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A Survey on Parallel Robots with Delta-like Architecture

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Abstract—*In the early 1980s, Reymond Clavel invented the Delta robot at the École polytechnique fédérale de Lausanne. The initial objective was the development of an industrial robot dedicated to high-speed handling tasks of very light objects. Nowadays, the Delta robot is one of the best-known and most widely spread parallel robots. Besides various different designs of the original architecture, e.g. Delta robots with rotary and/or linear actuation, current industrial versions employ additional serial mechanisms in order to obtain rotational degrees of freedom. This paper gives an overview about the different variants of translational three degrees of freedom Delta-like robots and serial-parallel hybrid as well as fully-parallel Delta-like robots with rotational degrees of freedom.*

Keywords: history of Delta-like robots, Delta parallel robot, parallel kinematic machines

I. Introduction

Parallel robots (also known as parallel manipulators or parallel kinematic machines) consist of a platform or end-effector, which is connected to a base frame by at least two kinematic chains. Depending on the number and design of the kinematic chains, three translational and/or three rotational degrees of freedom (dof) can be generated.

The history of parallel robots goes back to 1938 when Pollard filed his patent application about a "Position Controlling Apparatus" for car painting [1]. During the 1960s, Gough and Stewart designed a hexapod (also known as Gough/Stewart platform) incorporating six prismatic actuators [2], [3]. In the 1980s, Clavel invented a parallel robot at the École polytechnique fédérale de Lausanne (EPFL) known as Delta robot with three translational dof dedicated to high-speed application [4], [5]. The initial objective was to develop an industrial robot for manipulating chocolates, i.e. very light objects (approx. 10 to 35 grams), at a very high speed (three transfers per second) in order to automate a monotonous manual packaging process [6], [7], [8]. The robot should be able to respond to a variety of handling tasks (e.g. changing arrangements of products into different receiving trays and changing assortments).

The industrial development started 1987, when the Swiss company Demaurex purchased a license from the EPFL to commercialize the Delta robot. During that time ABB Flexible Automation bought another license and launched its first Delta robot (i.e. IRB 340 FlexPicker) in 1999. Meanwhile in 1996, Demaurex also bought another, similar patent from the EPFL and merged with Sigpack Systems in order to increase its competitiveness and to finally enter the world market. The merged companies in turn joined the Bosch Packaging Technology division in 2004.

Another license transaction with the Swedish company Elekta lead to the development of a surgical instrument, industrialized as SurgiScope [9]. Based on the CSEM (Centre Suisse d'Electronique et de Microtechnique) PocketDelta (cf. Sec. IV), Codourey founded the microbrobotics company Asyril SA [10]. Bonev [11] gives an extensive overview about the historical, academic and industrial development of the Delta robot.

In order to produce 3-dof for translational movements in space, a Delta robot consists of three symmetric kinematic chains of the type RRPaR, RUU or $R(SS)_2$ (where R: revolute joint, U: universal joint, S: spherical joint, Pa: Parallelogram). Thus, the orientation of the end-effector is constantly ensured by three spatial four-bar parallelograms, each attached distally to one of the rotationally actuated links. With this design, the distal links only need to transmit axial forces allowing for light-weight materials and thus, very low inertia compared to serial articulated robots [12]. An associated structural analysis based on the Group Theory can be found in [13]. Based on Clavel's Delta, many variants have been developed. Besides Delta robots with three translational dof, there is a current tendency of adding serial mechanisms to the original parallel Delta architecture, i.e. designing hybrid kinematic structures with orientation capabilities [14]. This trend can be observed in the expanded product portfolio of companies producing Delta robots, e.g. FANUC (Factory Automation Numerical Control, cf. Sec. V).

Based on the most famous variants of Delta robots with three translational dof in Section II, the various different designs to obtain rotational dof for Delta robots are presented in Section III. Sections IV and V give an overview about research and industrial applications including a market overview.

II. Translational 3-dof Delta-like robots

A Delta robot can be driven by rotary and/or linear actuators [6]. The following paragraphs summarize the main representatives of existing translational Delta robot variants with rotary (Sec. II.A) and linear

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(Sec. II.B) actuators. The different architectures of translational 3-dof Delta robots are partly described in [6].

