academic and industrial research, the Delta robot continues to be a focus of exploration for addressing challenges such as minimizing vibration, improving energy efficiency, and developing algorithms for optimal trajectory planning. Collaborative efforts between universities and companies have resulted in prototypes with augmented features, such as modularity for quick reconfiguration, which is vital in industries where production lines must adapt to ever-changing demands. The Delta robot stands as a testament to the transformative potential of robotic innovation. Its evolution mirrors the progress of industrial automation as a whole, offering a glimpse into the future where robotics will play an even more integral role in enhancing productivity, precision, and sustainability across diverse sectors.

## 2. Methodology

The methodology for this review paper on Delta robots was structured to comprehensively analyze the evolution, design, kinematics, and control systems of these robots, with a focus on their advancements and industrial applications. The following steps outline the methodological framework:

### *2.1. Literature Review*

A thorough literature review was conducted to gather information on the inception, development, and current trends in Delta robots. Key academic databases, including IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar, were used to source peer-reviewed journal articles, conference papers, patents, and industry reports. The search was focused on publications from 1980 to the present, ensuring coverage of both historical milestones and contemporary advancements. Keywords such as "Delta robot," "parallel robot," "pick-and-place robots," "robot kinematics," and "robotic control systems" were utilized to identify relevant works.

### *2.2. Selection Criteria*

Inclusion and exclusion criteria were established to ensure the relevance and quality of the sources:

Inclusion Criteria**:** Publications focusing on the design, kinematics, control strategies, and industrial applications of Delta robots; studies highlighting advancements such as modular designs, inverted configurations, and adaptive systems; and articles addressing challenges like singularities and workspace optimization.

Exclusion Criteria**:** Articles with limited technical depth, those focusing exclusively on unrelated robotic architectures, or publications lacking sufficient experimental or theoretical validation.

### *2.3. Thematic Categorization*

The collected literature was categorized into the following themes to facilitate systematic analysis:

- Historical Development: Examination of the origins of Delta robots, including Raymond Clavel’s pioneering design.
- Design Innovations: Analysis of subsequent iterations and configurations, such as modular and micro scale designs.
- Kinematics and Control: Evaluation of control strategies, including PID, sliding mode, and neural network-based methods, addressing issues like workspace optimization and energy efficiency.

## 3. Design

### *3.1. Historical Development of Delta Robot*

Mauro Maya, Eduardo Castillo, Alberto Lomeli, Emilio González-Galván and Antonio Cárdenas developed a reconfigurable Delta-type parallel robot, aimed at improving workspace flexibility and payload capacity. Unlike traditional robots, this new design allowed for dynamic adjustments to the link lengths, altering the workspace's shape and volume in real-time. A simple ball-screw mechanism powered by a single actuator was used to adjust the fixed platform radius, significantly enhancing the robot's adaptability. The design is illustrated in Figure 1, this design is not only improved operational flexibility but also optimized the carrying capacity for various tasks. [1]

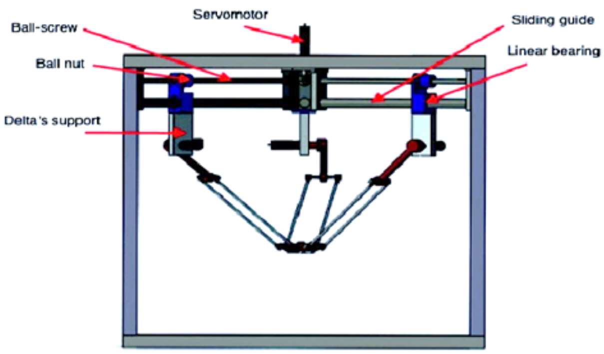



**Fig.1.** General view of the reconfiguring mechanism. [1]

In a quest to create a more adaptable and efficient robot, János Somló, Gábor Dávid Varga, Márk Zenkl and Balázs Mikó designed a revolutionary reconfigurable Delta-type parallel robot. Unlike traditional robots, which have fixed workspaces, this new robot can dynamically adjust its size and shape while operating, thanks to the ability to change the length of key components like the fixed platform radius, the actuated link, and the parallelogram. By adjusting these parameters, the robot's workspace and payload capacity could be optimized for different tasks. The breakthrough was in the simple yet effective reconfiguration mechanism, which used a single actuator to adjust the length of the links symmetrically. This allowed the robot to handle various weights and reach different areas of its workspace, offering unprecedented flexibility and performance. This innovative design opens the door to more versatile robots that can adapt to a wide range of applications in industries requiring precision and load-bearing capabilities; the design is detailed in Figure 2. [2]

**Fig.2.** Delta robot construction [2]

Rogelio de Jesús Portillo-Vélez, Iván Andrés Burgos-Castro, José Alejandro Vásquez-Santacruz and Luis Felipe Marín-Urías sought to enhance the speed and precision of industrial robots by designing a 3DOF Delta parallel robot, specifically tailored for capturing medicine bottles. The robot, characterized by its lightweight aluminium and carbon-fibre structure, utilized advanced kinematics and a modified door-shaped trajectory to minimize arm wobble during high-speed operations, a CAD model is detailed in Figure 3. By omitting sensors and relying on precise mechanical design, it achieved remarkable accuracy and repeatability, even at speeds of 200 motions per minute. Extensive tests validated its ability to perform flawlessly under demanding conditions, offering a reliable, cost-effective solution for high-speed industrial tasks while setting the stage for future enhancements with machine vision and advanced sensors. [3].

Reymond Clavel and Dr. Clavel made ground-breaking contributions to the field of robotics, with Clavel earning the prestigious Golden Robot Award in 1999, sponsored by ABB Flexible Automation [4, 5]. The invention of the Delta robot in 1983 marked a significant leap in robotic technology. The design of the Delta robot was based on a set of parallelograms that kept the output link fixed in relation to the input link [6- 14]. Three parallelograms fully controlled the orientation of the mobile platform, enabling it to perform only three translational movements. The input links were attached to rotating levers with revolute joints, driven by either rotational motors or linear actuators. A fourth leg transmitted rotary motion from the base to the end effector, which was mounted on the mobile platform. [4, 5]

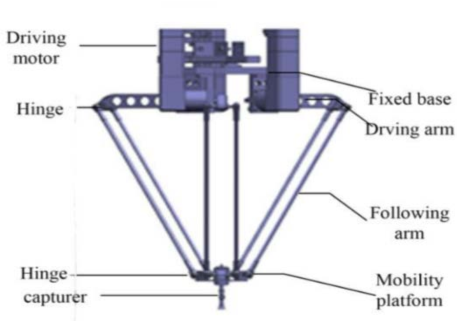



**Fig.3.** Delta parallel robot [3].

At the same time Marc-Olivier and Pascal Demaurex founded the company Demaurex in 1983. The company initially focused on refining Delta robot technology. Over the following years, Demaurex produced several application-specific versions of the Delta robot, commercializing four models (Pack-Placer, Line-Placer, Top-Placer, and Presto) as shown in Figure 4 designed to handle objects ranging from 20 grams to 1 kilogram.

**Fig.4.** Demaurex's Line-Placer installation for the packaging of pretzels in an industrial bakery (courtesy of Demaurex) [4].

By 1999, Demaurex had been acquired by Elekta, a Swedish company specializing in surgical technology. This acquisition spurred the development of a Delta robot designed for precise tasks, such as carrying a 20 kg microscope, the SurgiScope as shown in Figure 5. Later that year, Medtronic acquired technology, further advancing the use of Delta robots in medical fields.

In 1999, Demaurex licensed the Delta robot technology to the Japanese company Hitachi Seiki, which used it to manufacture small-sized Delta robots for applications like packaging (DELTA) and drilling (PA35) as shown in the Figure 6.

**Fig.5.** SurgiScope in action at the Surgical Robotics Lab, Humboldt-University at Berlin (courtesy of Prof. Dr. Tim C. Lueth) [4].


**Fig.6.** Hitachi Seiki's Delta robots for pick-and-place and drilling (Courtesy of Hitachi Seiki) [4]

The same year, ABB Flexible Automation launched its own version of the Delta robot, the IRB 340 Flex Picker as shown in Figure 7, which targeted industries such as food, pharmaceuticals, and electronics. The IRB 340 Flex Picker was designed for high-speed pick-and-release tasks, capable of handling objects up to 1 kilogram with a top speed of 10 meters per second and a picking rate of 150 picks per minute.


**Fig.7.** ABB Flexible Automation's IRB 340 Flex Picker (courtesy of ABB Flexible Automation) [4].

G. Reg Dunlop developed a large-scale Delta robot at the University of Canterbury, initially conceived as a stationary tool for precise calibration and load handling. Standing as tall as an average person and weighing about a third of a ton, this robot was later transformed into a walking machine by adding a triangular foot mechanism. By operating with a tripod gait, the robot could move by following a sequence of motions: placing a foot on the ground, using downward thrust to elevate its body, shifting sideways, and then repositioning its legs. Although the robot showed great promise, it faced challenges related to stability and torque, largely due to limitations in its gearbox, which restricted its step size and payload capacity Figure 8 shows this sequence. These challenges highlighted the need for advancements, such as incorporating hydraulic systems, to unlock the robot's full potential as a heavy-lifting crane or versatile mobile platform [15].

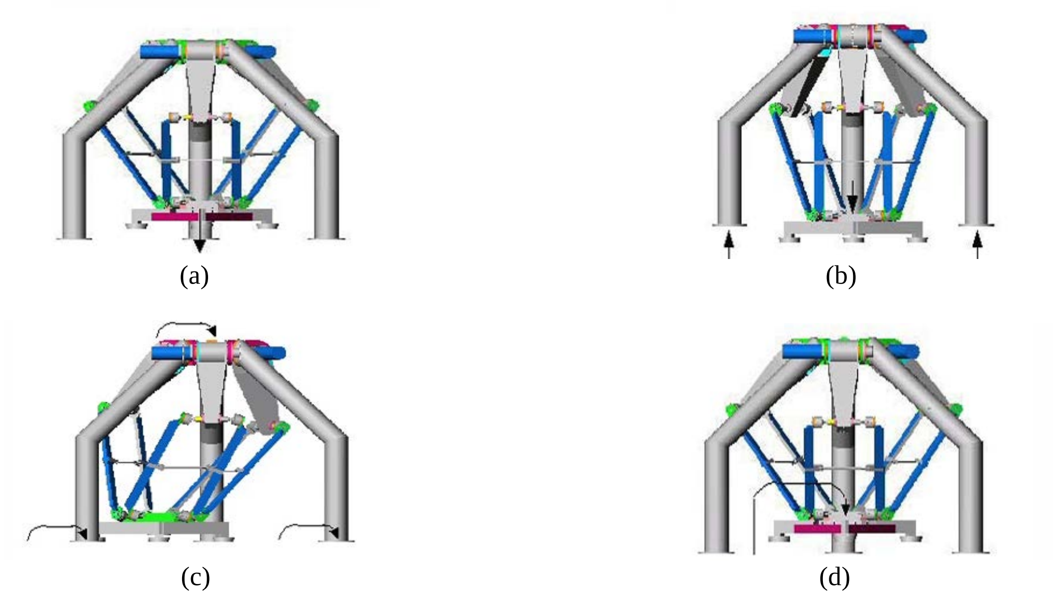


**Fig.8.** (a) The nacelle foot is placed on the ground, (b) Downwards thrust lifts the body, (c) The body is moved sideways, and support legs lowered to the ground, (d) The nacelle foot is lifted, moved sideways and placed at the new foothold [15].

Then M. Bouri, R. Clavel, M. Y. Zerrouki and W. Maeder redesigned the classic delta robot, and they titled it as Inverted Delta Robot. This new design aimed to improve efficiency and precision in pick-and-place operations by inverting the forearms of the traditional structure as shown in Figure 9. The new design minimized the links between the end effector and the base, enabling smoother, more natural motion without frequent motor direction changes. The novel kinematic arrangement optimized the robot for stability and avoided singularities, and the compact, triangularly symmetrical design was suited to small workspaces. A prototype demonstrated the robot’s potential, although refinements were needed to address sensitivity to dynamic disturbances and improve robustness. [16].

