

Parallel robotics

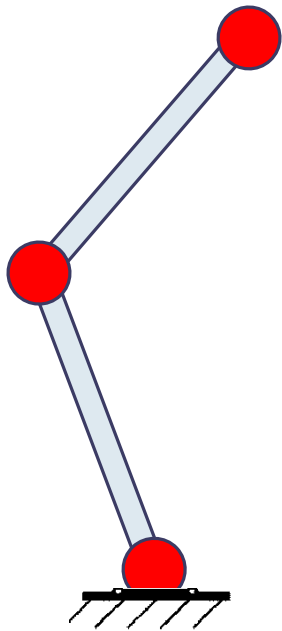
EPFL – Dr M. Bouri, 2025

- What is parallel robotics and why ?
- The example of the robot Delta.
- Calculation of mobility.
- The family of Delta robots.
- More DOFs.
- The Hexapods.

Parallel vs Serial robots

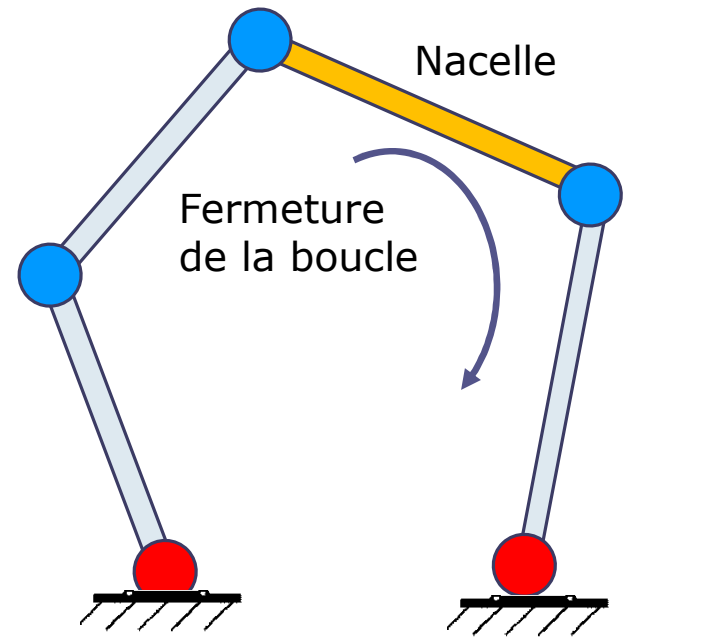
Serial robots

With **actuated segments in series**



Parallel robots

- ✓ Robots with closed kinematic chains
- ✓ All the motors are on the basis

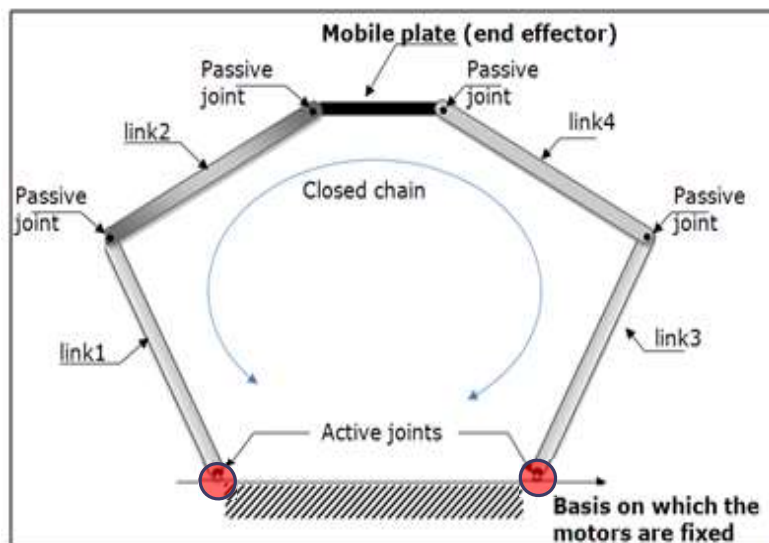


Leightweight, fast and stiff

1. All the kinematic **chains** from the basis to the mobile parts are **closed** to the basis.
2. All the **motors are on the basis** and no one is on the structure. The **intermediate joints** in the structure are all **passive**.



Mitsubishi RP 1AH



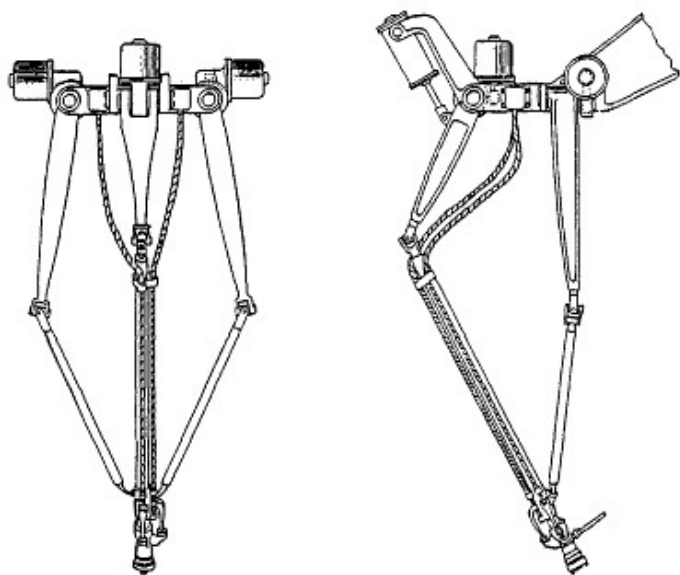
Close the chain and let us talk about parallel kinematics !



Parallel Robots

Since When?

The oldest «known» is Pollard robot (Pollard 1938) invented by Mr Pollard



Parallel link to remotely place an actuator and make the kinematic chain **stiffer** and **lighter** 7



Parallel kinematics....

The most known

The flight simulator

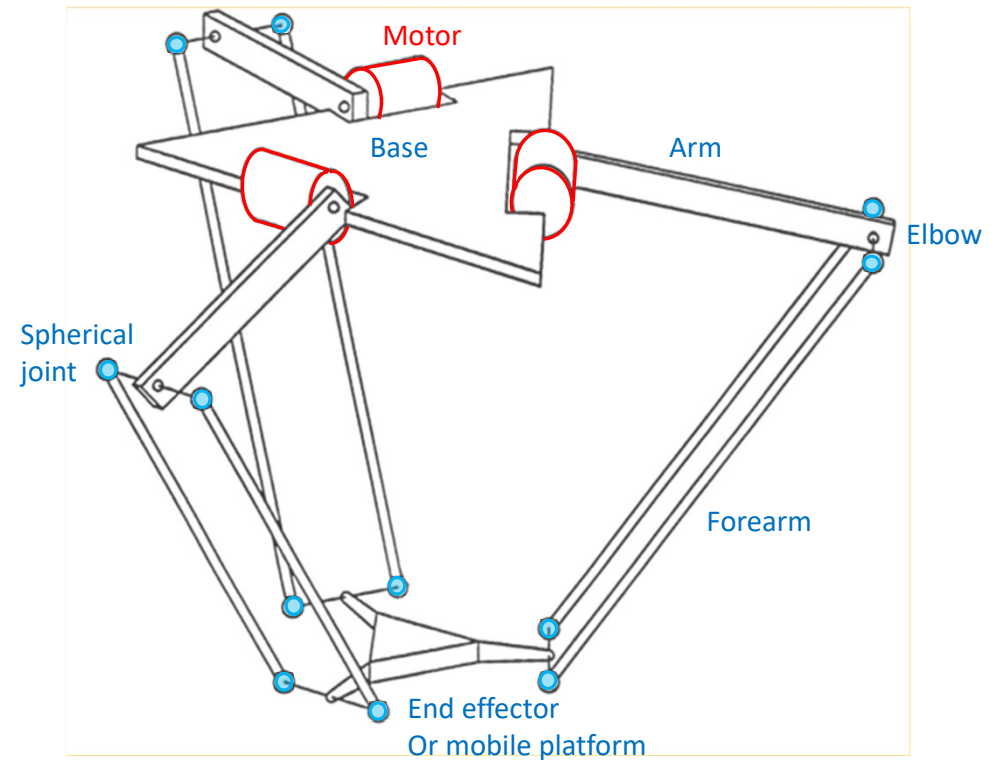
The Gough Stewart platform



The robot “Delta” The precursor for the market of parallel robotics.



Principle



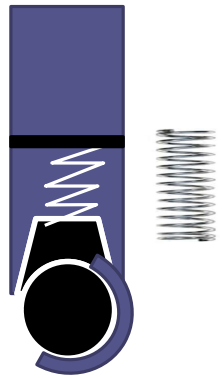
1985 – Patented by R. Clavel (EPFL)

1988 – The patent is sold to the Swiss company Demarex SA (now Demarex Robotics, Renens)

1992– The first customer was Nestlé.



More than **200 companies (unknown now)** have adopted this kinematics since **2007**, when the patent was in the [public domain](#)