A. 3-dof Delta-like robots with rotary actuation

To overcome the shortcomings of expensive and imprecise spherical joints as used within the original Delta architecture, Tsai and Stamper proposed the University of Maryland manipulator with rotary actuation that uses only revolute joints to constrain the end-effector movements to three translational dof [15], [16], [17], [18]. Miller proposed a new concept with a larger workspace volume by changing the motor axes orientation: the New University of Western Australia Robot (NUWAR) [19]. In [20] both, the motor positions and motor axes orientations are varied. Bouri et al. [21] and Briot et al. [22] presented an inverted Delta or Delta inverse robot, respectively, in which the parallelogram of a chain is attached to the base and not to the end-effector. Another interesting Delta variant utilizes wire-pulley for replacing the parallel four-link mechanism [23]. Other, less known 3-dof variants can be found in [24], [25], [26], [27]. Figure 1 shows some of the afore-mentioned variants.

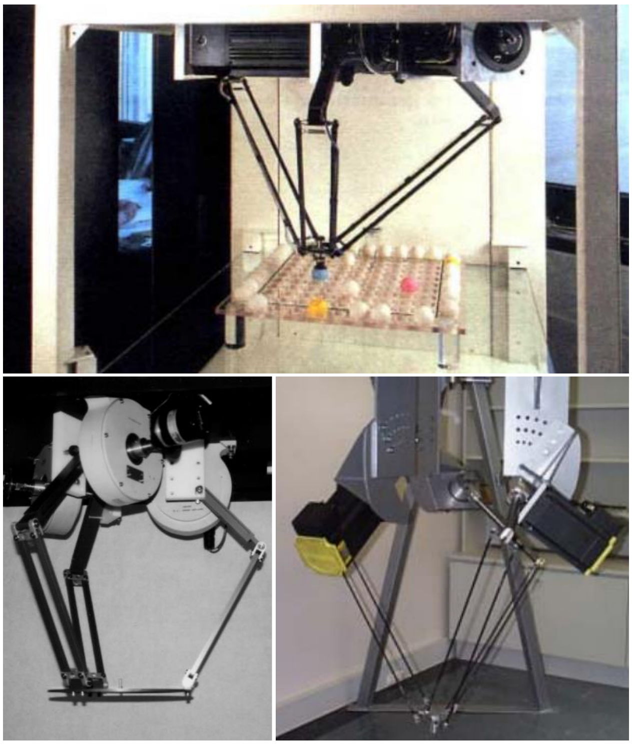

Figure 1: Clavel's Delta [28] (top), the University of Maryland manipulator [16] (bottom left), and NUWAR [29] (bottom right)

B. 3-dof Delta-like robots with linear actuation

For a linear actuation, the rotary actuators as well as the proximal links are replaced by linear actuators [4], [30]. This type of Delta robot is often referred to as Linapod or linear Delta [24], [31]. Depending on the orientation of the actuator axes, linear Delta robots can be further subdivided into orthogonal, horizontal, vertical and inclined types. There are also hybrid versions with two linear and one rotary actuator called Delta Ibis or at least two rotary actuators (e.g. [20]). Bouri [32] and Clavel [33] give a detailed overview about the aforementioned variants. Worth mentioning is also a variant with reversed chains, meaning that the linear actuators are attached to the end-effector and thus, not fixed to the base [34]. Table 2 summarizes the main represent-tatives of the different types of translational 3-dof Delta robots with linear actuation and their inventors. Some of these robots are displayed in Figure 2.

Table 2: Types of translational 3-dof Delta robots with linear actuation

Type	**Name**	**Inventor**	**Ref.**
Orthogonal	Orthoglide	Wenger, Chablat	[35]
	Ortho(tri)pod	Lou, Li	[36]
	Delta3/Delta Cube	Clavel et al.	[37], [38]
Horizontal, non-coplanar	Urane SX	Pierrot et al., Renault-A.	[39]
Horizontal, coplanar	Y-Star/H-Robot	Sparacino, Hervé	[40]
	Triaglide/Delta linéaire	Clavel et al.	[28], [41]
Vertical	Triglide	SFB 562	[42], [43]
Inclined	Delta Keops	Clavel et al.	[32]
Reversed	-	Mitova, Vatkitchev	[34]
Hybrid	Delta Ibis	Clavel et al.	[32]

Figure 2: Orthoglide [44] (left), Delta linéaire [32] (center), and Delta Keops [32] (right)

III. Delta-like robots with Schoenflies motion

Assembly and pick-and-place applications usually require an additional rotational dof, mostly around the axis perpendicular to the end-effector [45]. Motions with three translational and one rotational dof are generally called Schoenflies, 3T1R (with T: translational and R: rotational) or SCARA (acronym for Selective Compliance Assembly Robot Arm) motions. Compared to the well-known SCARA robots [46], Delta robots are generally faster (i.e. shorter transfer time) while allowing a smaller maximum payload. In Sec. III.A, serial-parallel hybrid designs of a Delta robot with an additional link are described. In Sec. III.B, fully-parallel Delta-like robots with Schoenflies motion are presented.