After that Qiaoling Yuan, Shiming Ji, Zhongfei Wang, Guan Wang, and Yuehua WanLi Zhan focused on designing a Linear Delta Robot (LDR) with optimal parameters to achieve a prescribed cuboid dexterous workspace (PCDW). The team analysed the robot's kinematics and developed algorithms to optimize the workspace. Using performance charts, they determined the maximal inscribed rectangle within the workspace and assessed the robot's dexterity and isotropy. This method ensured precision and flexibility, making it adaptable to various industrial tasks. [17]

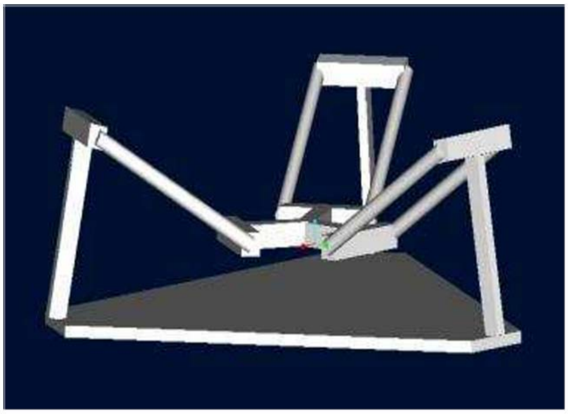


**Fig.9.** Delta Inverse Robot [16]

Then Limin Zhang and Yimin Song focused on optimizing high-speed Delta robots for improved power efficiency while maintaining dynamic performance. A 3D solid model was used for dynamic modelling, and the robot was constructed with lightweight materials like aluminium alloy and carbon fibre to enhance efficiency. This design process identified the ideal cross-sectional parameters for the robot’s components, striking a balance between high acceleration and reduced energy consumption as detailed in Figure 10. These optimizations made the robot ideal for high-speed pick-and-place tasks in light industries. [18]

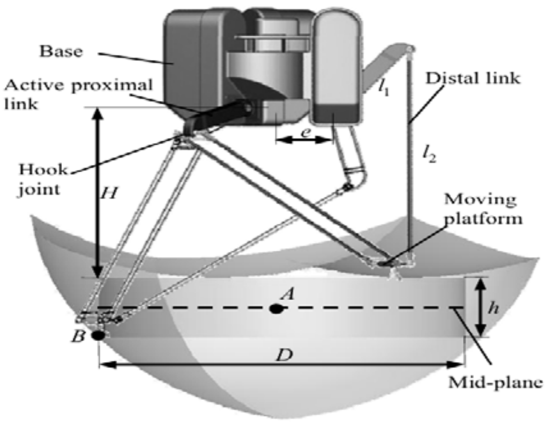



**Fig.10.** A 3D model of the Delta robot and its workspace [18].

Where, D and h represent the diameter and height of the workspace; H represents the vertical distance between the motor axis and the upper plane of the workspace; L1 represent the length of the active proximal link; L2 represent the length of the distal link.

Thereafter Viera Poppeova, Juraj Uricek, Vladimir Bulej, Rudolf Rejda and Xavier Romeo Alba devised a design using parallelograms to maintain the orientation of its mobile platform, offering three translational degrees of freedom. It employs rotating levers actuated by rotational motors or linear actuators, enabling high acceleration, low inertia, and suitability for high-speed or heavy-object handling. Known for its easy disassembly, low maintenance, and flexibility, the FANUC M-1iA 0.5A Delta robot shown in Figure 11 to adjust the fixed platform radius, significantly enhancing the robot's adaptability. This design not only improved operational flexibility but also optimized the carrying capacity for various tasks. [19]

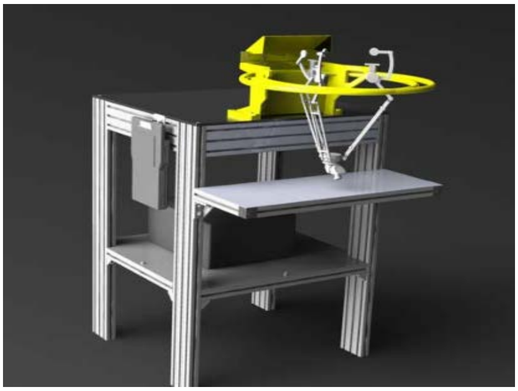


**Fig.11.** The design of workplace with Delta robot M-1iA FANUC Robotics [19].

Jonqlan Lin, Ci-Huang Luo and Kao-Hui Lin described that Delta robots had evolved into modular, reconfigurable systems, particularly in competitive robotics. The system featured a fixed supporting frame and a moving platform connected by three identical kinematic chains. These chains, powered by revolute motors, allowed for three translational degrees of freedom with a fixed orientation. The system also incorporated 3D-printed components for the end-effector, significantly reducing production costs and assembly time, the design is shown in Figure 12. Brushless DC servomotors were used for actuation, and the robot’s control system was integrated with image recognition, making it ideal for tasks like pick-and-place operations. [20]

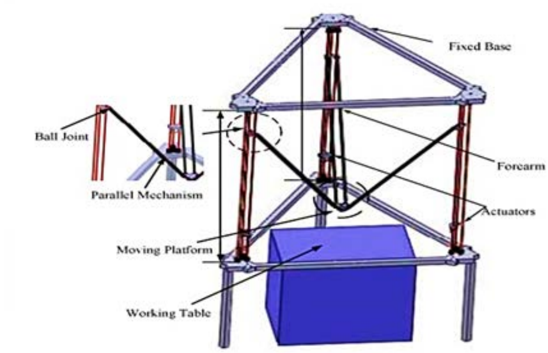
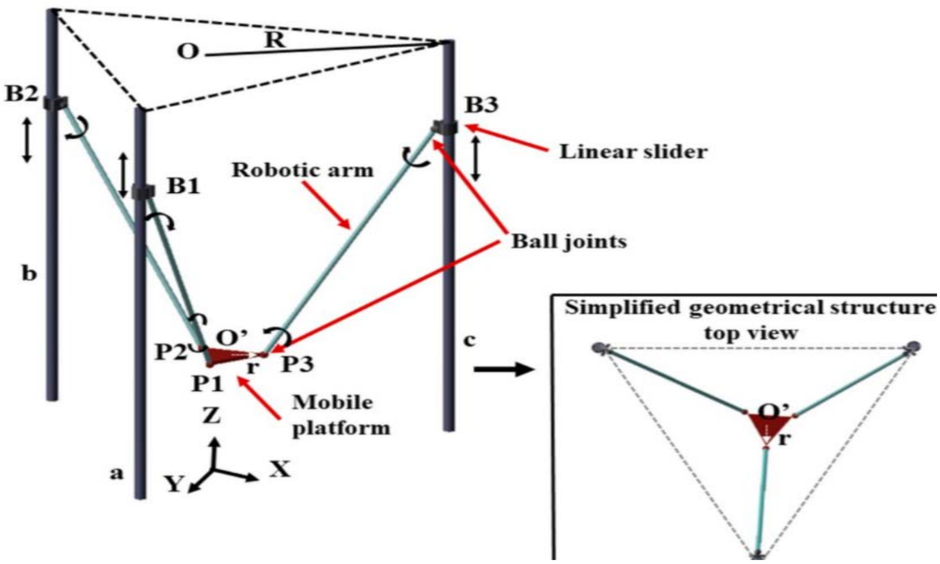



**Fig.12.** Robot architecture for the Delta robot [20].

The development of a Linear Delta Robot recently featured four key components: a linear drive subsystem, a rod-joint assembly, an end-effector, and a control system. The end-effector was connected to the drive system via parallel rods with ball joints, allowing rotational movement across X, Y, and Z axes as shown in Figure 13. The frame was made from extruded aluminium beams, connected using 3D-printed connectors for precise angular alignment. The system utilized my RIO 1900 FPGA, programmed with NI LabVIEW 2019, ensuring accurate operation. The design achieved micrometer-level accuracy, demonstrated in tasks like microsurgery and electronics assembly. [21]




(a) (b)

**Fig.13.** (a) Isometric view of the geometrical structure, (b) The top view of the geometric structure [21].

M. Pranav, A. Mukilan and C. S. Sundar Ganesh found out that the dynamic model of the Delta robot is crucial for calculating the system's dynamic parameters, which are used in strength analyses for its mechanical design. The design includes several subassemblies: the base plate (which holds the motor and gearbox), the bicep assembly (which transfers motor motion via ball joints), the forearm assembly (which positions the traveling plate), and the traveling plate (which holds the gripper). The base plate, designed as an equilateral triangle, supports the motor assembly, which includes a gearbox and flange, the work volume is shown in Figure 14. The bicep assembly uses bearings and ball studs, with the selected bearing rated to handle 6000 N for 30,000 hours under standard conditions. Stress analysis ensures the bicep tube, made of carbon fibre, can withstand high torques and inertial forces. The forearm assembly consists of a carbon fibre tube with aluminium heads, and ball joints made from Torlon for low friction and self-lubrication. The forearms are secured by four springs, designed to withstand high inertial forces. A spring with a force of 62.5N and a deflection of 10 mm is selected, with stress analysis confirming the deformation and stress are within safe limits. [22]

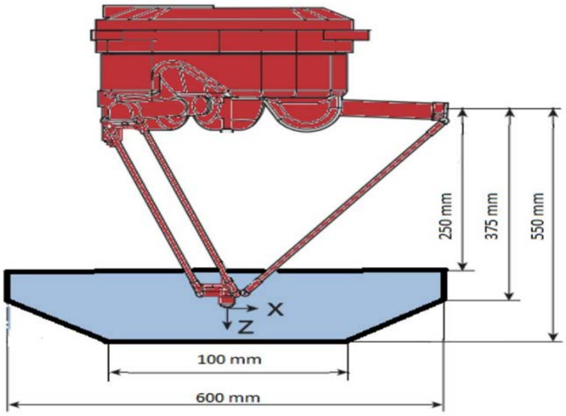



**Fig.14.** Volume of Delta robot [22].

Célestin Préault, Houssem Saafi, Med Amine Laribi and Said Zeghloula presented a document introduces a novel haptic device designed with four degrees of freedom (DoFs) based on the Delta robot architecture, aiming to improve both translational and rotational movement capabilities. By extending the classic Delta structure with a fourth leg, the device achieves enhanced motion flexibility, allowing for rotation by converting translational movements into rotational ones. This fourth leg is connected to two spherical joints, adding three rotational and one translational degree of freedom as shown in Figure 15. A 3D-printed prototype was developed to validate the design, demonstrating its ability to move freely across all four DoFs. The workspace is described in Euler space with constraints ensuring proper movement of the handle. A dexterity analysis based on the Jacobian matrix's condition number, shows that the device offers superior local dexterity, minimizing singularity effects. Furthermore, optimization techniques, using a genetic algorithm, fine-tuned the device’s geometric design to ensure the workspace aligns with the required volume, resulting in a highly effective solution. This new design, with enhanced dexterity and motion capabilities, holds significant promise for applications requiring precise manipulation, such as surgical tasks, positioning the device as a highly advanced tool in the field. [23]