Another implementation

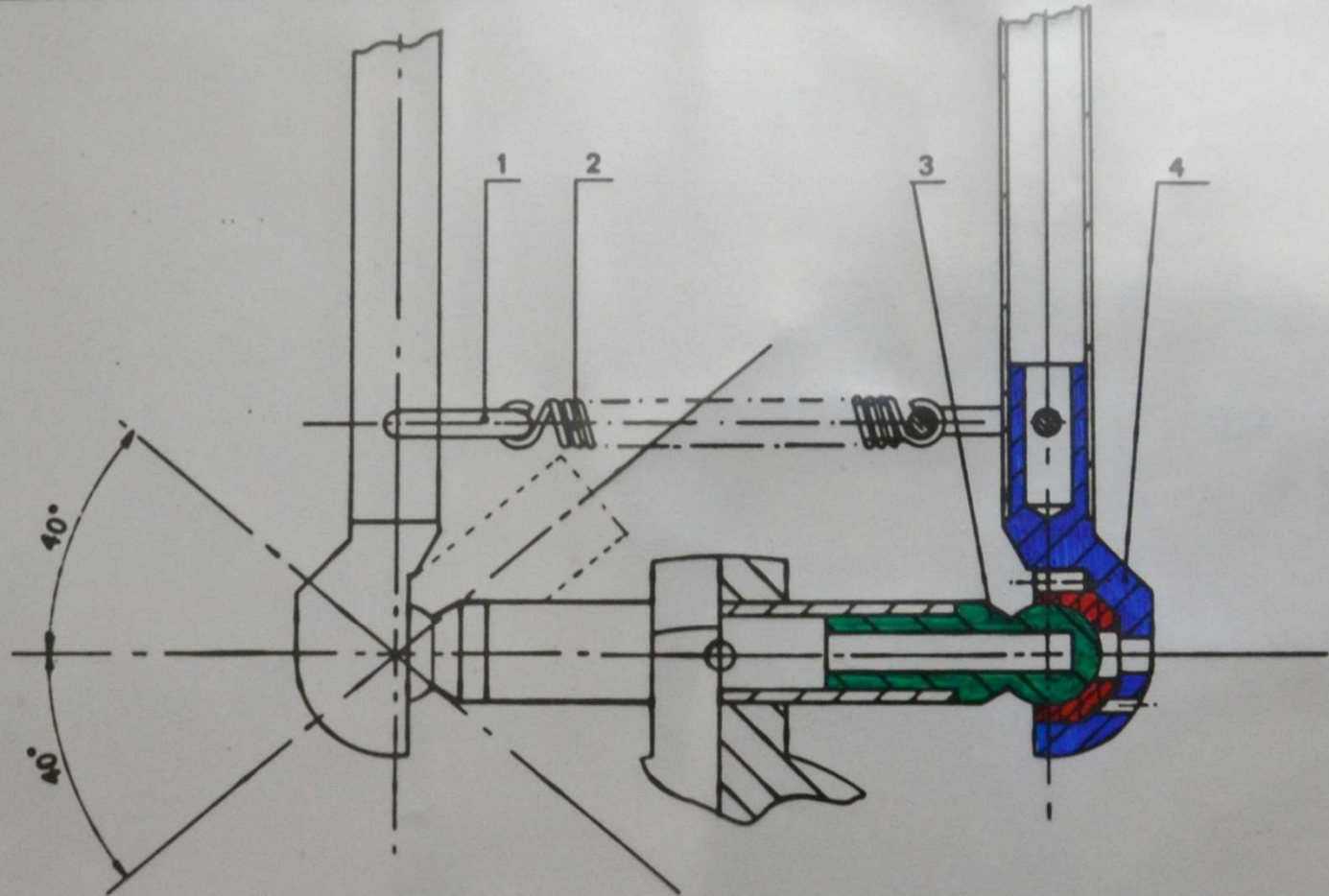
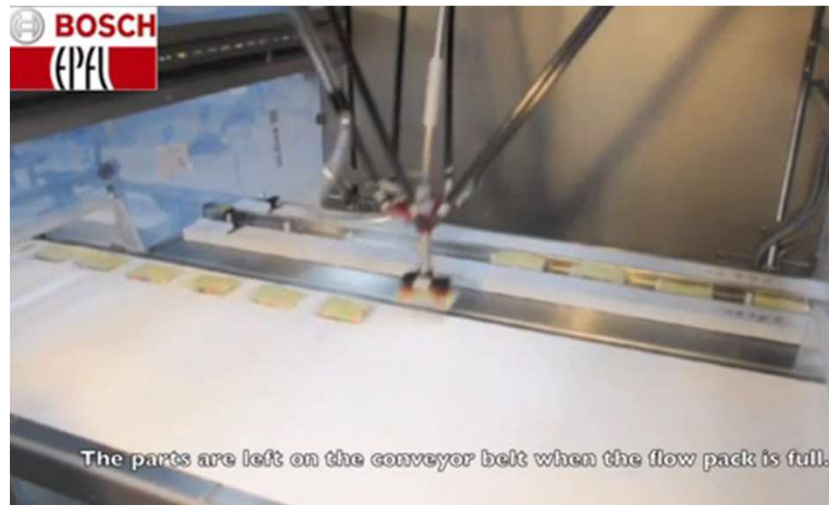


Fig.5. Detail of the construction of the arm - parallelogram joint.

The robot Delta is a pure translational robot

Only translations are possible, and the orientations of the end effector are blocked.



Direct Drive Actuated Delta realized for BOSCH Packaging Technology

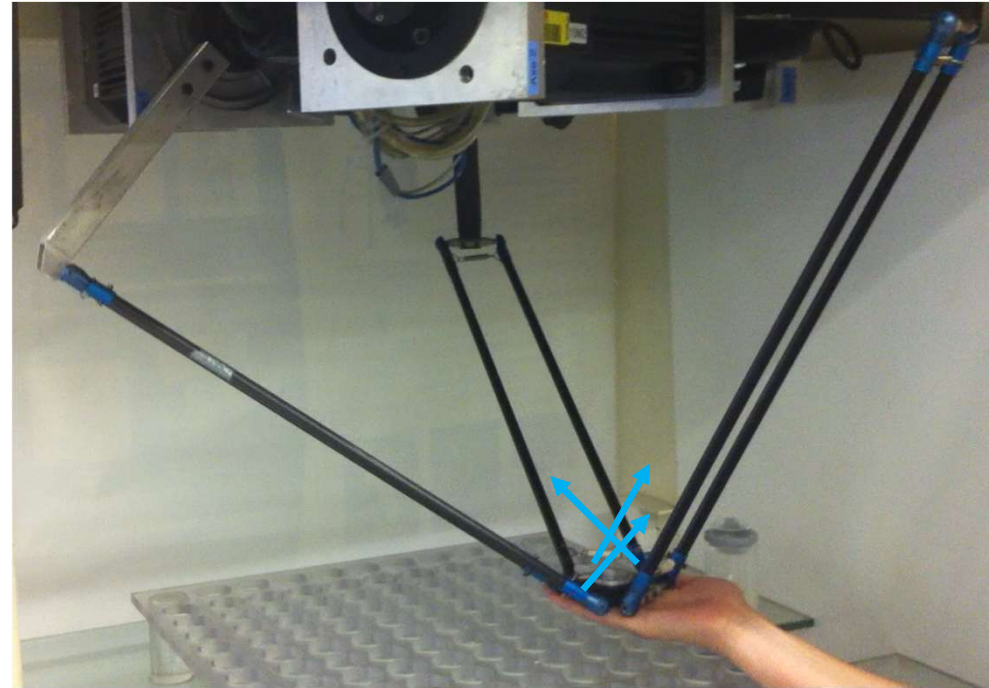
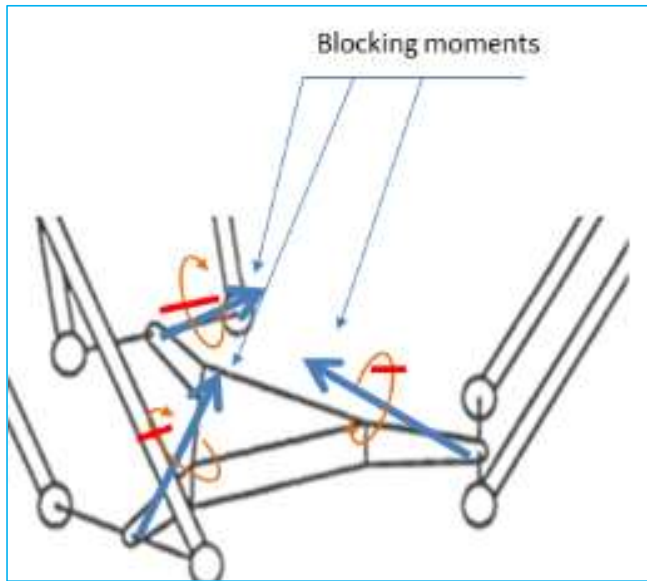


August 2019
0,4mm RMS_error @30 Ge
acceleration pick_and_place

[Patent 2015] Device For Moving And Positioning An Object In Space, Huser M., Tschudi M., Keiffer D., Teklits A., Bouri M., Clavel R., Demaurex MO., Device For Moving And Positioning An Object In Space, reference WO2012152559

Why the robot Delta is a pure translational robot?

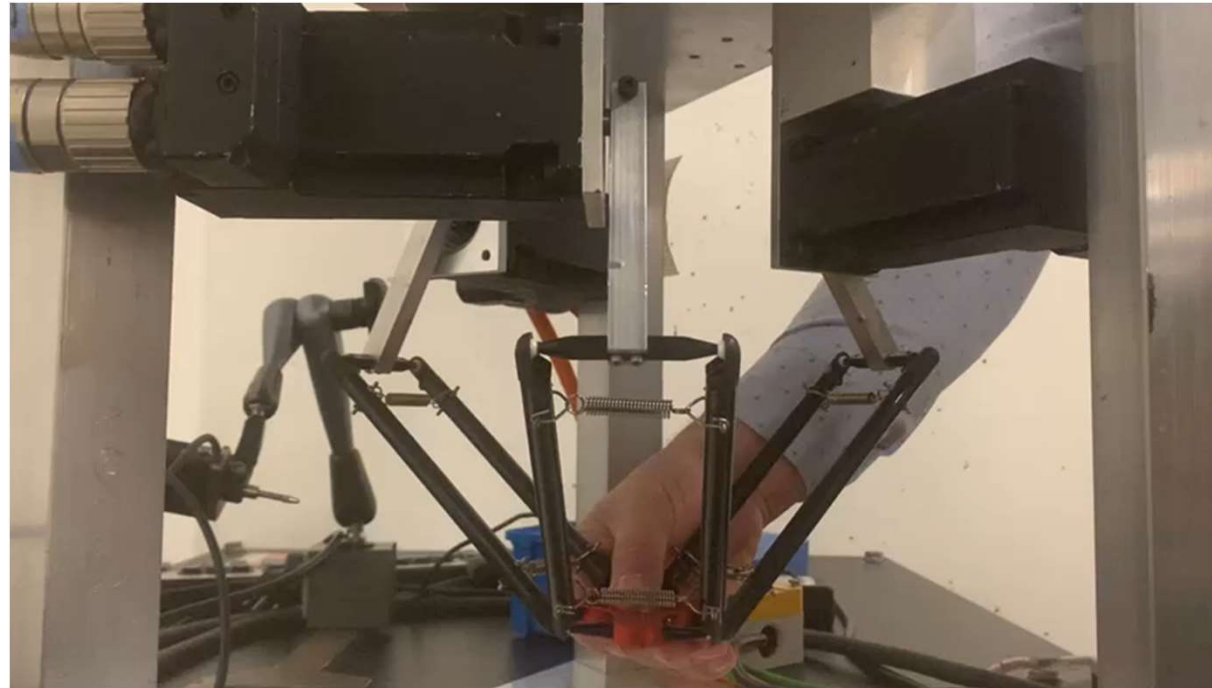
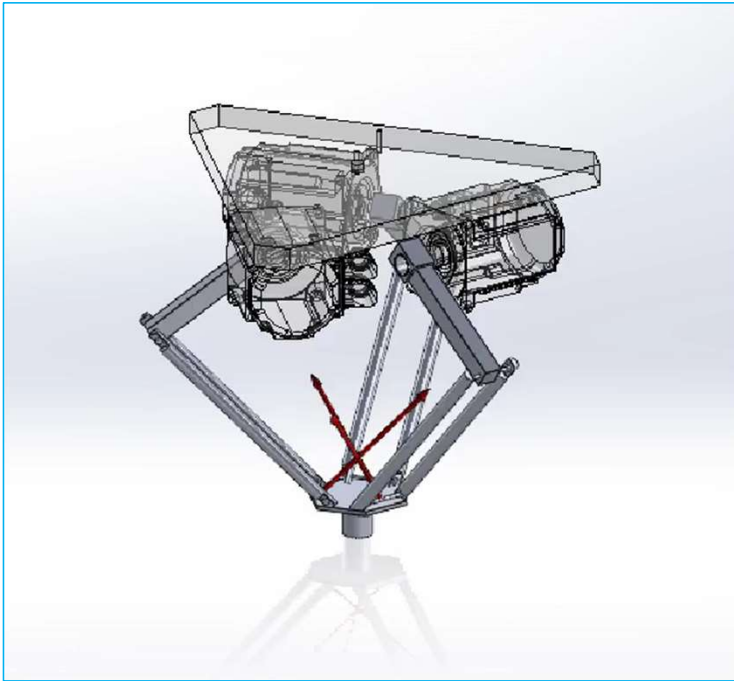
Only translations are possible, and the orientations of the end effector are blocked.



- The sum of the blocking moments is not null, **which explains that the orientations of the mobile plate are all blocked.**
- When the sum of the blocking moments is null, the robot is in **a singular position.**

The Delta: Singularities

When the sum of the blocking moments is zero in one of the directions



Mobility of parallel robots

In a parallel robot,

- There are active joints (**actuators**) and passive joints (**pivots, universal joints, spherical joints, and others**)
- Kinematic chains are closed.
- The number of DOF of the mobile plate does not suffice to illustrate some constrained internal mobilities and to illustrate free internal mobilities.