A. Serial-parallel hybrid designs

For an additional rotational dof, a mechanism (e.g. tool, gripper) can pivotally be mounted on the end-effector. This mechanism is rotationally actuated by a motor which is usually fixed on the frame and connected through an intermediary telescopic shaft (P) and universal joints (U) (cf. Figure 3 top right). Hence, the additional link between the base or motor and the end-effector can be described as UPU chain. FANUC invented a holder assembly which acts as a special universal joint allowing linear motions of the link [47]. The various different designs of the UPU chain (e.g. [48], [49], [50]), especially due to cleaning purposes, are not considered here. In his doctoral thesis about the Delta4 concept [6], Clavel describes additional variants such as:

- a flexible cable driven by a motor fixed on the frame with a mechanism transmitting the rotation of the gripper [51],
- a small motor mounted directly on the end-effector (cf. Figure 3 bottom right), and
- a cable pull with its cable wound on a drum and a torsion spring mechanism proving cable tension irrespective of the direction of rotation, all mounted on the end-effector.

Figure 3: FANUC M-3 Series (tl), ABB IRB 360 FlexPicker (tr), FANUC M-2 Series (bl), and Kawasaki YF03N (br), (image ref. upon request)

Other concepts consist of the basic Delta structure and a 3-dof rotational head or serial robotic wrist (type RRR) mounted on the end-effector and driven by three separate motors fixed on the frame (e.g. FANUC M-1 Series [52]), attached to the end-effector (e.g. SurgiScope [9], [53]) or the distal links (e.g. FANUC M-3 Series with six dof [54], [55], Figure 3 top left). Whilst the first two concepts were already described as 4-dof-concepts, the latter is also offered with a single rotational dof (e.g. FANUC M-2 Series, Figure 3 bottom left).

The influence of the change in mass distribution due to different motor arrangements (including motors attached to the proximal links) is, for the first time, analyzed in [56]. A systematic kinematic analysis considering the additional RRR-wrist is presented in [57]. To sum up, the motor(s) can be attached to the frame, the end-effector, the distal or to the proximal link(s). Depending on the number of motors, 4-6 dof can be achieved. Industrialized concepts usually employ UPU chains (more than 70% of 25 manufacturers analyzed, cf. Sec. V).

B. Fully-parallel designs

Serial-parallel hybrid designs of Delta robots with additional links may not be as efficient as a fully-parallel robot, it may cause reliability problems and, especially in respect to food applications, they are difficult to keep clean [58], [45], [59]. To overcome these drawbacks, Pierrot and Company [60] proposed a new family of 4-dof parallel robots based on the Delta technology. The H4-family (four independent kinematic chains with an H-shaped end-effector) incorporates different mechanisms with linear and/or rotary actuation. The most common mechanism among this family is actuated by four angular motors and referred to as H4 robot. In contrast to the Delta robot, four kinematic chains and an articulated traveling plate (i.e. an end-effector with internal mobility) are used to avoid additional links. In this concept, two kinematic chains, each containing a Delta-like spatial parallelogram, in pairs are connected to the traveling plate through revolute joints. An additional gear-based amplification system allows the gripper to rotate. The concept of an articulated traveling plate can also be found in Clavel’s HITA-STT, a parallelogram-based robot with linear actuation [61]. In order to reduce the limitations of the H4 robot (e.g. greatly varying Jacobian condition number, risk of singular configurations, and self-collisions), Krut et al. introduced the I4 robot with linear (L) and rotary (R) actuation. In this concept, the design of the traveling plate is adapted by replacing the revolute joints and gears by prismatic joints and a rack-and-pinion mechanism, respectively [62], [63], [64].

The main drawbacks of the concepts are the singular configurations of the H4 and the prismatic joints, as used in the I4 robot, with a short service life robot. Hence, a new prototype with a superior arrangement of actuators and only revolute joints on its articulated traveling plate is developed by Pierrot et al. [65], [66]. In addition, the amplification system of this prototype, called Par4, is a belt/pulleys-system allowing a complete turn of ±180°. A preliminary industrial Par4 was patented by Nabat et al. and the Fatronik Foundation [67]. A detailed overview of the aforementioned robots as well as of the first commercially available version of the Par4, i.e. Adept Quattro (cf. Sec. V), can be found in [67]. Other variants with articulated traveling plate are the Dual4 with unlimited rotation capability [45], the Heli4 with compact traveling plate [68], and, for example, the robot analyzed in [69], [70], [71]. Figure 4 displays the Par4-concepts and the Adept Quattro with articulated traveling plate.