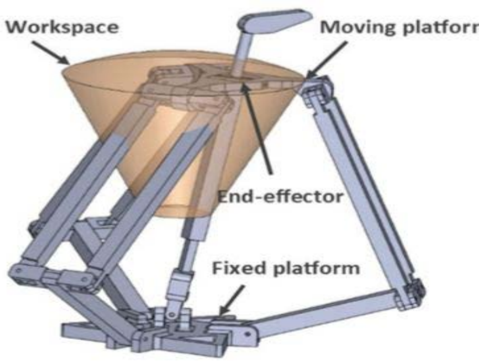



**Fig.15.** CAD model of Delta robot. [23].

### *3.2. Design Innovations of Delta Robots*

Hayley McClintock, Fatma Zeynep Temel, Neel Doshi, Je-sung Koh and Robert J. Wood invented A Milli Delta robot. It takes the Delta robot design to new heights by adapting its kinematics to operate at the millimeter scale, requiring significant modifications for miniaturization while maintaining precision and efficiency. Key to its design is innovative revolute flexural joints and assembly flexural joints, which enhance mechanical performance and ensure smooth, precise motion. The robot's structure features two parallel plates connected by three kinematic chains, each driven by a single-degree-of-freedom actuator, forming a stable parallelogram configuration for precise operation. Advanced 3D CAD and custom laminate design software were used to replace traditional universal joints with perpendicular revolute flexural joints, boosting the range of motion and simplifying the mechanics. Additionally, assembly flexural joints set at 45° reduce strain and improve durability by ensuring the joints remain unloaded during operation. All these are outlined in Figure 16. These thoughtful design choices make the Milli Delta a ground-breaking achievement in miniaturized robotics, offering exceptional precision and reliability for specialized tasks. [24]

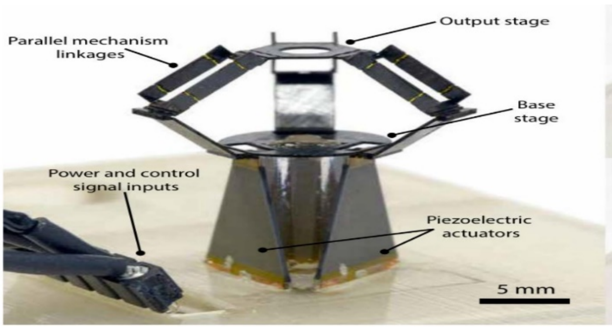



**Fig.16.**The Milli Delta with components labelled [24].

Oleksandr Stepanenko, Ilian A. Bonev and Dimiter Zlatanovn proposed parallel robot designed with five legs, where the first leg and the fifth leg work together to create a parallelogram structure, enabling precise movement and positioning of a tooltip with three degrees of freedom. The legs are connected to universal joints and powered by linear actuators, providing stability and flexibility for the robot's operations. A turntable at the base allows for multi-sided machining tasks, and the spindle holding the tooltip is oriented to always align with the axis formed by the first leg and the fifth leg, with the third leg enabling rotational adjustments. This design enhances rigidity and symmetry, while five actuators work together to ensure smooth operation without synchronization loss, thanks to the coupling of motors for the first legs and the fifth legs. The robot's leg chains, operating as universal-prismatic-universal (UPU) type chains, impose constraints that define the robot's mobility, with singularities arising from specific joint configurations that limit movement. The third Leg plays a crucial role in controlling the rotation of the end-effector, while the fifth leg enhances the overall stability and actuation. Overall, the robot's advanced control mechanisms, coupled with its flexible actuation and robust structure; make it a promising solution for complex machining tasks and other precision applications. [25]

Efrain Rodriguez, Alberto J. Alvares, and Cristhian Ivan Riaño Jaimes proposed that the design of the linear delta parallel robot features three vertically positioned linear actuators arranged symmetrically at 120-degree angles on a fixed base, providing high stiffness in the vertical direction. The actuators convert rotational motion into linear motion using a screw mechanism, ensuring torque and accuracy. Unlike the traditional linear delta, which uses expensive and limited spherical joints connecting the mobile platform to the actuators, the proposed design employs three kinematic chains with single links and revolute joints, incorporating a unique conventional linear delta topology. This setup replaces the mobile platform with a common revolute joint with 2-DOF, enhancing workspace capacity and reducing complexity and cost. The linear actuators transfer displacement to the end effector via the kinematic chains, ensuring precise positioning throughout the workspace Figure 17 shows this design. [26]

**Fig.17.**The fabricated aluminium prototype of the LDr-AM [26].

A bid to improve the performance of Delta parallel robots, a team of engineers named Vu Linh Nguyen, Chyi-Yeu Lin and Chin-Hsing Kuo introduced an ingenious gravity compensation system using a "gear-spring module" (GSM) shown in Figure 18. This system, which combines a gear-slider mechanism with a compression spring, was designed to reduce the robot's torque and energy consumption while maintaining its workspace. By carefully adjusting the spring's parameters, the GSM provided a near-perfect balance at various robot configurations. Testing on a theoretical model and a real industrial robot, the team found that the system significantly reduced peak torque by 38.4% and energy use by 55.4% during typical tasks. The GSM outperformed traditional spring-based solutions, offering a compact, efficient way to enhance Delta robots’ energy efficiency and precision in real-world applications. [27]

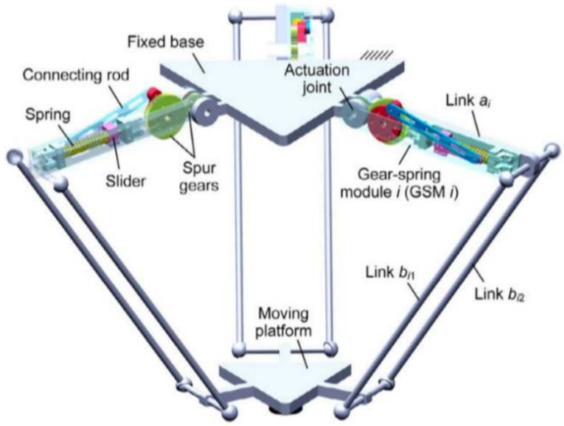



**Fig.18.** The gravity-compensated Delta parallel robot with three gear-spring modules (GSMs) [27].

Elio Matteo Curcio and Giuseppe Carbone invented the design of the novel robotic rehabilitation device focusing on creating a compact, lightweight, and affordable system for home-based upper limb rehabilitation. The design process began with a topology search, selecting a Delta-like parallel kinematics architecture featuring revolute joints for optimal payload-to-weight and workspace-to-size ratios as detailed in Figure 19. The mechanical design incorporated advanced simulations and 3D CAD modelling to refine the robot's motion behaviour, payload capacity, and ergonomics, while dynamic simulations ensured sufficient motor torque. The device uses a compact epicyclical gearbox to balance speed and torque, and structural integrity was verified through simulations. Future enhancements will include remote monitoring, expanded motion capabilities, and additional sensory feedback, ensuring that the device meets both clinical effectiveness and home practicality. [28]

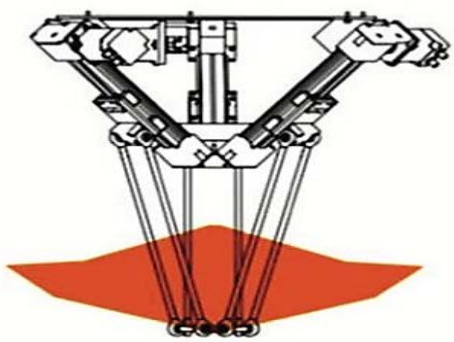
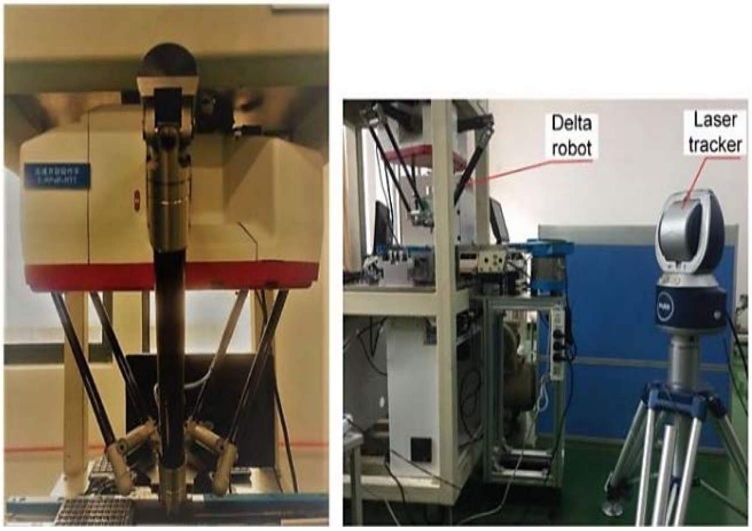


**Fig 19.** Linear Delta robot configuration [28].

The kinematics of the Delta robot have been extensively studied by Qingmei Meng, Ju Li, Huiping Shen, Jiaming Deng and Guanglei Wu to understand its design and optimize its functionality. The robot's coordinate system is defined using Cartesian coordinates. The joint design incorporates four spherical joints at the ends of a parallelogram mechanism, which improves the connection between the actuated link and the main structure, while hard springs are added for stability and to replicate the motion of a universal joint. Movement within the parallelogram is constrained to avoid mechanical collisions, requiring careful consideration of these limitations. Additionally, a footprint ratio constraint is implemented to optimize space usage on the shop floor, involving precise calculations based on dimensional parameters, Figure 20 shows the design. [29]




(a) (b)

**Fig.20.**The parallel Delta-S robot: (a) prototype; (b) kinematic calibration [29].

Then Qiaohong Chen and Chao Yang described the design of the 2PRU-UPR over-constrained parallel manipulator (PM) shown in Figure 21 involves a hybrid algorithm for multi-objective optimization, aiming to enhance its performance. The manipulator features a moving platform connected to a fixed platform via two PRU limbs and one UPR limb. The PRU limbs’ P-joints are aligned with fixed points B1 and B2, while the UPR limb’s P-joint aligns with points B3 and A3. The system's dimensional parameters, including actuator distances, define the manipulator’s configuration. The manipulator provides three degrees of freedom: rotation around the X and Y axes, and translation perpendicular to the U-joint axes. Transformation matrices model the relationship between the moving and fixed frames. This comprehensive optimization ensures the manipulator’s operational effectiveness under various conditions. [30]

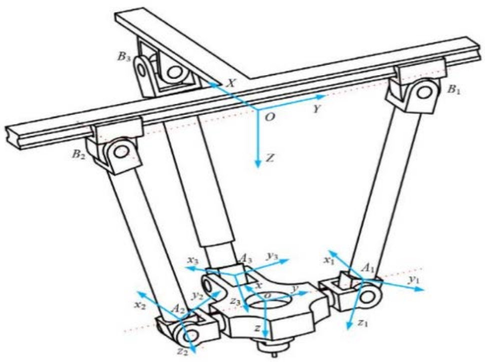


**Fig.21.** CAD model of 2PRU-UPR over-constrained PM [30].

Then Jingang Jiang, Dianhao Wu, Tianhua He, Yongde Zhang, Changpeng Li, and Hai Sun discussed a conceptual design process for a Delta robot, focusing on the design, component selection, optimization, and validation phases. Initial design tasks involve simulations, such as the MATLAB kinematic simulation, to verify robot performance. Key components, including motors, actuators, and structural parts, are selected based on the robot's physical architecture. The optimization process, using a genetic algorithm in MATLAB, focuses on determining kinematic parameters to maximize the robot's workspace. The Monte Carlo method helps refine the workspace objective function, with multiple simulations conducted to select the most stable solutions. The design is integrated into a SysML framework for co-simulation with MATLAB. For validation, 13 points are used to assess the performance of optimized kinematic architecture, leading to the selection of a final design based on energy efficiency. A rapid prototype is then built to test the kinematic motion, with the final design verified through simulations. The study introduces a concurrent design framework shown in Figure 22, incorporating optimization and decision-making tools, and compares it with existing Delta robot design methodologies. [31]

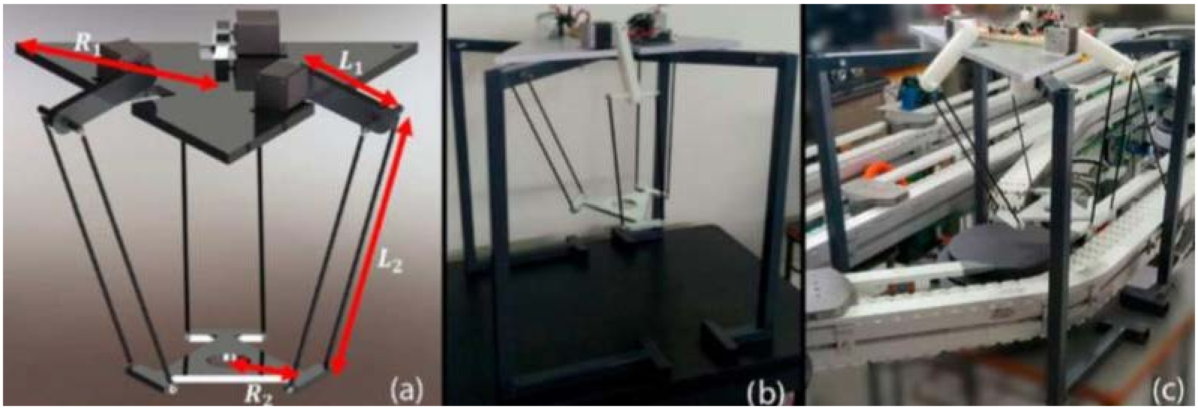



**Fig.22.**Final optimized architecture. (a) CAD rendering, (b) physical prototype, (c) mounting at the conveyor belt [31].