The number “**Mobility**” illustrates the resulting mobility of the robot, by considering all the joints and the segments of the robot.

Mobility of basic components

Reminder: Representations of kinematic links

Pivot

Pivot (fr)

Pivot joint / Rotary joint (en)



Cardan

Cardan (fr)

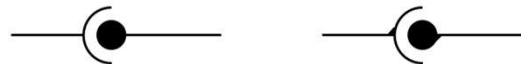
Universal joint / cardan joint (en)



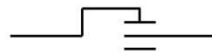
Spherical joint

Rotule (fr)

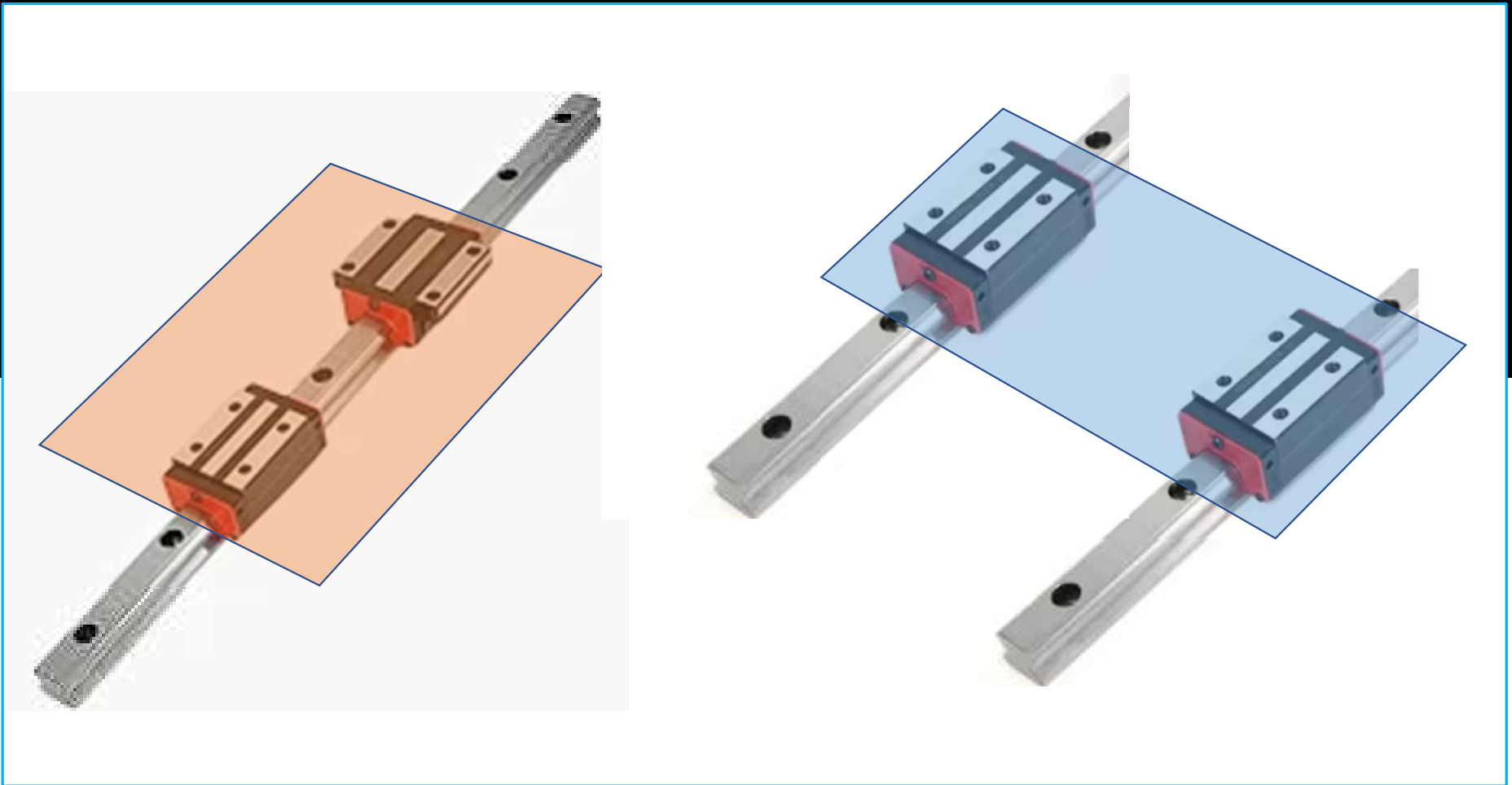
Spherical joint (en)



Prismatic joint



What are the mobility and DOFs of these mechanisms?



Mobility of parallel robots

The mobility is **the balance of the overall mobilities** of all the links that constitute the robot, by considering of course the existing kinematic constraints.

In the case of a serial robot, the mobility is equal to the number of actuated joints.

[!] It is also the **dimension of the joint space.**

For parallel robots (kinematics), two formulas allow to calculate the number (mobility)

- Formula of **Grübler.**
- Formula of **kinematic loops.**

Mobility of parallel robots

Formule of Grübler

By considering a kinematic structure composed by **n solid elements**, the degrees of freedom (called DOF or Mobility MO) of this set of elements before any assembly is obviously equal to **MO = 6.n** (each element has 6 spatial DOF). Each link between 2 elements reduces the total mobility by a value corresponding to the number of the generalized forces (NGF) in the considered link. With **k joints**, the mobility is computed as follows:

$$MO = 6n - \sum_{i=1}^k NGF_i$$

The number of the generalized forces (NGFi) involved in a considered joint is a complementary to 6 of the number of the degrees of freedom (MOi). We then obtain:

$$NGF_i = 6 - MO_i$$

And hence: $MO = 6n - 6k + \sum_{i=1}^k MO_i$

That gives: $MO = 6(n - k) + \sum_{i=1}^k MO_i$

Since one element of the structure is fixed on the frame, its 6 DOF must be differentiated from the total mobility number MO. We obtain:

$$MO = 6(n - k - 1) + \sum_{i=1}^k MO_i$$

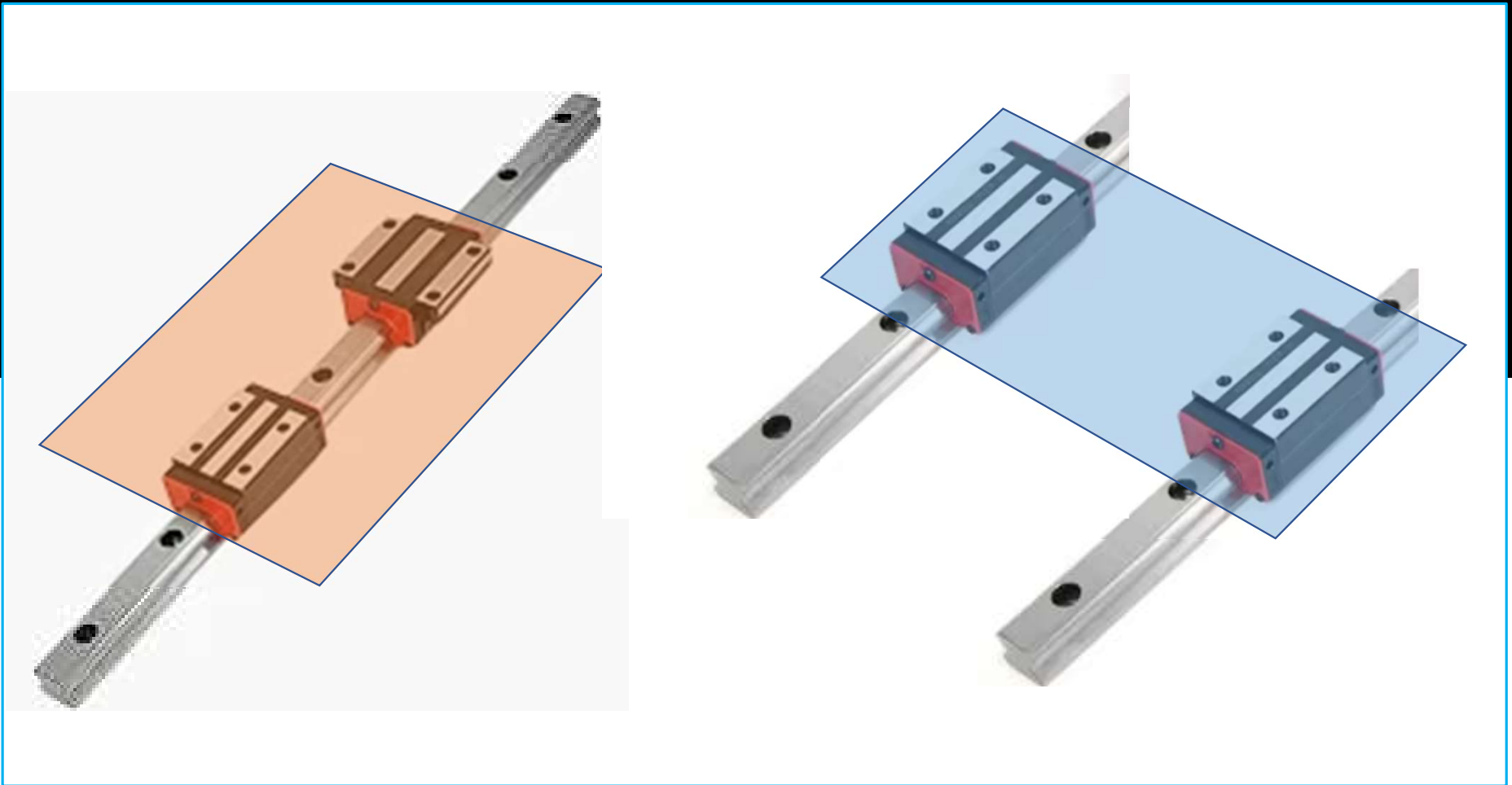
Mobility of parallel robots

Formula of kinematic loops

$$MO = \sum_{i=1}^k MO_i - 6bo$$

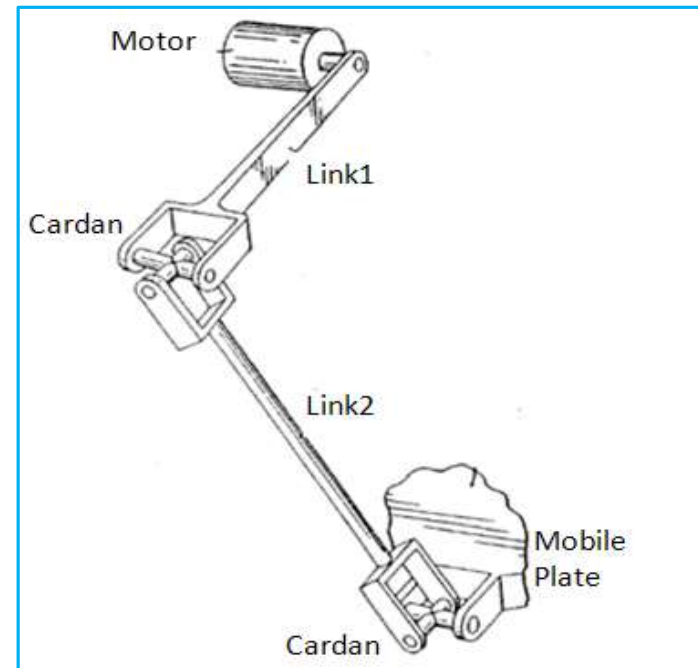
bo (boucles in French) is the number of disjointed kinematic loops in the structure.