Figure 4: Par4 (left[65]) and Adept Quattro (right), (image ref. upon request)

Further less known parallelogram-based mechanisms with Schoenflies motion are the Kanuk and Manta [72] and the manipulators presented in [73], [74], [75], [76], [77]. Delta-based robots with more than 4-dof (e.g. the 6-dof Hexa robot obtained by adding rotational actuators to each chain [78], [79] or the 6-dof 2-Delta robot combining two Delta structures [80]) or other than the hybrid design with additional link (cf. Sec. III.A) are not considered here.

IV. Research Applications

Research in the general fields of kinematics, dynamics, control, singular configurations, workspace, calibration, and mechanical design of Delta robots has been conducted extensively during the last decades. Gogu [81] and Zhao [82], for example, give a decent overview about the main contributions. Aside from that, research has been applied to analyze and develop various different Delta-like robots as presented in the following. The fields of application are micro robotics, visual control, dynamic balancing, medical haptic devices, redundancy, and others.

The EPFL developed a robot Delta3 or Delta Cube with flexure hinges, based on the Delta architecture, for ultra-high precision manipulation in the field of electro-discharge machining [37], [83], [84]. Analyses for a similar design can be found in [85]. Moreover, research focuses on Delta robots used for micro assembly tasks (e.g. a 3-dof compliant Triglide with six integrated combined flexure hinges [86] or the CSEM PocketDelta [6], [87], within small-size production systems or micro factories, e.g. [88], [89], [90], [91]) and for microsurgery (e.g. a linear Delta in [92], [93], [94]). Interestingly but without scientific relevance, the world's largest 5-metre tall Delta robot was built to manipulate the motion of luminaire for an architectural design project [95].

Ángel et al. introduce strategies for visual control in applications with dynamic environment based on a Delta robot called RoboTenis System, cf. e.g. [96], [97]. In [98] Delta robots are used for ball juggling to develop dynamic models based on reflection laws.

Baradat et al. develop a balancing mechanism (using a pantographic linkage) for load compensation and as coordinate measuring system of a Delta robot and spatial parallel robots in general [99], [100], [101]. Van der Wijk and Herder propose concepts for dynamic balancing to reduce vibrations of the Delta structure by means of counter-masses, additional links and actuation [102].

Flückinger et al. use a Delta robot as a haptic device with force feedback to enhance the intuitive interaction with software interfaces [103]. Similarly, 3-dof Delta structures are analyzed for cardiopulmonary resuscitation, and as haptic devices with force feedback for telesurgery [104], [105]. In [53] and [106] a Delta robot with a 3-RRR mechanism is presented. It is used in a double parallel haptic device and as non-tactile surgical instrument, respectively. Woo and Kim [107] propose and analyze a 6-dof mechanism by connecting two 3-dof Delta robots via a needle-type handle used in minimally invasive interventional therapy.

Another current field of research is the actuation redundancy of Delta robots (i.e. a Delta robot with at least one additional actuated chain or, for example, a Par4 robot with rigid end-effector) in order to improve acceleration capabilities [108], [109]. [110] proposed a redundantly driven translational haptic device with a Delta-like architecture exhibiting only two kinematic chains, but four actuators.

Research is also conducted in sensor redundancy. In [111] a Delta robot is combined with an additional, independent 6-dof measuring system to separate actuation and measurement and thereby, enhance its accuracy.

To improve safety of human-robot interaction, Lauzier and Gosselin present a Cartesian force limiting device that disconnects the Delta robot from its end-effector and thus, protects a person involved in collision [112]. Within a European research project AIRobots (innovative aerial service robots for remote inspections by contact), a 4-dof Delta structure is attached to an Unmanned Aerial Vehicle to move sensors and take measurements at specific locations, respectively [113], [114]. In [115] a reconfigurable Delta robot is analyzed. In this concept the link lengths are simultaneously adjusted in order to produce a dynamic workspace shape and volume as well as to vary payload capacity. [116] demonstrates a Triglide robot which is capable of dynamically changing the configuration in order to enlarge the usable workspace.

V. Industrial Applications and Market Overview

The following paragraphs try to give an overview about the industrial fields of applications and the market of Delta robots.