In a quest to improve material handling efficiency Muhizi Musa and JinLiang Li designed and simulated a 3DOF end effector tailored for Delta robots. This system features enhanced flexibility and a wide working range, mimicking the precision of the human hand. Using sliding rails for horizontal motion, the robot expands its workspace, efficiently performing pick-and-place tasks. Equipped with yaw, pitch, and roll motions, the end effector rotates smoothly, ensuring stability and accuracy. Employing computer vision, the robot identifies objects by size or colour, seamlessly adapting to various scenarios all these details are shown in Figure 23. Simulation and dynamic analyses confirmed the system’s reliability, cost-effectiveness, and potential for diverse industrial applications, showcasing a promising evolution in robotics for material handling. [32]

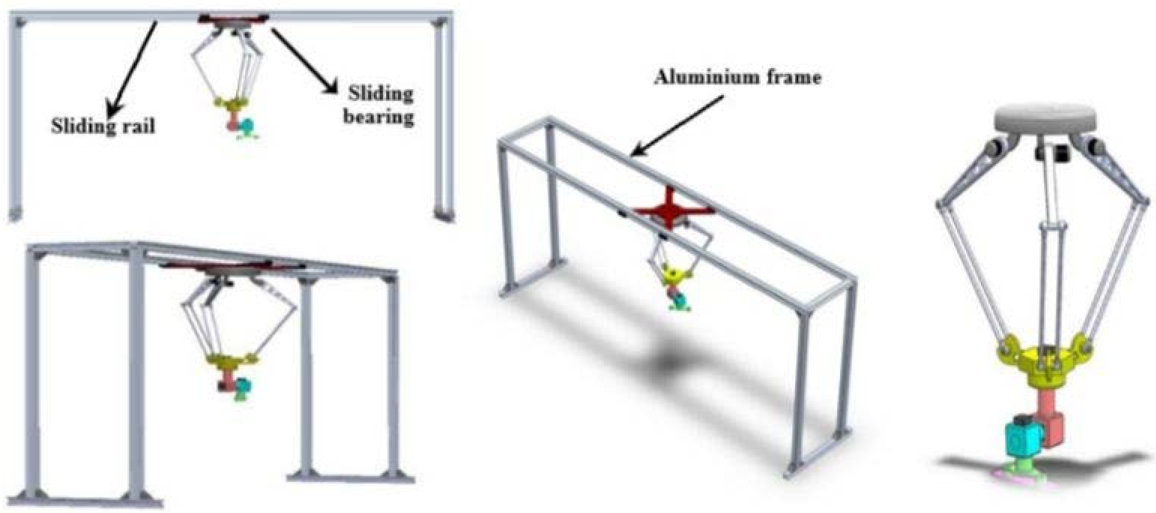



**Fig.23.** Detailed structure of material handling delta robot [32].

Ma Jun-lin, Liu Ying, Zhang Ying-kun and Hao Cun ming then presented a 2-DOF parallel lifting mechanism for a stereoscopic parking robot, focusing on the design and optimization of its structure for improved kinematic performance. The forward and inverse kinematics, workspace, and singular configuration were analysed, and a set of evaluation indexes for consistency, workspace, and singularity were proposed. Structural parameters were optimized within a feasible region, achieving the lowest singularity and consistency indices, ensuring regular operation of the mechanism. A physical prototype was built, and dynamic verification experiments demonstrated the effectiveness of the size optimization, providing stable movement with low energy consumption. The design method, based on multiple kinematics performance indexes, was implemented using MATLAB to iteratively refine the size parameters for optimal motion performance, the design is shown in Figure 24 Future work will focus on developing more efficient search algorithms, integrating clean energy solutions, and enhancing the energy efficiency of the parallel lifting mechanism while maintaining reliability and practicality.[33]

Nikhil Bhomle, Anirudhha Khandekar, Sandeep Sonaskar, and Saurabh Chakole developed the study that investigates the design and development of a Delta Robot for pick-and-place operations, covering its history, advantages, and limitations compared to other robotic systems. It details the mechanical design, including the framework, actuation, end-effector, and material selection, and explores kinematic aspects such as forward and inverse kinematics, singularity, and workspace analysis.

The study also examines the control system, including controller architecture, feedback sensors, trajectory planning, and motion control algorithms. Key applications of Delta Robots in industries such as automation, food, pharmaceuticals, and electronics are discussed. The paper offers valuable insights for researchers and practitioners while suggesting future research directions, such as advanced control strategies, human-robot collaboration, optimization techniques, sensing, and the potential for mobile Delta Robots.

The conclusion highlights the educational potential of the Delta Robot, emphasizing its applicability for understanding robot modelling, though it acknowledges the need for accurate improvements before it can be used in industrial settings [34]. Comparison of the different Delta Robot designs is provided in Table 1, where a relative comparison of features from each of these Designs is presented.

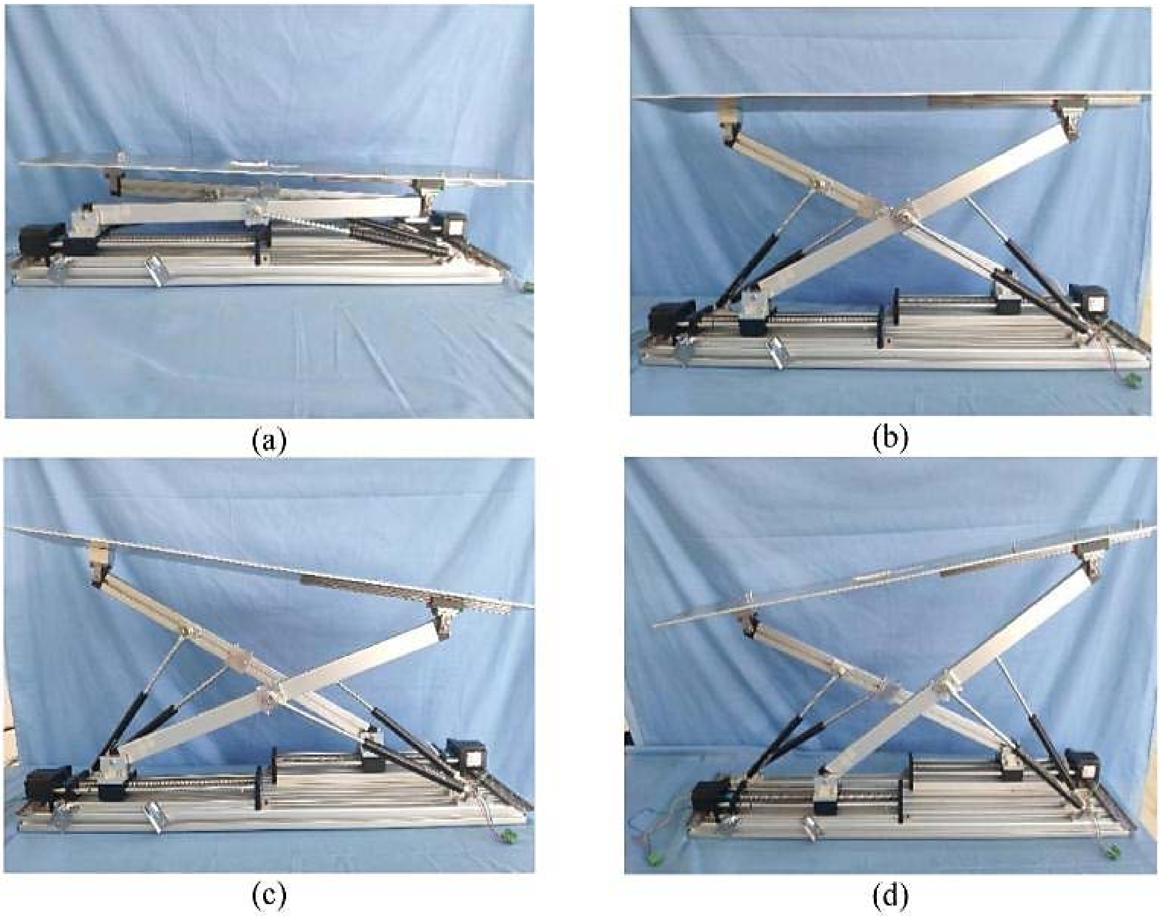



**Fig.24.** Different position and stance of the validation model. (a) Initial position, (b) Lifting position, (c) Right rotation position, (d) Left rotation position [33].

**Table .1.** Delta robot design

| Seq. | Authors | Delta Robot | Design |
|---|---|---|---|
| 1 | Clavel, R. [1] | Parallel Delta Robot | Design relies on a system of three parallelograms that maintain the output link in a fixed position relative to the input link. These parallelograms control the orientation of the mobile platform, allowing it to perform only three translational movements. The input links are connected to rotating levers with revolute joints, which are powered by either rotational motors or linear actuators. Additionally, a fourth leg transmits rotary motion from the base to the end effector. |
| 2 | M. Bouri [13] | Inverted Delta Robot | The new design minimized the links between the end effector and the base, enabling smoother, more natural motion without frequent motor direction changes. |
| 3 | Q. Yuan, S. Ji, Z. Wang, G. Wang [15] | Linear Delta Robot (LDR) | The design analysed the robot's kinematics and developed algorithms to optimize the workspace. The maximal inscribed rectangle within the workspace was determined using performance charts |
| 4 | G. R. Dunlop [12] | Large walking delta robot | A Robot standing as tall as an average person and weighing about a third of a ton, this robot was later transformed into a walking machine by adding a triangular foot mechanism. By operating with a tripod gait, the robot could move by following a sequence of motions: placing a foot on the ground, using downward thrust to elevate its body, shifting sideways, and then repositioning its legs. |
| 5 | M. Maya et al. [17] | Reconfigurable Delta-type parallel robot | New design allowed for dynamic adjustments to the link lengths, altering the workspace's shape and volume in real-time. A simple ball-screw mechanism powered by a single actuator was used to adjust the fixed platform radius, significantly enhancing the robot's adaptability. |
| 6 | V. Poppeova, J. Uricek [16] | Delta robot M-1iA FANUC Robotics | Three translational degrees of freedom delta robot employs rotating levers actuated by rotational motors or linear actuators, enabling high acceleration, low inertia, and suitability for high-speed or heavy-object handling. |
| 7 | Célestin Préault, Houssem Saafi [22] | Four DoFs Delta Robot | By extending the classic Delta structure with a fourth leg, the device achieves enhanced motion flexibility, allowing for rotation by converting translational movements into rotational ones. This fourth leg is connected to two spherical joints, adding three rotational and one translational degree of freedom |
| 8 | Chen, Q. and Yang, C. [29] | 2PRU-UPR over-constrained parallel manipulator | The manipulator provides three degrees of freedom: rotation around the X and Y axes, and translation perpendicular to the U-joint axes. Transformation matrices model the relationship between the moving and fixed frames. This comprehensive optimization ensures the manipulator’s operational effectiveness under various conditions. |
| 9 | V. L. Nguyen, C.-Y. Lin, and C.-H. Kuo [26] | Gravity-compensated Delta parallel robot | This system, which combines a gear-slider mechanism with a compression spring, was designed to reduce the robot's torque and energy consumption while maintaining its workspace. |
| 10 | Meng, Q., Li, J., Shen, H. [28] | The parallel Delta-S robot | The joint design incorporates four spherical joints at the ends of a parallelogram mechanism, which improves the connection between the actuated link and the main structure, while hard springs are added for stability and to replicate the motion of a universal joint. Movement within the parallelogram is constrained to avoid mechanical collisions, requiring careful consideration of these limitations. |

## 4. Kinematics and Control

Tatsu Aoki proved robotics and automation are transforming industries; the Delta robot stands out as a marvel of engineering, celebrated for its unparalleled speed, precision, and rigidity. Delta robot ingenious design comprises three limbs that create a highly coordinated dance of movement, enabling tasks like packaging and assembly with remarkable accuracy. However, unlocking its full potential requires more than robust mechanics, Delta robot demands precise control. Researchers explored this challenge by deriving compact inverse kinematics equations using screw theory, enabling them to calculate actuator positions with precision.