What are the mobility and DOFs of these mechanisms?



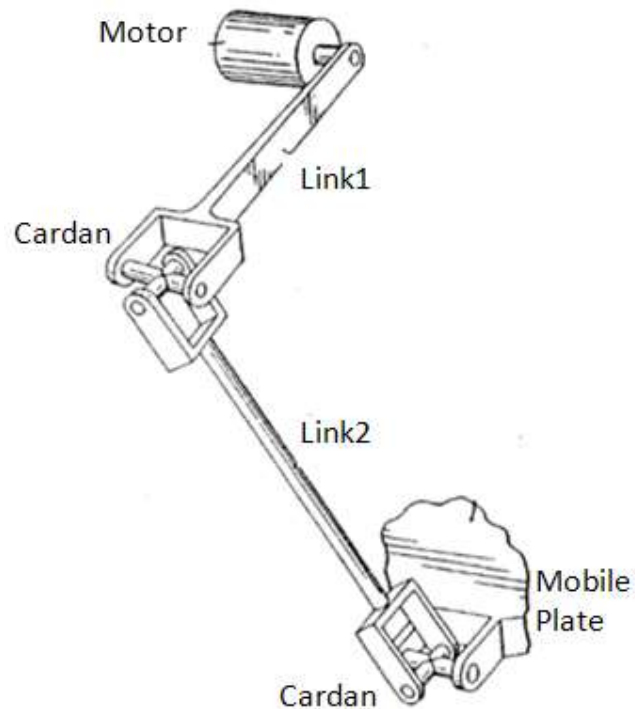
Example 1,

- Illustrate the Kinematic representation of a Delta with gimbals.
- Calculate its mobility.
- Conclude...

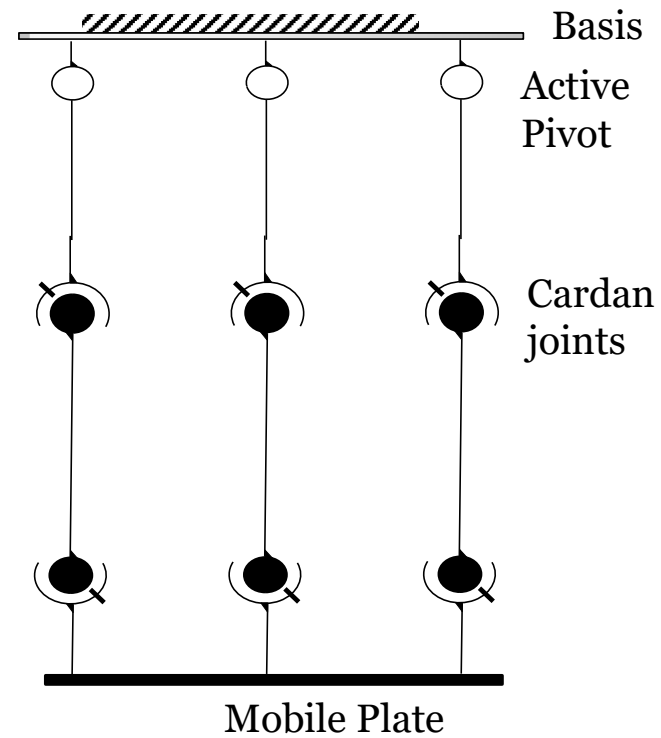


Representation of one kinematic chain of the cardan based Delta

Example 1: The simplest variant: with cardans at the passive joints



Representation of one kinematic chain



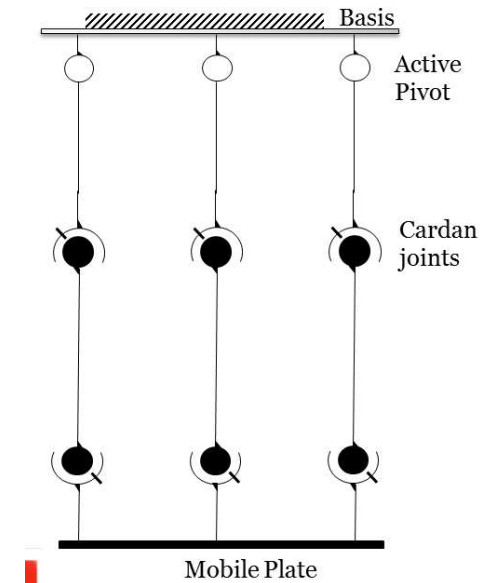
Delta with cardans: Calculation of the Mobility ☺

By applying the Grübler formula, we have:

- The number of elements of the structure is **$n = 8$** (1+1+3.2) {1 basis + 1 mobile plate + 3 arms + 3 forearms}.
- The number of joints **$k = 9$** {(1 pivot + 2 cardans) X 3 identical links}.
- The mobility of the pivot is equal to **1**. The mobility of each cardan is equal to **2**. The total mobility of this Delta is then computed as follows:

$$MO = 6 \cdot (8 - 9 - 1) + \{1 + 2 + 2\} \cdot 3 = -12 + 15 = 3$$

$$MO = 6(n - k - 1) + \sum_{i=1}^k MO_i$$



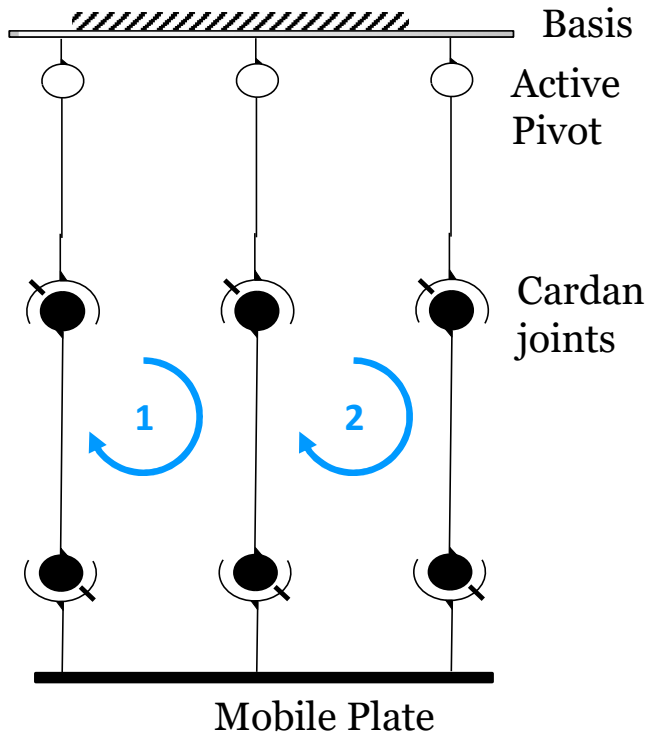
Delta with cardans: Calculation of the Mobility using the the Ilop formula ☺

Formula of kinematic loops

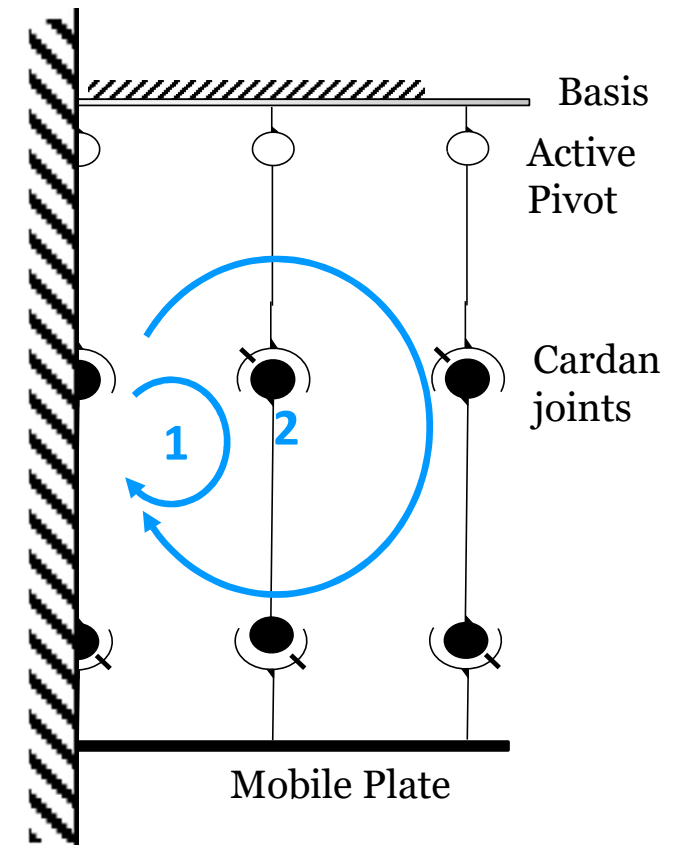
$$MO = \sum_{i=1}^k MO_i - 6b_0$$

How to count the loops ?

1- Disjointed loops

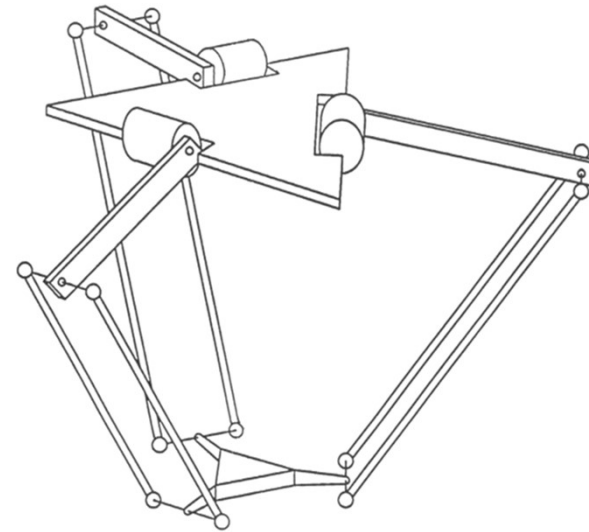
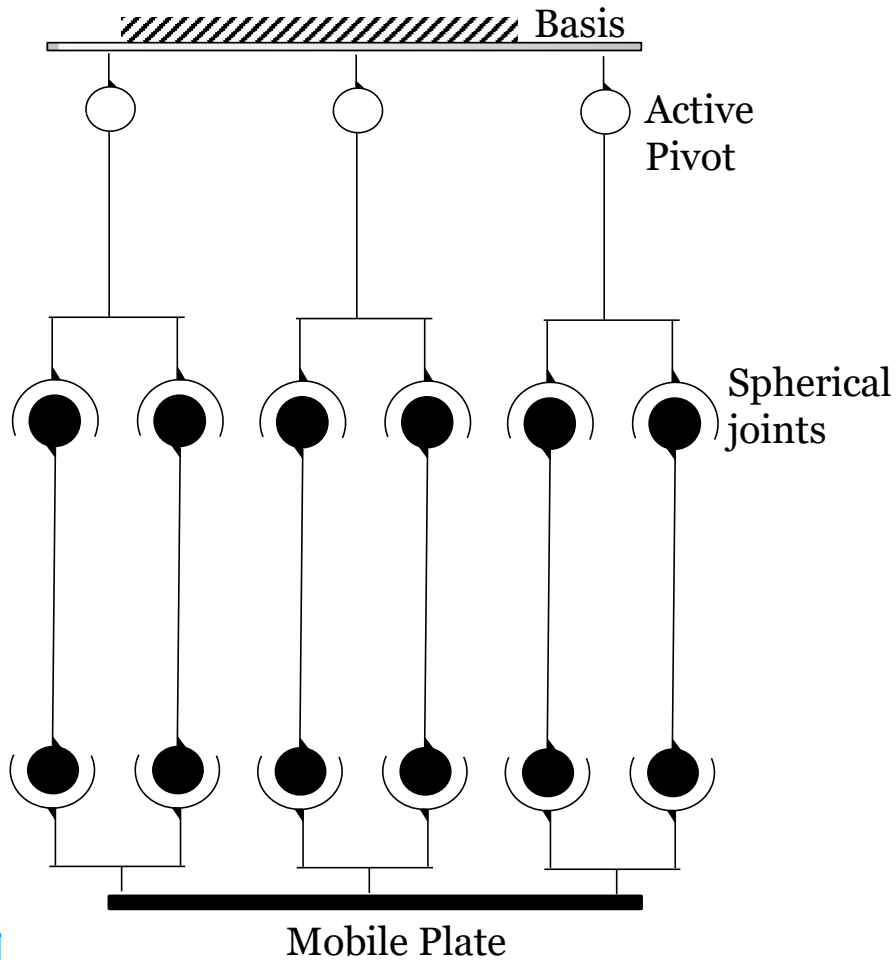