A. Industrial Fields of Applications

Delta robots have generally been designed and optimized to meet the requirements of very fast product handling, low cost, and easy disassembly for cleaning within food (e.g. dough cutting or pancake stacking) and packaging industries (e.g. top-loading, feed placing and assortment placing) [117], [118]. Other fields of application are the medical field, the electronics sector, pick-and-place tasks for cells and wafers in the photovoltaic industry [119], laser cutting [120], [121], high-speed milling [122], drilling [123], wood tooling [124], and the use as 3-dof haptic device with force-feedback for the gaming industry (e.g. Novint Falcon [125], [126], [127]). In [128] a Delta robot is used within an apparatus for producing motor vehicle license plates (i.e. stamping markings). Furthermore, agricultural applications can be found: a Delta-based prototype for soft manipulation of vegetables [129], an autonomous field robot platform with a Delta robot for single plant treatment [130], [131], and similarly, a non-chemical weed controller for vegetables presented in [132].

B. Market overview

The workspace of a Delta robot is relatively small in comparison to its installation space (i.e. poor workspace/footprint ratio) making it difficult to scale up the robot for other applications within efficient production systems [42], [133]. In addition, the field of Delta robots is a niche and thus, it is difficult to enter new markets. However, the ABB FlexPicker is the most sold and fastest commercial parallel robot in the world today [133], [134].

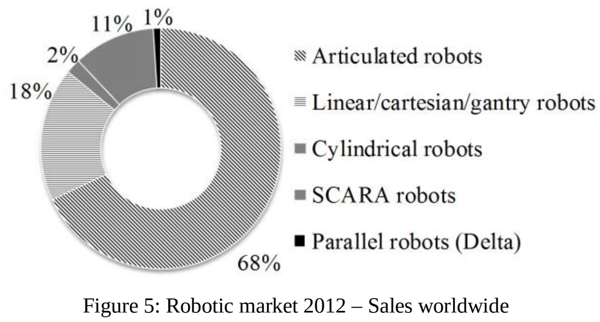

Figure 5: Robotic market 2012 – Sales worldwide

Considering a classification of robots by [135], [136], parallel robots and Delta robots are used synonymously, emphasizing the importance of Delta robots within the commercial parallel robots sector. Nonetheless, the worldwide market share of parallel robots was only 1% in 2012 (about 1,650 robots, cf. Fig. 5 [135]).

Compared to 2011, the sales volume of parallel robots declined by 21% in 2012. On the other hand, SCARA robots showed a significant increase of sales numbers. An analysis of 25 Delta manufacturers (e.g. ABB, Adept, Bosch, Codian, FANUC, Kawasaki and MAJAtronic) shows that the payload is usually limited to 1-3 kg (reaching up to 8 kg (ABB IRB 360), 15 kg (Adept Quattro s650H) or even 20 kg (MAJAtronic IP 65). Obtaining a working area with an average diameter of 700-1350 mm, the average cycle time is around 180 cycles per minute depending on cycle and load. The maximum diameter of the working area is around 1600 mm.

All manufacturers optionally offer the afore-mentioned additional dof (cf. Sec. III.A). Similar to the Par4-concept proposed by Pierrot et al. and brought to market as Adept Quattro (cf. Sec. III.B), Penta Robotics recently launched a modular four-link concept, called Veloce, with exchangeable articulated traveling plate and adjustable workspace [137]. Other companies usually deploy the central telescopic shaft (72%) and/or a direct drive attached to the end-effector (36%). In 2009, the Japanese company FANUC introduced the first 6-dof Delta robot with additional wrist mechanism driven by three motors attached to the distal links. This concept is also used for 4-dof designs and solely offered by FANUC.

VI. Conclusions

Almost 30 years after the initial concepts, commercial Delta and Delta-like robots serve the niche market for high-speed pick-and-place applications. Expired patents and new fields of applications have led to increased research and development during the last decades. The increased scientific focus on extended architectures with additional rotational dof resulted in different serial-parallel hybrid as well as fully-parallel designs. These concepts meet the industrial demands for novel complex handling tasks, increased payload capacities, and hygienic designs.

The group of Delta robots is the main representative within the segment of parallel robots. According to the manufactures the market prospects are very good. However, the sales volume of parallel robots declined, while SCARA robots showed a significant increase in 2012.

In this paper we have tried to give an overview about the various different designs of Delta-like robots and their fields of application as evolved from scientific research and industrial demands including a market overview.

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