Researchers then tested three advanced control strategies: the reliable but traditional PID, the dynamically adaptive controller, and the highly robust Sliding Mode Control (SMC). Simulations showcased the strengths of each method, with PID offering solid baseline performance, adaptive control excelling in noise rejection, and SMC emerging as the leader in tracking complex trajectories. SMC's fast and accurate responses to disturbances highlighted its superiority, while adaptive control demonstrated resilience under high-frequency noise. These findings not only solidify the Delta robot's place as a leader in high-speed automation but also illustrate the power of modern control techniques in overcoming challenges, setting the stage for even greater advancements in robotic performance and versatility.

[35,36,37] M Lo´pez, E Castillo, G Garcı a, and A Bashir explained; Delta robots celebrated for their speed, precision, and adaptability, are indispensable in industries like food packaging, pharmaceuticals, and electronics. Delta robot's parallel manipulator structure, consisting of a moving platform linked to a fixed base through three kinematic chains, allows rapid and accurate motions. However, these systems face challenges from singularities, configurations where their performance significantly deteriorates. To address this, researchers dived into the critical role of Jacobian matrices in analyzing and mitigating singularities. Researchers explored three types of Jacobians: inverse, direct, and intermediate. The inverse Jacobian identifies singularities at the workspace boundaries, such as when the manipulator fully extends or contracts, restricting movement. The direct Jacobian reveals internal singularities within the workspace, where limb alignment causes unintended motions or changes in degrees of freedom. A novel contribution is the introduction of intermediate Jacobians, which focuses on the robot's sub-loops.

This method not only captures traditional singularities but also uncovers structural issues, like unfavorable dimension ratios between the moving and fixed platforms, which affect stability and functionality. By providing a comprehensive understanding of these singularities, the study empowers engineers to refine Delta robot designs, enhancing robustness and efficiency. These insights pave the way for safer, more reliable robots that excel in high-speed and high-accuracy tasks, reinforcing their role as vital tools in modern automation. [38,39] ZHAO Qing, WANG Panfeng and MEI Jiangping confirmed the Delta robot stands as a marvel of engineering, with a unique design featuring a fixed base, a traveling plate, and three identical kinematic chains. The motion of the traveling plate remains purely translational, enabled by the synchronized movement of parallelogram mechanisms in the distal links. Researchers delved into the robot's intricate kinematics and dynamics, constructing an inverse kinematic model and performing velocity analysis to predict and control movement under ideal conditions, such as frictionless joints. A PD controller with acceleration feed-forward was implemented to maintain accuracy by compensating for inertia variations that could disrupt precision.

The servo drive system, a key component of motion control, was carefully modeled using a transfer function derived through frequency-sweeping techniques. By exciting the servo system with sinusoidal inputs and analyzing the response using least squares fitting, parameters such as resistance, inductance, and torque constants were identified, resulting in an accurate and dynamic model. Given the nonlinear and coupled nature of the Delta robot, controller parameters were optimized across the entire workspace, employing forward kinematic analysis to minimize trajectory errors. A prototype developed at Tianjin University facilitated simulations and experiments to validate the approach. The hardware setup included an industrial computer, advanced servo systems, and real-time velocity and position feedback mechanisms. MATLAB tools like invfreqs played a pivotal role in identifying servo parameters, which further refined the drive model and improved control precision. Results demonstrated significant enhancements in trajectory accuracy and high-speed performance, highlighting how precise modeling and system identification can elevate Delta robot capabilities, establishing a benchmark for the future of robotics [40, 41, 42].

Yong-Lin Kuo and Peng-Yu Huang proved that Delta robots are widely utilized for pick-and-place tasks that demand high accuracy and efficiency. These robots, composed of three kinematic chains connected to a fixed base and a moving platform, rely on advanced motion control systems to achieve optimal performance. Traditional position-based control systems, which treat the robot as separate motor units, often lack the dynamic considerations needed for high accuracy. To address this limitation, researchers proposed a model-based control system that integrates the robot's kinematics and dynamics into the control loop. This approach computes motor torques based on the robot's inverse dynamics and compares them with desired torques to correct errors through feedback control.

Experimental studies using a Delta robot prototype, equipped with compact brushed DC motors and incremental encoders, demonstrated substantial improvements in positioning accuracy with the model-based approach. Unlike the position-based system, which showed positioning errors of up to 3 cm and joint errors of approximately 10°, the model-based system reduced these errors to 0.5 cm and 3°, respectively. The study incorporated path planning techniques to ensure smooth motion without oscillations, validating the system's performance through both simulations and physical experiments. This innovative control strategy underscores the potential of model-based designs to enhance the precision and reliability of parallel robots in high-demand industrial applications [43].

X. Yang, Y. Dong, and H. Yang proved that D2 Delta Robot is based on a planar six-bar mechanism design, as shown in figure 25. The entire structure is distributed within the XY plane, with points A and B serving as rotation axes. Lever AB functions as the fixing bracket, while levers BC and AF act as the driving arms. Levers CD and FE serve as the slave arms, and lever ED is the end effector. During operation, the driving arms AB and BC rotate around axes

A and B, respectively, driving the movement of the slave arms CD and FE, which ultimately controls the movement of the end effector ED. To prevent the end effector ED from rotating during motion and to ensure it remains parallel to the fixed bracket AB, the mechanical design incorporates parallelogram link mechanisms for the active arm BC and the slave arm CD. To avoid interference during movement, the slave arms FE and CD are designed as crank arms. After several modifications and adjustments, a CAD model of the robot was created using Solid Works. The CAD design was then printed using 3D printing technology, and the printed structure was tested for functionality to ensure it meets application requirements. [44]

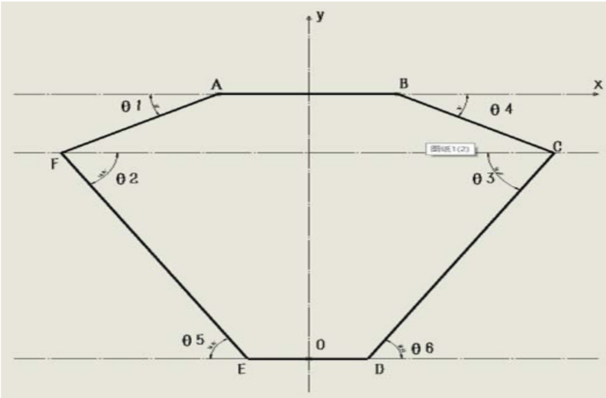



**Fig.25.** D2 Delta Robot structure schematic [44].

Chems Eddine Boudjedir, Djamel Boukhetala, Mohamed Bouri explained Delta robot renowned for speed and precision, serves as a versatile tool in industries such as manufacturing and agriculture. Researchers explored its potential through simulations in the ROS 2 Foxy Fitzroy environment, focusing on developing a robust framework for kinematic motion and stereo camera visualization. By integrating Gazebo simulation with the Simulation Description Format (SDF) file, the robot's closed-loop kinematic structure was successfully replicated; overcoming limitations associated with traditional Unified Robot Description Format (URDF) files. A stereo camera mounted on the robot’s end-effector provided depth perception, enabling advanced imaging capabilities for tasks like object detection. Through the use of Gazebo plugins, such as tricycle drive for motor control and teleop twist keyboard for velocity commands, precise inverse kinematics were achieved, reducing angular errors to an average of 3.92%, 3.72%, and 2.92% across joints.

This innovative approach optimized the Delta robot’s performance and demonstrated its utility in complex tasks using advanced simulation techniques. The study laid the foundation for integrating automated control and image processing, signaling promising advancements in both industrial and agricultural robotics. [45] Le Minh Thanh, Luong Hoai Thuong, Phan Thanh Loc, Chi-Ngon Nguyen focused on Delta robots, celebrated for speed and precision but challenging to manage due to complex dynamics. An innovative control system was introduced, utilizing Single Neuron PID controllers enhanced with Recurrent Fuzzy Neural Network (RFNN) identifiers. Each robot arm was equipped with a neuron-based PID controller, where the weights corresponding to the proportional, integral, and derivative gains were updated online using Jacobian information derived from the RFNN.

This design enabled the controller to dynamically adapt to the system's nonlinear behavior, surpassing the limitations of traditional PID controllers. Simulations in MATLAB/Simulink demonstrated the effectiveness of this approach, showing faster settling times (0.3 ± 0.1 seconds) and the elimination of steady-state errors, even under varying load conditions. The results revealed significant improvements in trajectory tracking accuracy, making this adaptive neural control system a promising solution for optimizing Delta robot performance. This work establishes a foundation for applying intelligent control strategies to industrial robotics, paving the way for more efficient and responsive automation, as shown in Figure 26, and Figure 27. [46]

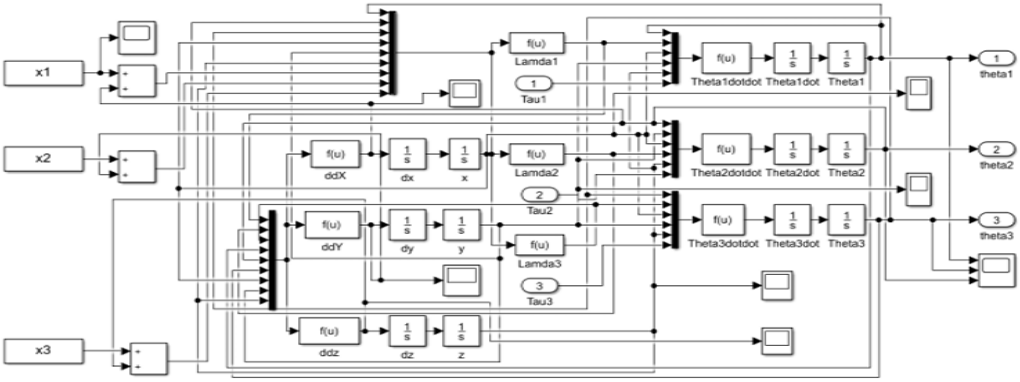



**Fig.26.** Inside of parallel robot module [46].

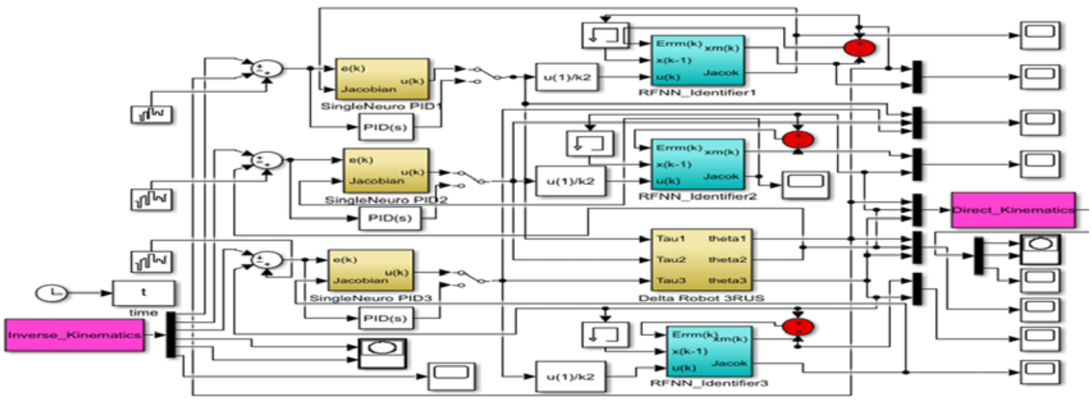



**Fig.27.** Delta parallel robot controller diagram in MATLAB/Simulink [46].

ALI Sharida &Iyad Hashlamon evidenced that in the fast-evolving world of robotics, Delta robots are celebrated for unparalleled speed and precision, yet complex control demands pose significant challenges. Researchers addressed this by designing a real-time distributed control system using four low-cost microcontrollers interconnected via the

CAN Bus protocol. In this innovative setup, one microcontroller calculates the control law, while the other three functions as Intelligent Sensor-Actuator Systems (ISAS), each paired with an actuator and encoder to manage specific tasks. These microcontrollers communicate seamlessly, exchanging motor positions and torque commands to ensure smooth operation. The distributed design reduces computation time and enhances flexibility by allowing additional nodes for future functionalities, such as vision control. Simulations in MATLAB’s True Time toolbox and practical implementation on a Delta robot prototype demonstrated the system’s stability and efficiency, achieving sampling times as low as 6.5 milliseconds. The robot effectively tracked both constant and spiral trajectories, maintaining precision even under high-speed conditions. This distributed approach revolutionizes Delta robot control by offering a scalable, efficient solution applicable to various industrial manipulators, setting a new benchmark in real-time robotic systems.as shown in Figure 28 [47].