2- Closed loops with same reference



Example 2: The most common realization, Delta with parallel bars and spherical joints

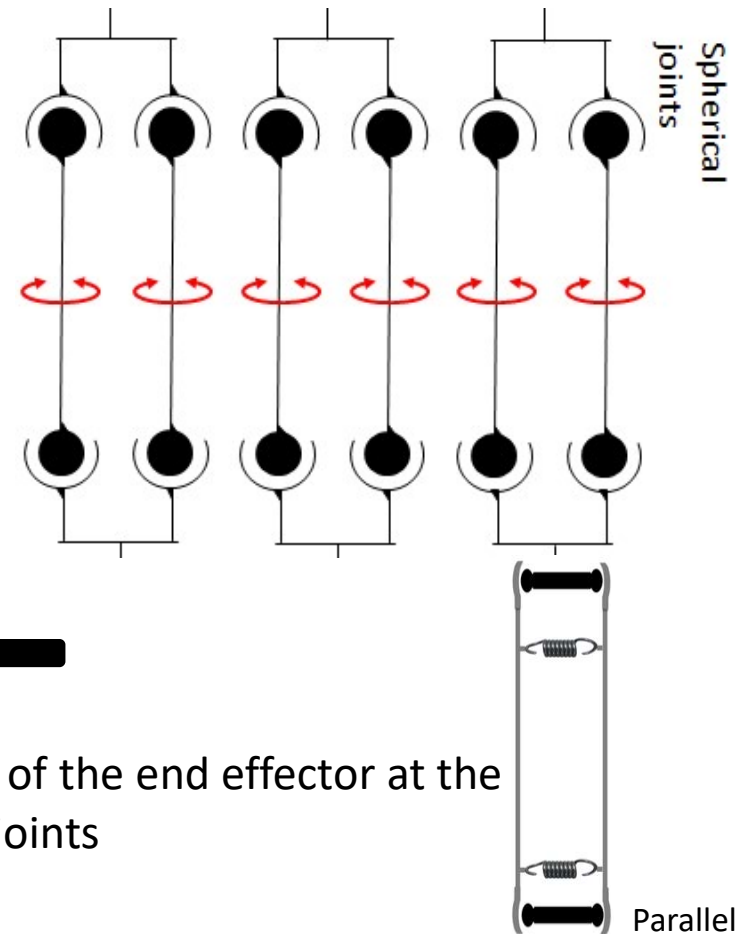
25



- $n = 11$ (1+1+3.3) {1 basis + 1 mobile plate + 3 arms + 6 bars}.
- $k = 15$ {(1 pivot + 4 spherical joints) X 3 identical links}.

$$\begin{aligned}
 MO &= 6 \cdot (11 - 15 - 1) + \{1 + 4 \cdot 3\} \cdot 3 \\
 &= -30 + 39 = 9
 \end{aligned}$$

- The Delta robot as designed with the parallel bars and spherical joints has 6 supplementary mobilities.
- These mobilities concern **internal mobilities** not affecting **the pure translation of the mobile plate**.
- They are actually related to the **rotation of each bar around its principal axis**.



- Springs limit the internal mobility at the cost of friction
- The internal mobility does not affect the final precision of the end effector at the condition of an ideal spherical contact of the spherical joints

Using cardans instead of a set of parallel bars and spherical joints



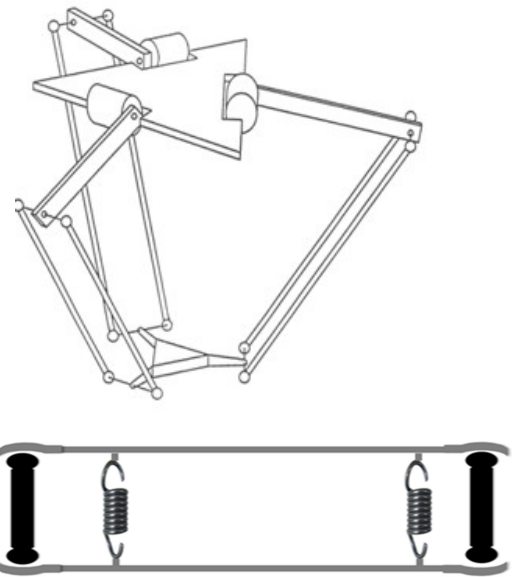
Never do it....

- The structure is not enough stiff
- Not easy to find cardans with reduced play.
- The play will reduce the proper mechanical frequency

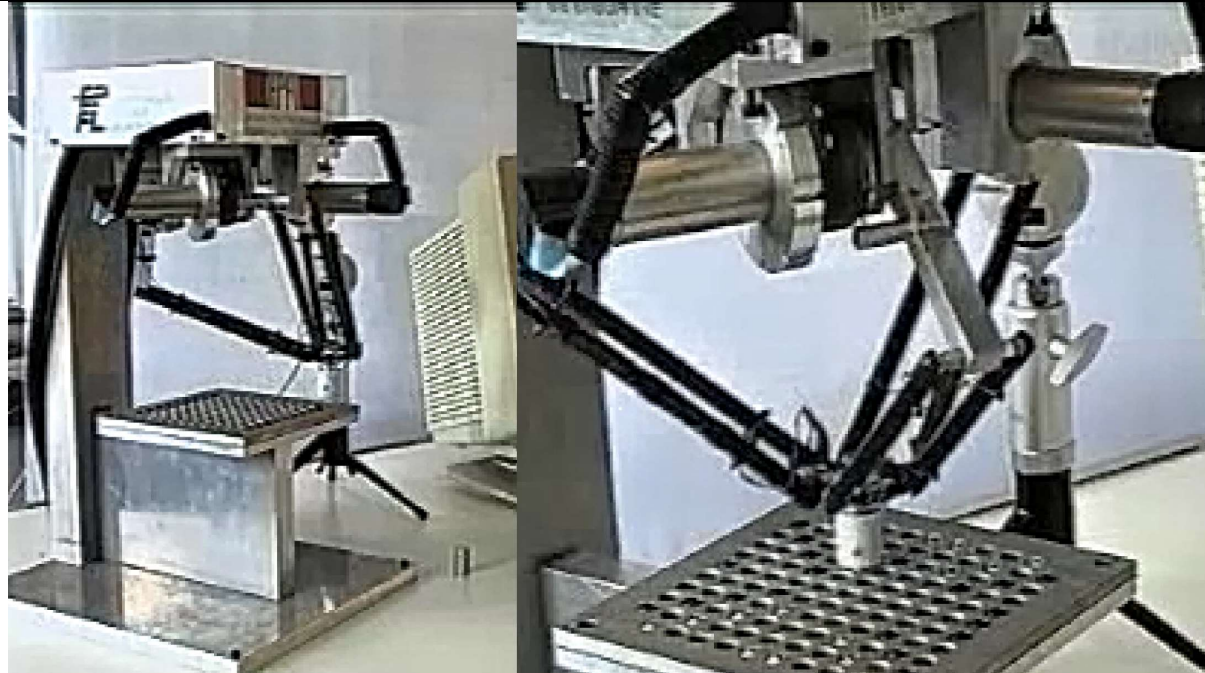


Never say never

Why is the Delta robot so simple?



Parallel bars



Motor + Gear Box + Arm + Forearms

Motor + Gear Box + Arm + Forearms

Motor + Gear Box + Arm + Forearms

+

Mobile plate



Three identical kinematic chains, including the actuators

Delta Omega: a parallel robot for haptic feedback



How to reduce friction ?

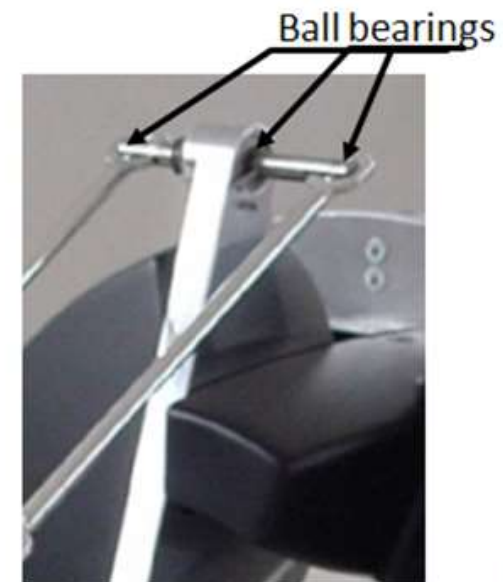
Bearings in series instead of spherical joints



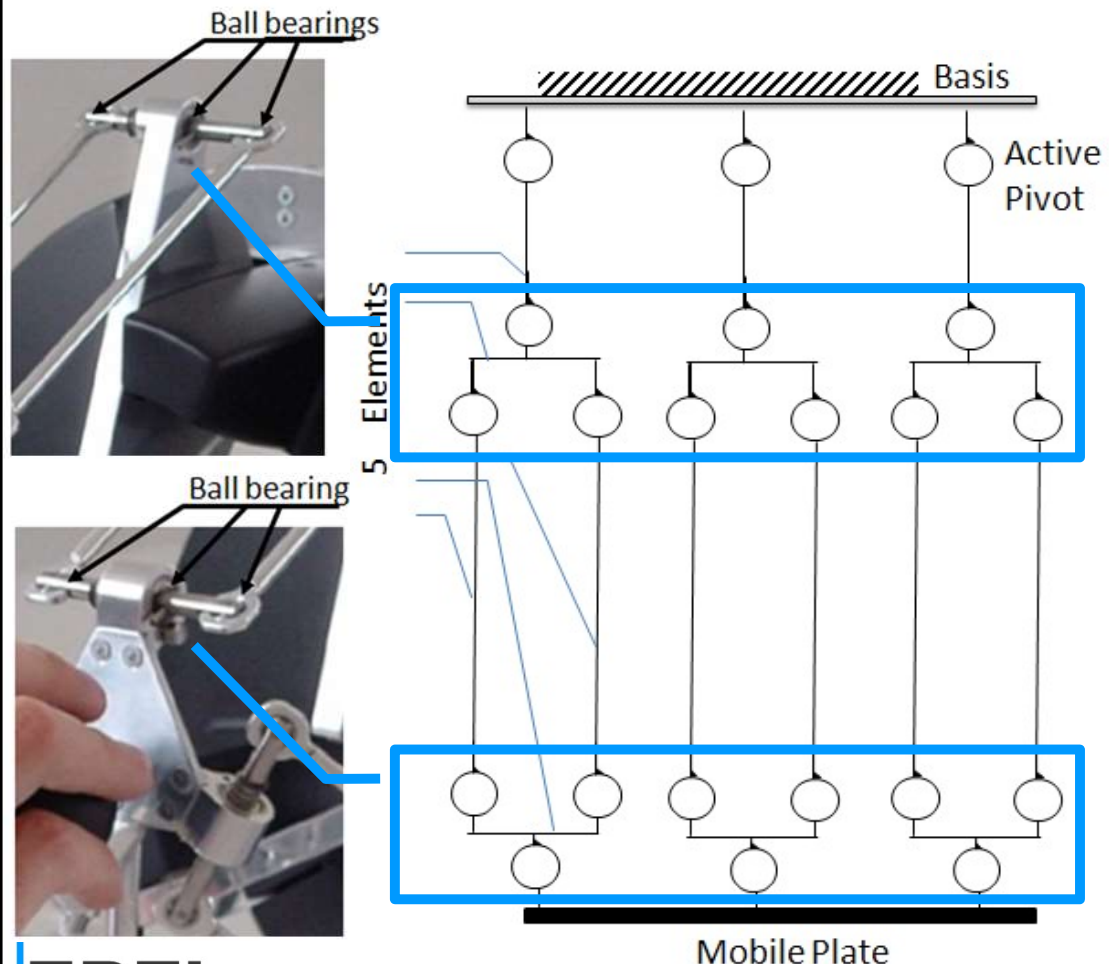
How to reduce friction while keeping big torques ?