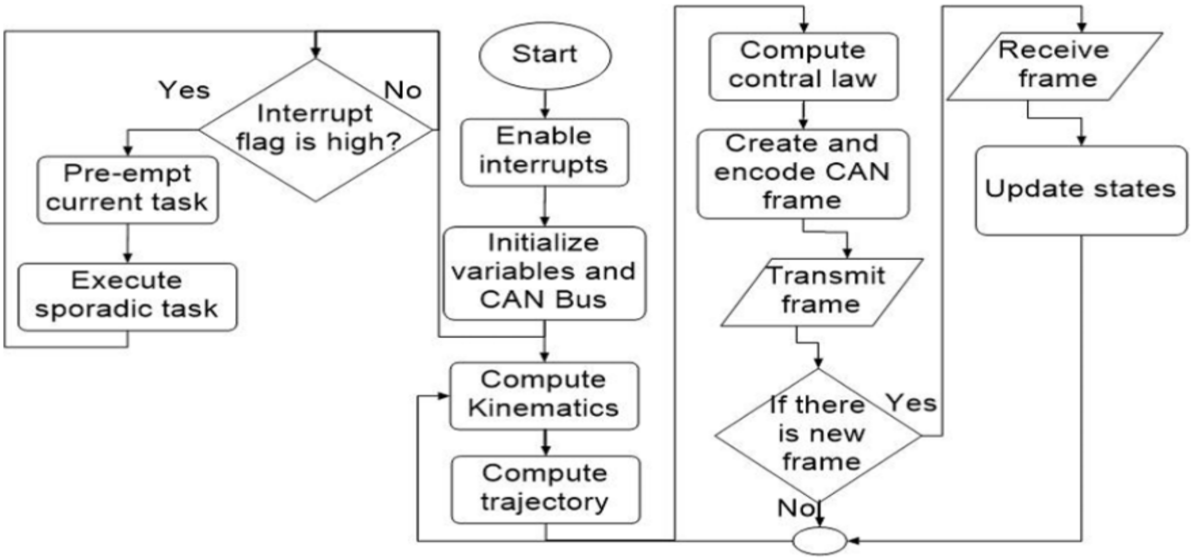



**Fig.28.** Main controller algorithm [47].

Mingkun Wu, Jiangping Mei, Jinlu Ni and Weizhong Hu proved that delta robots are admired for high-speed and precision, yet control design remains challenging due to nonlinear dynamics and susceptibility to disturbances. Researchers developed a novel PD+ controller, complemented by a momentum-based disturbance observer (MDO), to address these challenges and improve trajectory tracking during high-speed and high-acceleration operations. Unlike traditional controllers like Computed Torque Control (CTC), which heavily rely on precise dynamic models, the PD+ controller integrates dynamic characteristics while maintaining lower dependency on model accuracy.

The momentum-based disturbance observer estimates and compensates for system disturbances without requiring the computationally expensive inversion of the inertia matrix, resulting in faster response times. Simulations demonstrated that the PD+ controller significantly outperformed CTC and conventional PD controllers, achieving smaller angle and trajectory errors under both internal disturbances and external interferences. The system's tracking accuracy improved by over 50%, with the disturbance observer effectively reducing errors and enhancing stability. This innovative control strategy paves the way for robust, high-performance Delta robots capable of maintaining precision in demanding industrial applications, setting a new standard in parallel robotic control systems.

[48] Iyad Hashlamon explained in the realm of robotics, Delta robots are celebrated for speed and precision, but complex dynamics and susceptibility to disturbances challenge engineers. To tackle these issues, researchers explored adaptive disturbance estimation and compensation techniques. Three methods were investigated: The Adaptive Kalman Filter (AKF), the Low-Pass Filtered Dynamic Model (LFDM), and the Acceleration Measurement-Based (AMB) method. These approaches addressed challenges such as unmolded dynamics, joint friction, and noise, aiming to improve trajectory tracking. The AKF emerged as the most effective, leveraging recursive updates to track disturbances with minimal overshot and noise sensitivity. LFDM, though simpler and less computationally demanding, showed limitations in steady-state accuracy. Meanwhile, the AMB method suffered from high overshoot and noise susceptibility, making it less reliable. By integrating the estimated disturbances with a proportional-derivative (PD) controller, trajectory tracking was enhanced through the introduction of a tuning gain that dynamically adjusted disturbance compensation. The combination of AKF and adaptive control proved most successful, offering smooth and accurate performance under challenging conditions. This study not only advanced Delta robot control but also provided a robust framework applicable to various robotic systems.

[49,50] Faraz Abed Azad, Saeed Rahimi, Mohammad Reza Hairi Yazdi, Mehdi Tale Masouleh in the world of advanced robotics, the Delta robot stands out as a masterpiece of speed, precision, and adaptability, making the technology indispensable in industries like manufacturing, food packaging, and pharmaceuticals. The design three limbs connecting a fixed base to a mobile platform provides exceptional stiffness and rapid movement capabilities but introduces complexities in kinematics and dynamics. Researchers tackled these challenges using screw theory, deriving concise inverse kinematic models to calculate precise actuator positions for specific end-effector locations. Simulations in MATLAB’s Simscape environment verified these models, laying the groundwork for innovative control strategies. To optimize performance, three control methods were implemented and tested: PID, adaptive control, and Sliding Mode Control (SMC). PID control, while simple and effective for basic tracking, struggled with noise and required additional filtering, limiting robustness and adaptability.

Adaptive control dynamically adjusted parameters using Lyapunov stability, achieving superior noise rejection and stability, especially in unpredictable environments. SMC, however, emerged as the standout performer, delivering the fastest and most accurate responses by employing a sliding surface and Lyapunov-based stability, enabling precise tracking of nonlinear trajectories with minimal oscillations. Rigorous tests on a complex 3D path revealed that SMC excelled in accuracy (root means square error, RMSE: 0.4188), while adaptive control excelled in noise rejection time (standard to peak, TSP: 0.1130), both outperforming PID control. These findings demonstrate that advanced control strategies like SMC and adaptive control can overcome the Delta robot's challenges in motion control, enhancing reliability and efficiency. This research highlights the potential of these techniques to revolutionize parallel manipulator performance in industrial applications.

[51] In addition, both Le Minh Thanh, Luong Hoai Thuong, Pham Thanh Tung; Delta robots are celebrated for their precision and speed, but complex dynamics require innovative control systems to achieve optimal performance. Researchers focused on addressing these challenges by exploring advanced controllers for trajectory tracking and error reduction. Traditional PID controllers, single-neuron PID controllers, and a novel Recurrent Fuzzy Neural Network-PID (RFNNC-PID) controller were compared, with the latter designed to adapt dynamically to changing control conditions such as varying speed and load. The RFNNC-PID combines the strengths of fuzzy logic and neural networks, enabling real-time adjustment of control parameters. Simulations demonstrated that the RFNNC-PID outperformed other methods, achieving faster response times of approximately 3.8 seconds and eliminating steady-state errors, even under increased loads. The system was tested on elliptical and figure-eight trajectories, showcasing stability and accuracy.

By integrating neural networks and fuzzy logic, the RFNNC-PID controller provides a robust, adaptive solution for Delta robots, paving the way for advancements in precision robotics and industrial automation. [52] Akram Gholami, Taymaz Homayouni, Reza Ehsani and Jian-Qiao proved that in an effort to enhance the performance of Delta robots, a cutting-edge system was developed that integrates a neural network for real-time prediction of joint angles, with the ability to adapt dynamically during operation through online learning. Initially trained with 2000 data points, the neural network predicts joint angles based on inputs like the desired trajectory, current position of the moving platform, and the robot's active joint angles. As the robot operates, new data points are constantly added, updating the network to reflect real-time conditions. For each new point, an older one is removed to maintain dataset balance, ensuring that the network always learns from the most current data. Every 10 new data points trigger a retraining cycle, refining the neural network's accuracy. The system's driving unit then translates these predictions into precise commands for the robot's actuators, which carry out the movements, closing the control loop with real-time feedback on joint angles and platform position. This continuous process of adaptation ensures that the robot can perform complex tasks with exceptional precision, even in dynamic environments.

[53] Khairul Muzzammil Saipullah, Wira Hidayat Mohd Saad, Sook Hui Chong, Muhammad Idzdihar Idris explained the Delta robot renowned for its speed and precision, serves as a versatile tool in industries such as manufacturing and agriculture. Researchers explored its potential through simulations in the ROS 2 Foxy Fitzroy environment, developing a robust framework for kinematic motion and stereo camera visualization. By integrating Gazebo simulation with the Simulation Description Format (SDF) file, a closed-loop kinematic structure of the robot was successfully replicated, overcoming the limitations of traditional Unified Robot Description Format (URDF) files. A stereo camera mounted on the robot's end-effector enabled depth perception, enhancing imaging capabilities for tasks

like object detection. Through the use of Gazebo plugins, including tricycle drive for motor control and teleop twist keyboard for velocity commands, precise inverse kinematics were achieved, reducing angular errors to an average of 3.92%, 3.72%, and 2.92% across joints.

This innovative approach optimized Delta robot performance and demonstrated its utility in complex tasks through advanced simulation techniques. The study laid a foundation for integrating automated control and image processing, paving the way for advancements in both industrial and agricultural robotics. [54] MLo ´pez, E Castillo, G Garcı´a, and A Bashir explained the Delta robot, a type of parallel manipulator, features a moving platform connected to a fixed base by three parallel kinematic chains, each incorporating a rotational joint driven by actuators. Analyzing kinematics involves examining key points on the fixed and moving platforms using Cartesian coordinate frames.

Various angular and positional variables govern the system, which are essential for deriving its Jacobian matrix. This matrix describes the relationship between the robot's joint variables and the velocity of the moving platform. Jacobian analysis involves differentiating loop closure equations, leading to an understanding of both inverse and direct kinematics. Singularities, which occur when the determinant of the Jacobian becomes zero, are categorized into inverse kinematic singularities, found at the boundary of the workspace, and direct kinematic singularities, occurring within the workspace. Intermediate Jacobians simplify the analysis of these singularities and are critical for understanding the robot's structural limitations. The article also explores the impact of these singularities on the robot's movement and workspace, providing valuable insight into the robot's dynamics and design considerations. This analysis helps optimize performance and ensures operation within the robot's feasible range.