Cable transmission instead of gears

Robot Omega from Force Dimension (Nyon) for haptic feedback and tele-manipulation



What is about the mobility of the Delta Omega ?



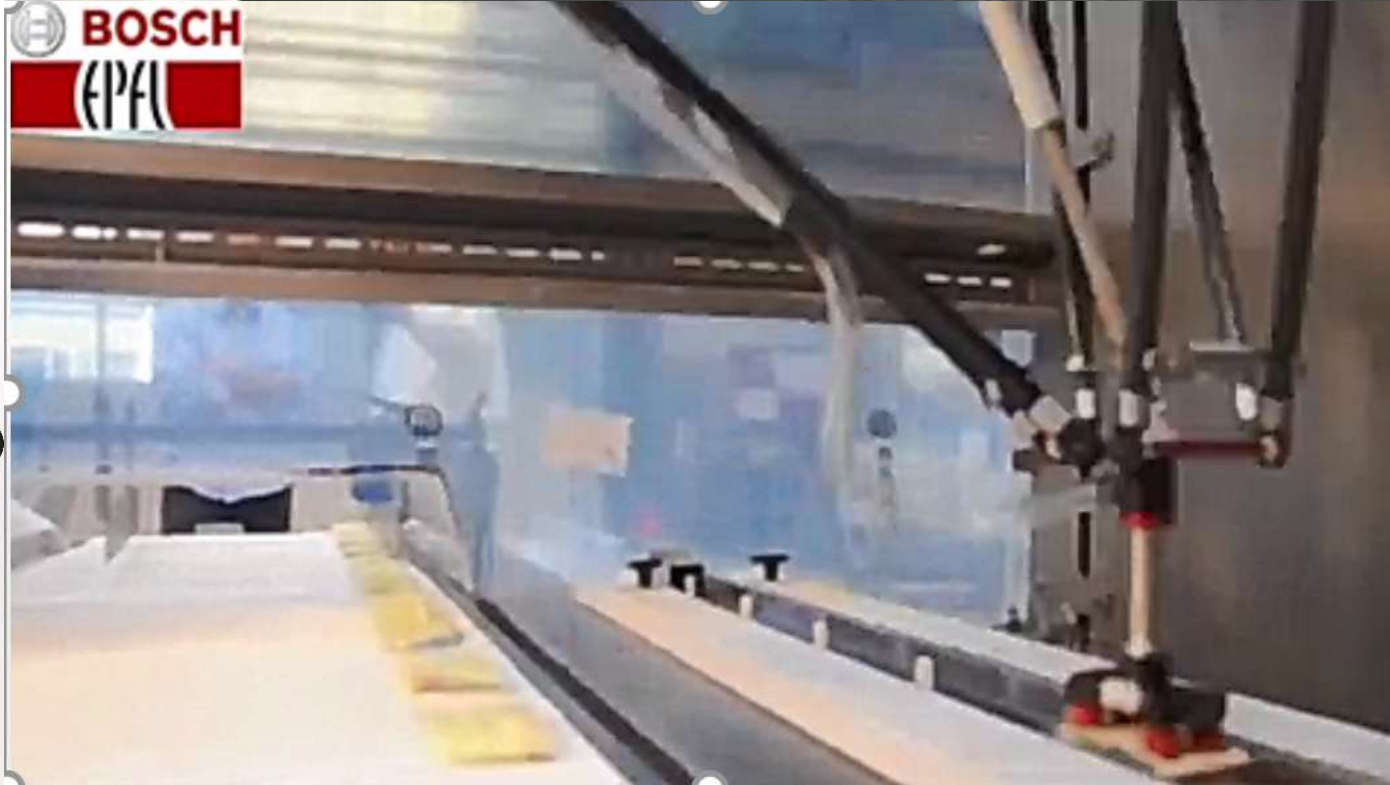
- **$n = 17$** (1+1+5 X 3)
 {1 basis + 1 mobile plate + 5 elements X 3}.
- **$k = 21$** {(1 pivot + 6 pivot joints) X 3 identical links}.

$$MO = 6 \cdot (17 - 21 - 1) + \{21\} = -9$$

Over-constraint of order 12

Even simpler without gearboxes : the trend

Direct Drive Actuated Delta realized for **BOSCH Packaging Technology**

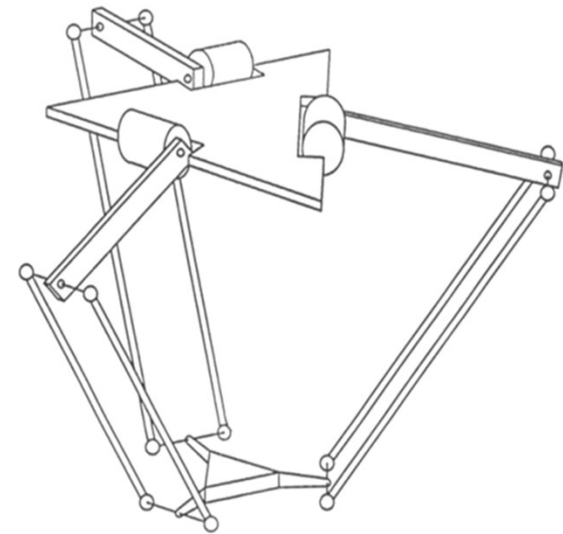
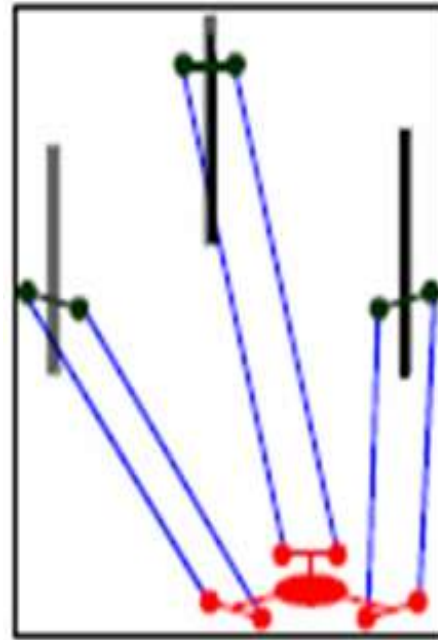


[Patent 2012] **Device For Moving And Positioning An Object In Space**, Huser M., Tschudi M., Keiffer D., Teklits A., **Bouri M.**, Clavel R., Demaurex MO., Device For Moving And Positioning An Object In Space, reference WO2012152559

Linear Variants

Variants with linear movements

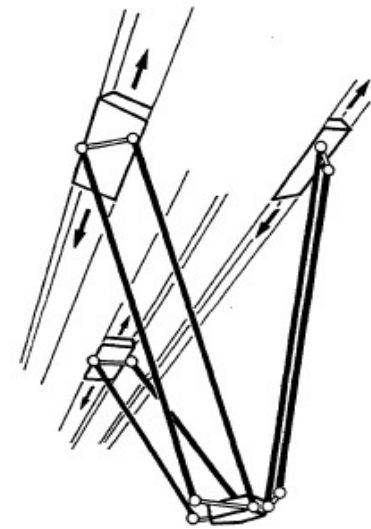
- for applications requiring stiffness.
- For applications requiring precision



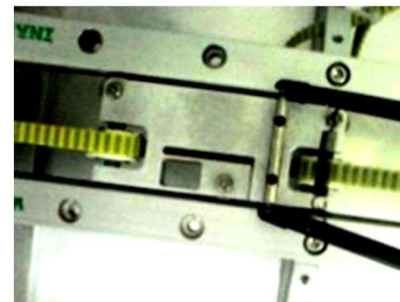
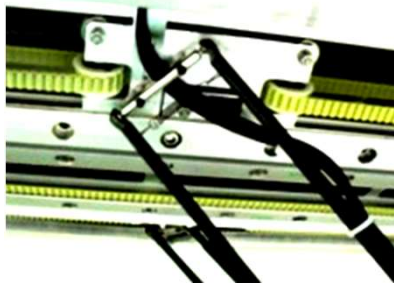
Linear **versus** Angular

- **The speed** of linear variants **is only limited by the actuators**
- **The stiffness** of rotational variants is only limited by the stiffness of the arm.
- **Increasing the resolution** of the rotational variants is only limited by the sensor quality.

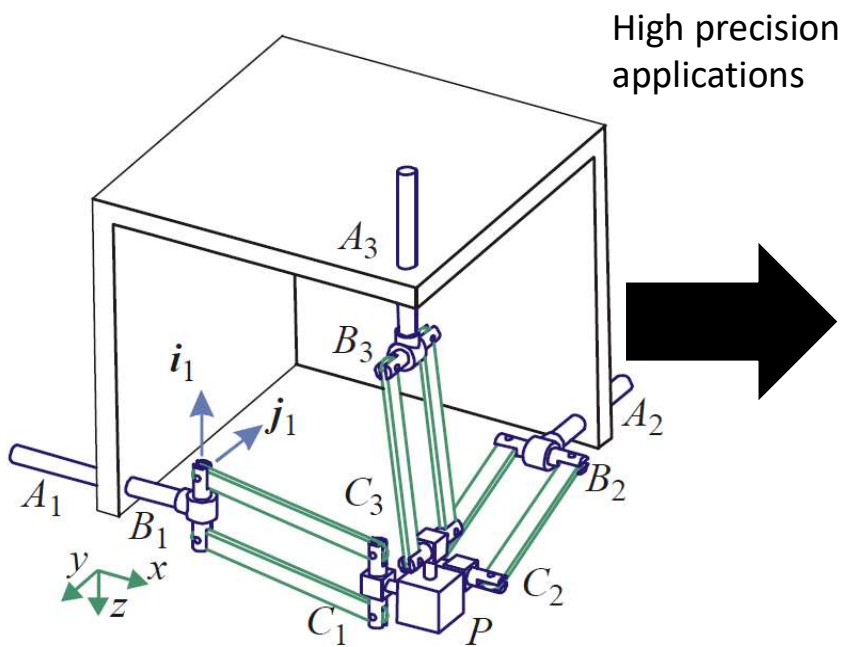
The Horizontal family



Double hoist system as a translational transmission
(FR, double palan)

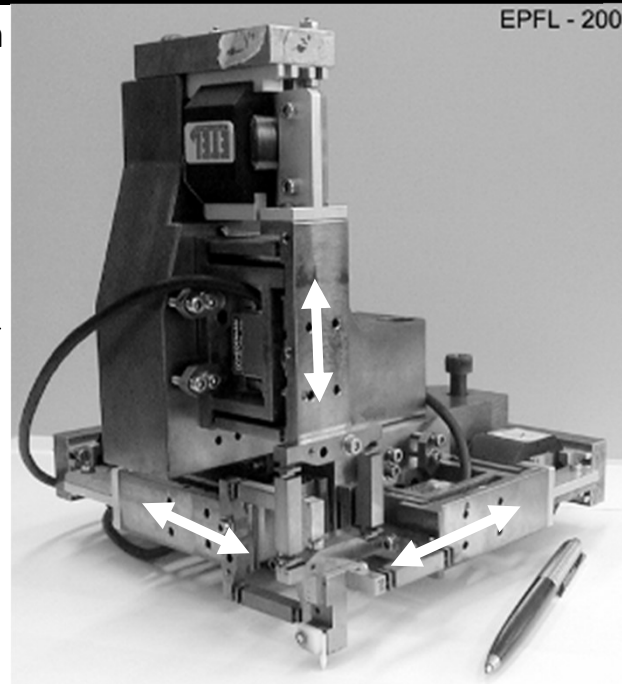


The orthogonal family



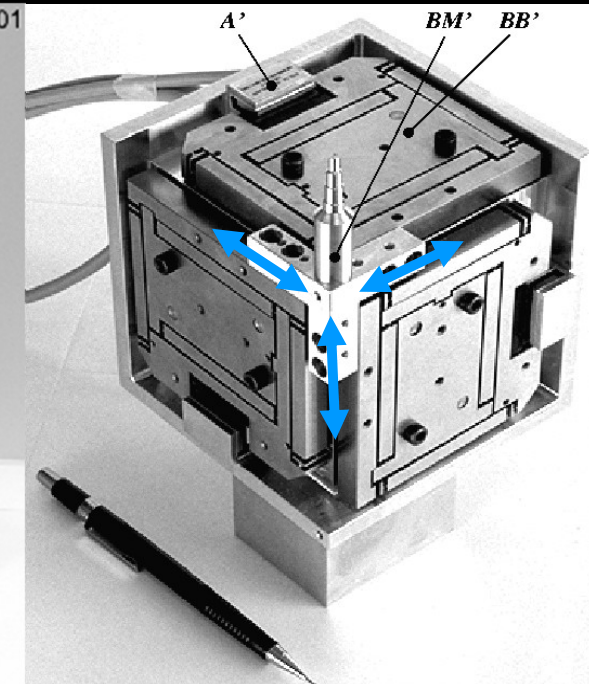
The orthoglide from IRCCyN

[!] Problem of the orthogonality of the three plans



MX3000 from MECARTEX SA

<http://www.mecatex.ch/>



Delta Cube I

Thesis, Simon Henein, EPFL

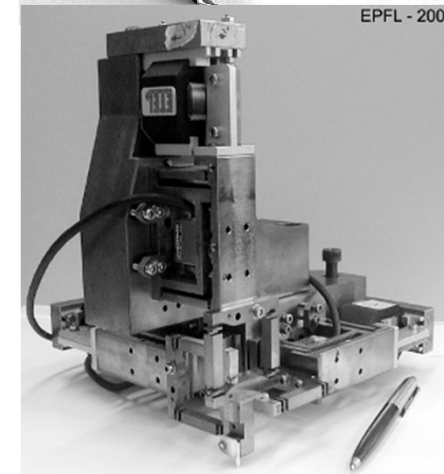
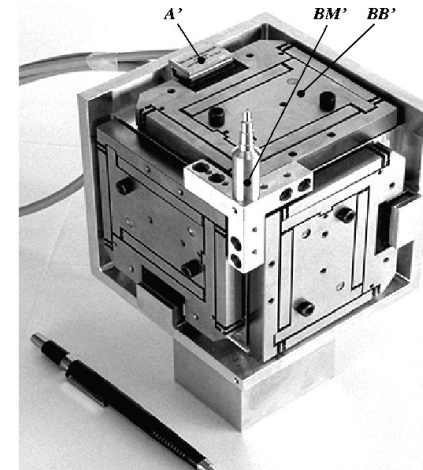
The orthogonality of the three plans is solved through a monolithic machining

More details

This Delta structures called “**Delta Cube**” reach a repeatability of $\pm 10\text{nm}$.

“**Delta Cube I**” that has a travel of $\pm 1\text{mm}$ in each direction.

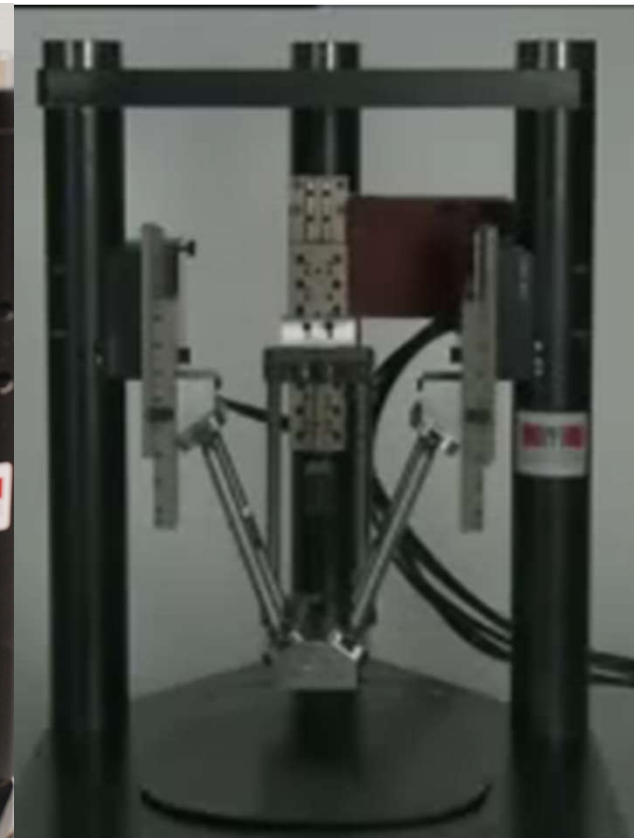
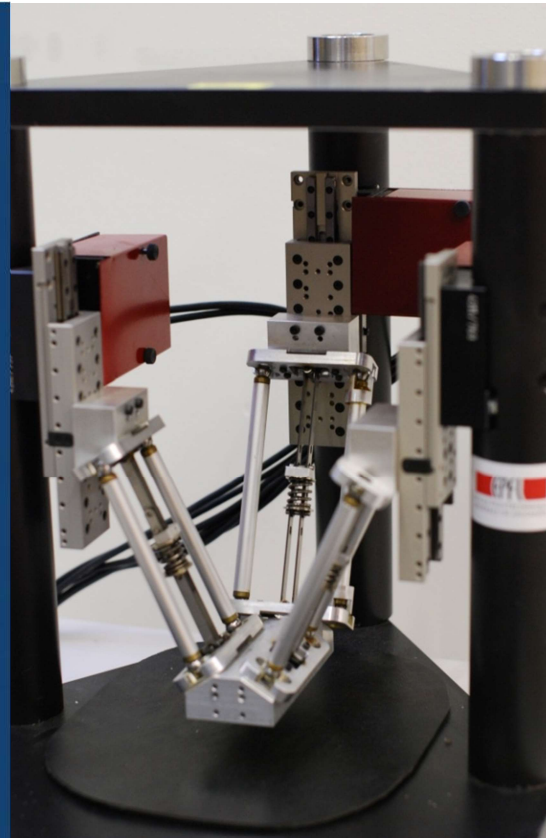
“**Delta Cube II**” has a travel of $\pm 4\text{mm}$ in each direction with a proper frequency of 350Hz .



Developments and applications

The Vertical family

1. Assembly for microEngineering



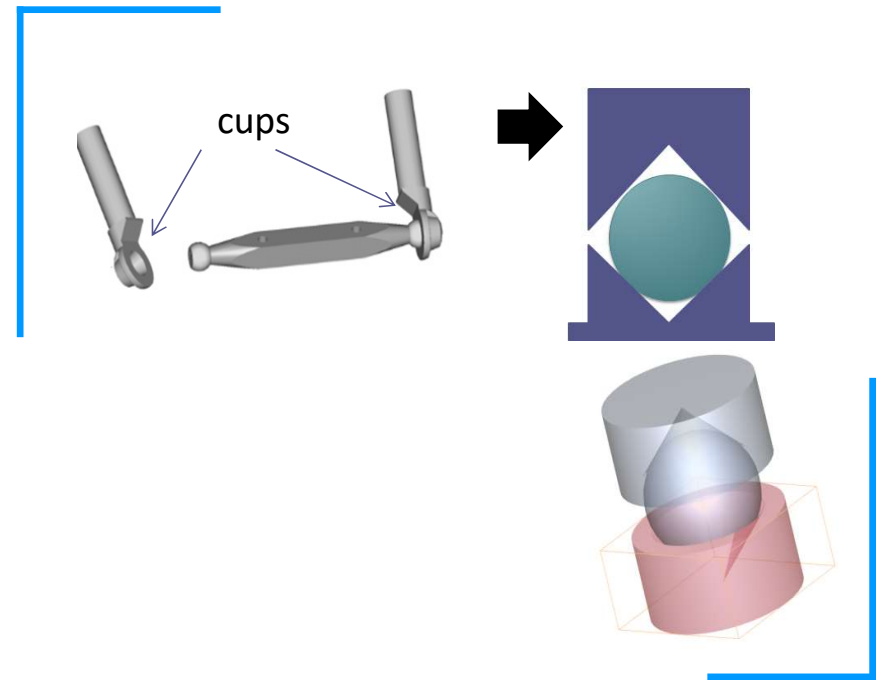
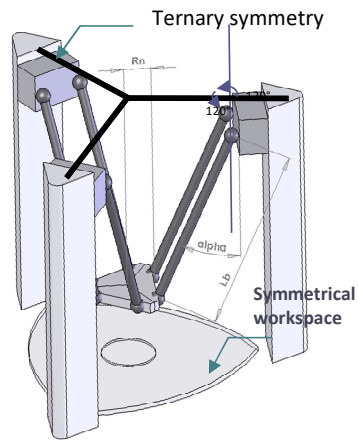
Developments and applications

The Vertical family

2. Towards PIN insertion for watch industry

- ➔ Stiffnes
- ➔ Speed
- ➔ Simplicity

Modify the spherical joints
Adapt the parallel bars
Use ball screw to increase insertion forces up to 300N