[55] M. Rachedi, et al; two control strategies for a Delta parallel robot were explained; Computed Torque Control (CTC) and Ho robust control. The Ho controller designed using the mixed sensitivity approach, offers better robustness and performance in trajectory tracking and disturbance rejection compared to CTC. Unlike CTC, which relies on the inverse dynamic model (IDM) in its feedback loop for decoupling and linearization, Ho eliminates the need for IDM, significantly reducing computational demands. Simulations on a semi-elliptic pick-and-place trajectory demonstrated that Ho achieved superior precision, even with parametric disturbances like additional loads on the robot. This makes Ho an effective choice for robust control of nonlinear dynamic systems.

[56] T. Abut and S. Soygüder The motion control, kinematic, and workspace analyses of a Delta-type parallel robot with three degrees of freedom (3-DOF) were proved, emphasizing applications requiring precision, rigidity, and high-speed operation. Actual parameters for the Delta robot were used, with forward and inverse kinematic analyses conducted to calculate movement and positions. Workspace analysis was performed to understand the operational limits within a three-dimensional Cartesian space. The Sliding Mode Control (SMC) method was employed to achieve robust and stable motion control with zero oscillation, addressing external disturbances and ensuring precise trajectory tracking. A saturation function was integrated into the SMC method to mitigate chattering, simplifying

implementation while maintaining stability according to Lyapunov criteria. Simulation results confirmed the approach's effectiveness, with positioning errors minimized to near zero and motion control aligning closely with reference inputs. The study highlighted the practicality and efficiency of SMC in enhancing the operational capabilities of Delta robots, particularly in industries where speed, accuracy, and minimal maintenance are crucial.

[57] Dachang Zhu, Yonglong He, Xuezhe Yu and Fangyi; an innovative solution for industrial robotics was introduced through the design and implementation of a low-cost, microcontroller-based Delta robot. Recognizing the need for affordable and efficient robots in industries like assembly, packaging, and material handling, researchers aimed to create a cost-effective alternative to expensive industrial robots. Microcontrollers were utilized as the core of the robot's control system, significantly reducing hardware costs while maintaining functionality. The Delta robot, known for its parallel kinematics, offers high precision and speed, making it ideal for tasks requiring rapid and accurate movement.

The design focused on minimizing components while ensuring reliable performance in real-world industrial settings. Through careful selection of materials and optimized control algorithms, a low-cost, efficient system capable of performing tasks with precision was developed. The design incorporated affordable actuators and a simple yet effective control interface using microcontrollers. This solution is particularly relevant for small to medium-sized businesses needing automation but with limited budgets for traditional robotic solutions. The successful implementation of this robot demonstrates the potential for accessible, scalable automation in industries, paving the way for broader adoption of robotics in sectors previously unable to invest in high-end systems.

[58] Torgny Brogardh, a novel approach to trajectory planning for Delta parallel robots, was introduced, aiming to enhance precision and efficiency in real-world applications. The focus was on the challenge of smoothing of trajectory, a critical aspect of robotic movement that reduces mechanical wear, improves accuracy, and ensures smoother transitions between different points in a robot's workspace. Traditional trajectory planning typically considers either Cartesian space or joint space separately, but Zhu's approach combines both, offering a more integrated solution. By blending the strengths of Cartesian space for global positioning and joint space for precise movement control, the method ensures smoother paths and better coordination between the robot's end effectors and its joints.

The proposed method accounts for the robot's kinematic constraints, ensuring that trajectory planning avoids collisions and optimizes motion to minimize energy consumption and improve speed. Through simulations and analysis, the combined approach demonstrated smoother, more efficient trajectory planning, particularly for complex tasks involving high-speed motions or delicate operations. This breakthrough in trajectory smoothing has significant implications for industries like manufacturing, where Delta robots are used for fast, high-precision tasks such as pick-and-place, packaging, and assembly, improving performance and reducing operational costs. [59] M. Bouri et al proved; The fire wire PC-based motion controller consists of two main components: the real-time Windows-based

PC, which implements a powerful motion controller with a trajectory generator, a real-time control loop running at a 2ms sampling period, and the real-time firewire communication interface, and the fire wire Centralp2 axis module, which provides a remote encoder interface and digital-to-analog converters.

The control loop on the PC communicates with the axis module every sampling period via the firewire link to request encoder values and send corrected values to the amplifiers. The control algorithm implemented is a PID controller with simple feed-forward spring torque compensation. The PID control parameters are set equally for each axis due to the triangular symmetry of the structure. Around the central position, the gravity effect is evenly distributed across the motors, and its effect is rejected by the integrator [60]. Comparison of the different Delta Robot control types is provided in Table 2, where a relative comparison of features from each of these controls is presented.

**Table .2.** Delta robot Control

| Seq. | Authors | Control | Control Type |
|---|---|---|---|
| 1 | T. Aoki[35,36,37] | Sliding Mode Control (SMC) | The Delta robot is celebrated for its speed, precision, and rigidity, with its full potential unlocked through advanced control strategies like PID, adaptive control, and Sliding Mode Control (SMC). SMC, in particular, proves superior in handling complex trajectories and disturbances, highlighting the power of modern control techniques in robotics. |
| 2 | M. López, et al[38,39] | Adaptive control | introduced intermediate Jacobians to identify both traditional and structural singularities, improving Delta robot design for enhanced stability and efficiency in automation |
| 3 | Q. Zhao, P. Wang, and J. Mei[40,41,42] | PD CONTROLL | Mentioned that the Delta robot's engineering marvel is enhanced by precise modelling, inverse kinematics, and a PD controller with acceleration feed-forward to maintain accuracy and compensate for inertia variations. |
| 4 | Y.-L. Kuo and P.-Y. Huang[43] | Inverse dynamic& feedback Control | Delta robots used for pick-and-place tasks. By integrating inverse dynamics and feedback control, the model-based approach significantly reduces positioning and joint errors, demonstrating improved precision and reliability in industrial applications. |
| 5 | X. Yang, Y. Dong, and H. Yang[44] | Kinematic control& trajectory control | The D2 Delta Robot utilizes a planar six-bar mechanism with driving and slave arms, incorporating parallelogram link mechanisms to keep the end effector parallel to the fixed bracket. Its structure was modeled in CAD using SolidWorks, 3D printed, and tested to ensure functionality and application suitability. |
| 6 | C.E. Boudjedir, D. Boukhetala, and M. Bouri [45] | ROS2& Gazebo | In simulations using ROS 2 Foxy Fitzroy, integrating Gazebo for kinematic motion and stereo camera visualization to improve accuracy in tasks like object detection. Inverse kinematics control was applied. |
| 7 | L. M. Thanh, L. H. Thuong, P. T. Loc, and C.-N. Nguyen[46] | Single Neuron PID controllers | Introduced an innovative control system for the Delta robot, combining Single Neuron PID controllers with Recurrent Fuzzy Neural Network (RFNN) identifiers to adapt to nonlinear dynamics. |
| 8 | A. Sharida and I. Hashlamon [47] | Real –time distributed control | Introduced a real-time distributed control system for Delta robots, using four microcontrollers connected via CAN Bus to manage tasks with enhanced stability and efficiency. |

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| 10 | I. Hashlamon[49,50] | Adaptive PD Control | The challenges faced by Delta robots, such as disturbances from friction and noise, can impact trajectory tracking. To address this, three adaptive methods—AKF, LFDM, and AMB—were explored. Among them, AKF combined with adaptive PD control was found to be the most effective solution, providing precise and smooth performance. |
| 11 | F. A. Azad, et al[51] | PID, adaptive control, and Sliding Mode Control (SMC) | Delta robots face challenges in optimizing performance, which can be addressed through advanced control methods. Using screw theory for kinematics, three strategies—PID, adaptive control, and Sliding Mode Control (SMC)—were tested. While PID was effective but limited in noise rejection, adaptive control offered superior stability and noise rejection, and SMC excelled in speed, accuracy, and nonlinear trajectory tracking, making it ideal for industrial applications. |
| 12 | L. M. Thanh, L. H. Thuong, et al[52] | PID(RFNNC-PID) controller | The development of advanced control methods for Delta robots includes a novel Recurrent Fuzzy Neural Network-PID (RFNNC-PID) controller, which integrates fuzzy logic and neural networks. This controller outperforms traditional PID and single-neuron PID controllers in trajectory tracking by delivering faster response times and eliminating steady-state errors, even under varying loads. The RFNNC-PID approach significantly enhances Delta robot performance, offering a robust solution for precision robotics. |
| 13 | A. Gholami, et al[53] | Adaptive control& intelligent control | A system was developed to improve Delta robot performance by incorporating a neural network for real-time prediction of joint angles. This network adapts dynamically during operation through online learning, updating with new data to enhance accuracy. By predicting joint angles based on the desired trajectory, platform position, and active joint angles, the system enables precise control, allowing the robot to perform complex tasks with high precision in dynamic environments. |
| 14 | K. M. Saipullah, et al[54] | ROS 2 | A simulation framework for Delta robots was developed using ROS 2, Gazebo, and stereo cameras. This system overcame the limitations of URDF, enabling precise inverse kinematics and optimized robot performance. The integration of motor control and depth perception enhanced the robot's capabilities for industrial and agricultural tasks. |
| 15 | M. López, E. Castillo, G. García, and A. Bashir[55] | Jacobian matrix | The Jacobian matrix is used to analyse Delta robot kinematics, focusing on how inverse and direct singularities affect movement and workspace. Understanding these singularities is crucial for optimizing performance and ensuring the robot operates within its feasible range. |
| 16 | M. Rachedi, M. Bouri, and B. Hemici[56] | Computed torque control | Two control strategies for Delta robots, Computed Torque Control (CTC) and Ho robust control, were compared. The Ho controller, designed using the mixed sensitivity approach, provides better robustness, performance, and reduced computational requirements compared to CTC. It excels in trajectory tracking and disturbance rejection, achieving superior precision even under parametric disturbances, making it well-suited for robust control of nonlinear dynamic systems. |
| 17 | T. Abut and S. Soygüder[57] | Sliding mode control | The motion control, kinematic analysis, and workspace analysis of a 3-DOF Delta robot were explored, with a focus on the use of Sliding Mode Control (SMC) for achieving stable motion and precise trajectory tracking without oscillations. A saturation function was integrated to reduce chattering, and simulations showed the effectiveness of this approach in enhancing the robot’s performance, especially in high-speed, high-accuracy applications requiring minimal maintenance. |

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| 18 | D. Zhu, et al[58] | Trajectory control | A low-cost, microcontroller-based Delta robot was developed for industrial applications, emphasizing affordability without compromising precision and speed. The design uses microcontrollers and affordable actuators, making it ideal for tasks such as assembly, packaging, and material handling. This accessible solution is particularly beneficial for small to medium-sized businesses, supporting the wider adoption of robotics in industries with limited budgets. |
| 19 | T. Brogårdh[59] | Optimal& trajectory control | A novel approach to trajectory planning for Delta robots was developed, focusing on trajectory smoothing to improve precision, efficiency, and reduce mechanical wear. By integrating both Cartesian and joint spaces, the method optimizes movement control, minimizes energy consumption, and ensures smoother paths while avoiding collisions. This approach enhances performance in high-speed or delicate tasks, making it particularly beneficial for industries like manufacturing, where Delta robots are used for precision tasks such as pick-and-place and assembly |
| 20 | M. Bouri et al[60] | Pc based motion control system | A PC-based motion control system for a Delta robot was developed, featuring a real-time Windows PC with a trajectory generator and firewire communication interface, paired with a Centralp2 axis module for remote encoder and analog control. The system employs a PID controller with feed-forward spring torque compensation, with equal PID parameters for each axis due to the robot's symmetrical structure. Operating at a 2ms sampling period, the control loop ensures precise movement and effective compensation for gravity effects. |

## 5. Discussion

### *5.1. Introduction to Reconfigurable Delta Robots*

Mauro Maya, Eduardo Castillo, Alberto Lomeli, Emilio González-Galván, and Antonio Cárdenas developed a reconfigurable Delta-type parallel robot aimed at improving workspace flexibility and payload capacity. Unlike traditional robots, this new design allowed for dynamic adjustments to the link lengths, altering the workspace's shape and volume in real-time. A simple ball-screw mechanism powered by a single actuator was used to adjust the fixed platform radius, significantly enhancing the robot's adaptability. This design not only improved operational flexibility but also optimized the carrying capacity for various tasks.

### *5.2. Innovative Designs for Dynamic Adaptability*

In a quest to create a more adaptable and efficient robot, János Somló, Gábor Dávid Varga, Márk Zenkl, and Balázs Mikó designed a revolutionary reconfigurable Delta-type parallel robot. Unlike traditional robots, which have fixed workspaces, this new robot can dynamically adjust its size and shape while operating, thanks to the ability to change the length of key components like the fixed platform radius, the actuated link, and the parallelogram. By adjusting these parameters, the robot’s workspace and payload capacity could be optimized for different tasks. The breakthrough was in the simple yet effective reconfiguration mechanism, which used a single actuator to adjust the length of the links symmetrically. This allowed the robot to handle various weights and reach different areas of its workspace, offering unprecedented flexibility and performance.

### *5.3. Enhancing Speed and Precision in High-Speed Operations*

Rogelio de Jesús Portillo-Vélez, Iván Andrés Burgos-Castro, José Alejandro Vásquez-Santacruz, and Luis Felipe Marín-Urías sought to enhance the speed and precision of industrial robots by designing a 3DOF Delta parallel robot, specifically tailored for capturing medicine bottles. The robot, characterized by its lightweight aluminium and carbon-fibre structure, utilized advanced kinematics and a modified door-shaped trajectory to minimize arm wobble during high-speed operations. By omitting sensors and relying on precise mechanical design, it achieved remarkable accuracy and repeatability, even at speeds of 200 motions per minute. Extensive tests validated its ability to perform flawlessly under demanding conditions, offering a reliable, cost-effective solution for high-speed industrial tasks while setting the stage for future enhancements with machine vision and advanced sensors.

### *5.4. Historical Developments and Commercial Success*

Reymond Clavel and Dr. Clavel made ground-breaking contributions to the field of robotics, with Clavel earning the prestigious Golden Robot Award in 1999, sponsored by ABB Flexible Automation. The invention of the Delta robot in 1983 marked a significant leap in robotic technology. The design of the Delta robot was based on a set of parallelograms that kept the output link fixed in relation to the input link. Three parallelograms fully controlled the orientation of the mobile platform, enabling it to perform only three translational movements. The input links were attached to rotating levers with revolute joints, driven by either rotational motors or linear actuators. A fourth leg transmitted rotary motion from the base to the end effector, which was mounted on the mobile platform. At the same time, Marc-Olivier and Pascal Demaurex founded the company Demaurex in 1983, initially focusing on refining Delta robot technology. Over the following years, Demaurex produced several application-specific versions of the Delta robot, commercializing four models (Pack-Placer, Line-Placer, Top-Placer, and Presto), which handled objects ranging from 20 grams to 1 kilogram. By 1999, Demaurex had been acquired by Elekta, a Swedish company specializing in surgical technology, sparking advancements in Delta robots for medical applications.

### *5.5. Material Innovations for Enhanced Performance*

The use of lightweight materials, such as carbon fiber composites and lightweight alloys, has further refined the Delta robot's performance. These materials reduce overall weight, allowing for faster accelerations and decelerations while maintaining structural integrity. This has been particularly beneficial in applications that demand repeated cycles over extended periods, ensuring durability and long-term reliability.

### *5.6. Medical Applications and Precision Robotics*

In 1999, Demaurex licensed Delta robot technology to the Japanese company Hitachi Seiki, which used it to manufacture small-sized Delta robots for applications like packaging (DELTA) and drilling (PA35). The same year, ABB Flexible Automation launched its version of the Delta robot, the IRB 340 Flex Picker, designed for high-speed pick-and-release tasks in industries such as food, pharmaceuticals, and electronics. The IRB 340 Flex Picker was capable of handling objects up to 1 kilogram, with a top speed of 10 meters per second and a picking rate of 150 picks per minute. These advancements highlighted the potential of Delta robots for high-precision tasks, both in industrial automation and medical fields, such as carrying microscopes and assisting in surgeries.

### *5.7. Challenges in Stability and Torque Management*

G. Reg Dunlop developed a large-scale Delta robot at the University of Canterbury, initially conceived as a stationary tool for precise calibration and load handling. However, this robot later faced challenges related to stability and torque, particularly due to limitations in its gearbox. These issues restricted its step size and payload capacity. The addition of a triangular foot mechanism and the use of a tripod gait allowed the robot to move by following a sequence of motions. Although the robot showed great promise, its challenges underscored the need for innovations, such as incorporating hydraulic systems, to enhance its stability and unlock its full potential for heavy lifting or as a mobile platform.

### *5.8. The Future of Modular and Autonomous Delta Robots*

Subsequent redesigns, such as the Inverted Delta Robot by M. Bouri, R. Clavel, M. Y. Zerrouki, and W. Maeder, focused on improving efficiency and precision in pick-and-place operations by inverting the forearms of the traditional structure. This minimized the links between the end effector and base, enabling smoother, more natural motion. Modular designs that integrate autonomous systems are paving the way for Delta robots to handle a wide range of tasks, offering substantial flexibility and performance improvements. Technologies like 3D printing, sensors, and machine vision will continue to play a key role in their development.

### *5.9. Control Strategies for Enhanced Performance*

Researchers tested three advanced control strategies to optimize the Delta robot's performance: the traditional PID controller, the dynamically adaptive controller, and the highly robust Sliding Mode Control (SMC). Simulations revealed that while PID provided reliable baseline performance, adaptive control excelled at noise rejection, and SMC proved superior in tracking complex trajectories. SMC's rapid and accurate responses to disturbances demonstrated its capability in high-speed automation tasks, underscoring the value of modern control techniques in overcoming robotic challenges.

### *5.10. Addressing Singularities with Jacobian Matrices*

Delta robots, renowned for their adaptability in industries such as food packaging, pharmaceuticals, and electronics, face challenges from singularity configurations where their performance deteriorates. Researchers focused on Jacobian matrices to analyze and mitigate these singularities. They examined inverse, direct, and intermediate Jacobians to understand the impact of workspace boundaries, internal singularities, and structural issues, such as unfavorable dimension ratios between the moving and fixed platforms. This deeper understanding of singularities helps engineers refine Delta robot designs for greater stability and efficiency.

### *5.11. Inverse Kinematics and Dynamic Control Modeling*

Zhao Qing, Wang Panfeng, and Mei Jiangping explored the intricate kinematics and dynamics of the Delta robot, constructing an inverse kinematic model for velocity analysis under ideal conditions. Using a PD controller with acceleration feed-forward, they accounted for inertia variations that could affect precision. The servo drive system, modeled using a transfer function, was analyzed through frequency-sweeping techniques, improving trajectory accuracy and performance. This research highlights the critical role of precise modeling and system identification in enhancing Delta robot control systems.

### *5.12. Model-Based Control for Improved Accuracy*

Yong-Lin Kuo and Peng-Yu Huang tackled the challenges of achieving high precision in pick-and-place tasks. They proposed a model-based control system that integrates the robot's kinematics and dynamics into the control loop. By computing motor torques based on inverse dynamics and correcting errors with feedback control, this system demonstrated significant improvements in positioning accuracy. With errors reduced to just 0.5 cm and 3°, the model-based system outperformed traditional position-based methods, emphasizing the potential of this innovative approach for industrial robots.

### *5.13. Innovative D2 Delta Robot Design*

The D2 Delta Robot, based on a planar six-bar mechanism, features a sophisticated mechanical design that ensures precise movement without interference. Researchers developed a CAD model using SolidWorks and tested it using 3D printing technology to validate its functionality. The design incorporates parallelogram link mechanisms to prevent the end effector from rotating during movement, ensuring high precision and reliability in its tasks.

### *5.14. Advancements in Simulation and Stereo Camera Integration*

Chems Eddine Boudjedir, Djamel Boukhetala, and Mohamed Bouri explored Delta robot performance through simulations in the ROS 2 Foxy Fitzroy environment. By integrating Gazebo simulation with advanced stereo camera systems, they achieved high-precision inverse kinematics with angular errors averaging just 3.92%, 3.72%, and 2.92%

across joints. This innovative approach demonstrated the potential for enhanced robotic performance in both industrial and agricultural settings, laying the groundwork for future advancements in automated control and image processing.

### *5.15. Adaptive Neural Networks for Improved Trajectory Tracking*

Le Minh Thanh, Luong Hoai Thuong, Phan Thanh Loc, and Chi-Ngon Nguyen introduced an innovative control system utilizing Single Neuron PID controllers enhanced with Recurrent Fuzzy Neural Network (RFNN) identifiers. This approach allowed the controller to adapt dynamically to the system's nonlinear behavior, improving trajectory tracking accuracy and eliminating steady-state errors. Simulations in MATLAB/Simulink demonstrated faster settling times and robust performance under varying load conditions, showcasing the effectiveness of intelligent control strategies for Delta robots.

### *5.16. PD+ Controller with Disturbance Observer for Precision Control*

Mingkun Wu, Jiangping Mei, Jinlu Ni, and Weizhong Hu developed a PD+ controller with a momentum-based disturbance observer (MDO) to enhance Delta robot performance. The PD+ controller integrates dynamic characteristics with reduced dependency on precise models, while the MDO compensates for system disturbances. This innovative approach resulted in faster response times and improved trajectory accuracy, setting a new standard for Delta robot control in high-speed and high-acceleration operations.

### *5.17. Adaptive Disturbance Compensation for Trajectory Tracking*

Iyad Hashlamon explored various disturbance compensation techniques for Delta robots, including the Adaptive Kalman Filter (AKF), Low-Pass Filtered Dynamic Model (LFDM), and Acceleration Measurement-Based (AMB) method. The AKF proved the most effective, offering minimal overshoot and noise sensitivity while enhancing trajectory tracking accuracy. Combined with a PD controller, AKF provided smooth and reliable performance, addressing the challenges posed by complex dynamics and disturbances in robotic control.

### *5.18. Neural Network Integration for Real-Time Adaptation*

Faraz Abed Azad, Saeed Rahimi, Mohammad Reza Hairi Yazdi, and Mehdi Tale Masouleh developed a system integrating a neural network for real-time prediction of joint angles. This system adapts dynamically during operation through online learning, ensuring that the Delta robot performs complex tasks with high precision in dynamic environments. By continuously updating the neural network with new data points, the robot can optimize its performance and maintain accuracy in real-time applications.

### *5.19. The Evolution and Future of Delta Robots*

As research and development continue, Delta robots have evolved from a basic concept into versatile, high-performance systems capable of handling diverse industrial and medical applications. The incorporation of advanced materials, dynamic reconfigurability, and precision robotics ensures their relevance across a variety of sectors. The ongoing innovation in modular and reconfigurable designs, coupled with advancements in sensors and artificial intelligence, signals a promising future for Delta robots, making them integral tools in modern automation and precision tasks across industries.

## 6. Conclusion

The Delta robot stands as a testament to engineering excellence and innovation, with its parallel kinematic structure, driving advancements in high-speed, precision-driven applications. From its origins in the 1980s to its present-day iterations, the Delta robot has evolved through innovative design modifications, such as inverted configurations, linear adaptations, and reconfigurable systems, making it indispensable in diverse industrials. This paper highlights the significant progress in control strategies, including PID, sliding mode control, and neural network-based approaches, which address challenges like singularities, energy efficiency, and dynamic stability. These advancements have enhanced robots' capabilities, allowing them to meet the demands of complex and high-precision industrial tasks. Looking ahead, the integration of adaptive designs, advanced motion planning, and sustainable materials promises to further expand the potential of Delta robots. This evolution ensures their continued relevance in automation, paving the way for smarter, more efficient systems capable of addressing emerging challenges in robotics.

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