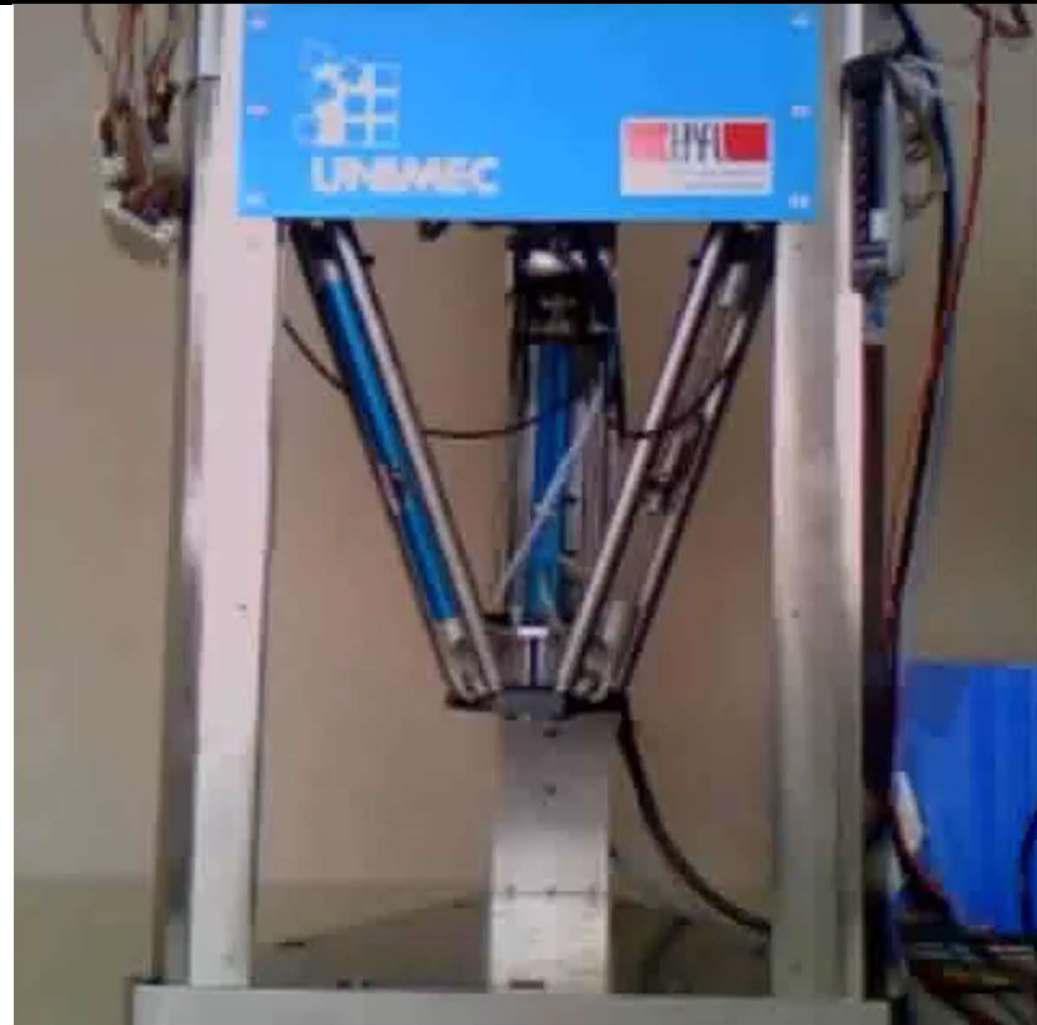


Developments and applications

The Vertical family

2. Towards Pin insertion for Watch Industry

Length of parallel bars:	<i>300 mm</i>
Space resolution:	<i>0.1-0,25 μm</i>
Vertical resolution (center):	<i>0.1 μm</i>
Velocity:	<i>0.4 m/s</i>
Acceleration:	<i>50 m/s²</i>
Vertical force:	<i>$\leq 350\text{N}$</i>
Stiffness:	<i>50N/mm (5.10⁷N/m)</i>
Working space:	$\phi = 240 - 280 \text{ mm}$ <i>H = 80 mm</i>



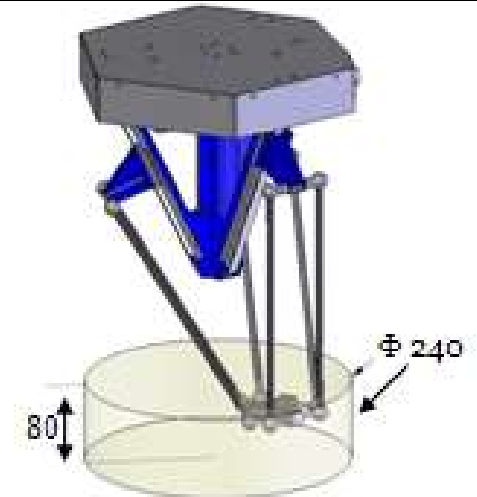
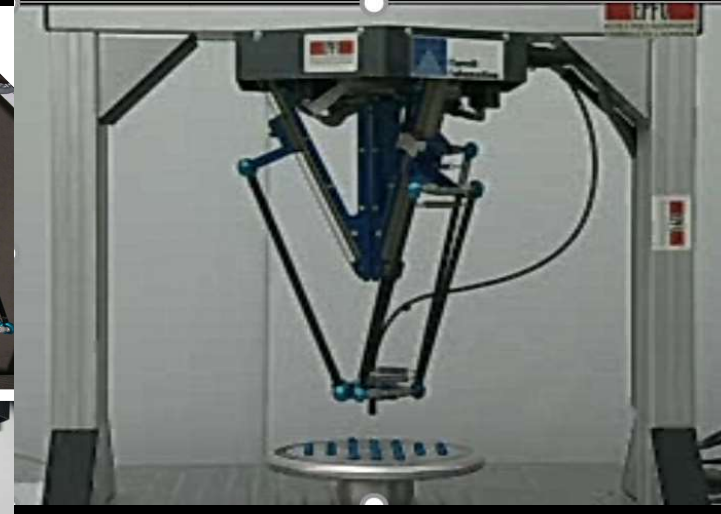
Developments and applications

The Vertical family

The Inclined **Keops-** Advantage 1

Workspace .vs. robot size

Resolution on the linear axis is **7.5 μm** ;
 the worst resolution in the workspace is
 better than **20 μm** ;
 the velocity can easily reach **3.5m/s** at
 the acceleration value of **3.5g**.

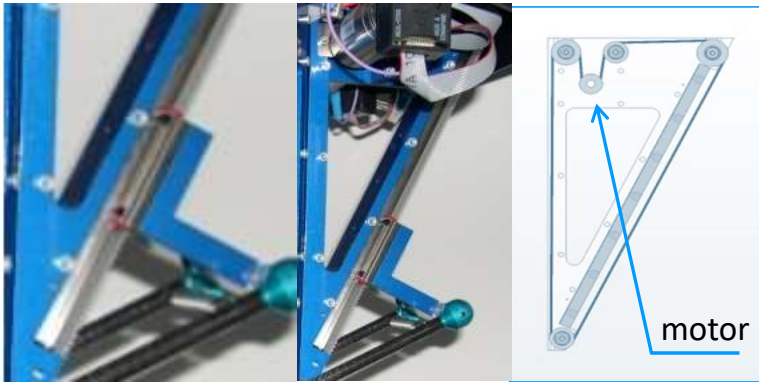


Developments and applications

The Vertical family

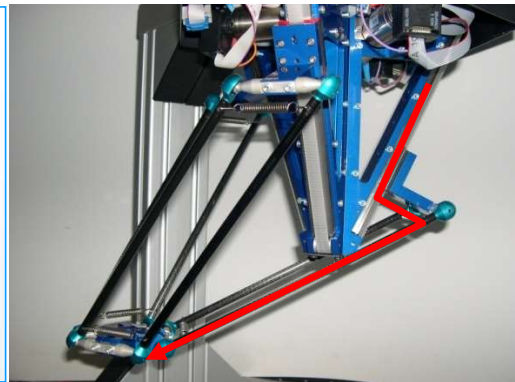
The Inclined **Keops-** Advantage 2

Simplicity



The Inclined **Keops-** Advantage 3

Stiffness at the extremity of the volume

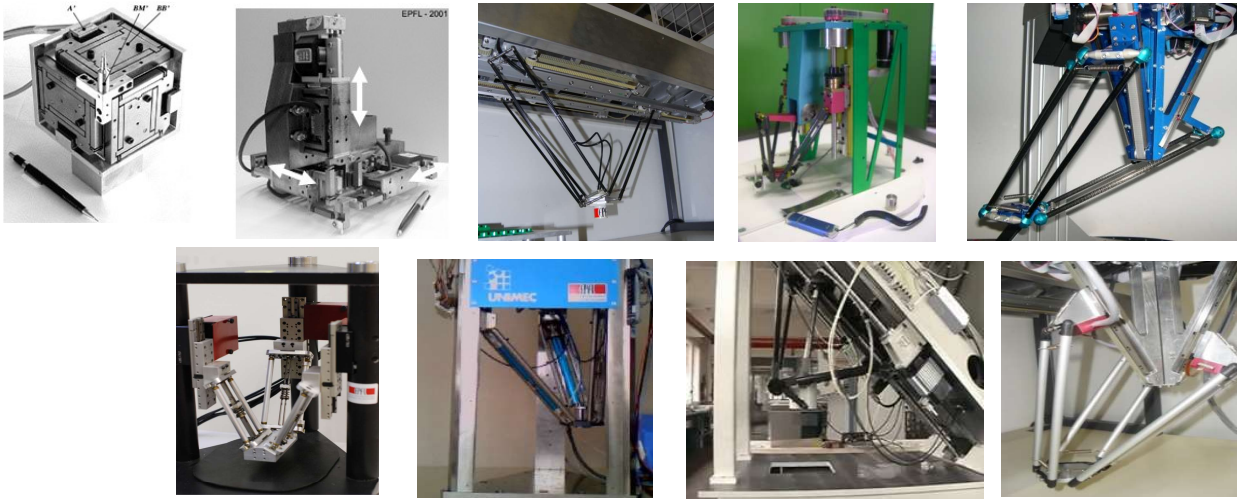


What else...

1 μ m - sensors integrated to Schneeberger guideways.

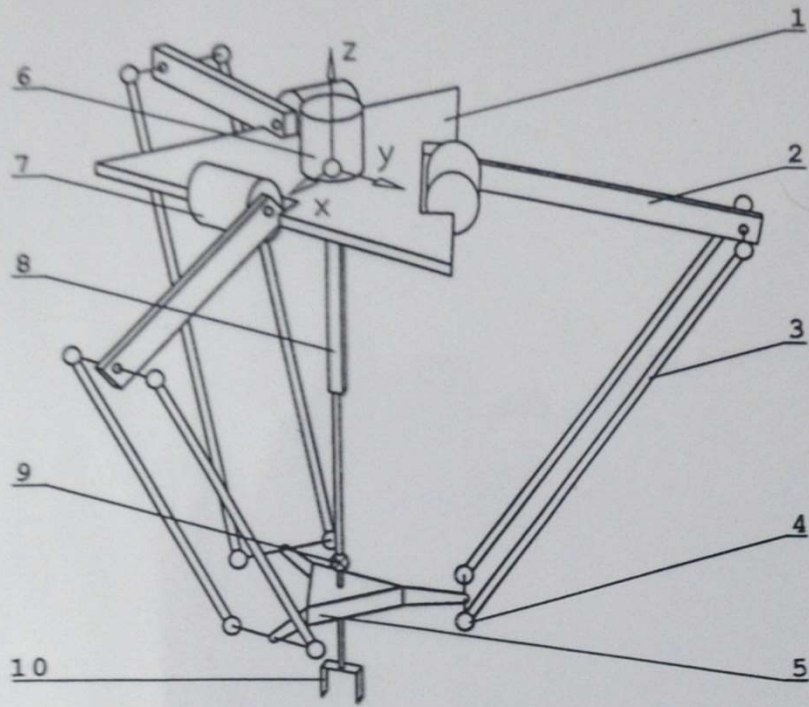


Plenty of Δ -structures....

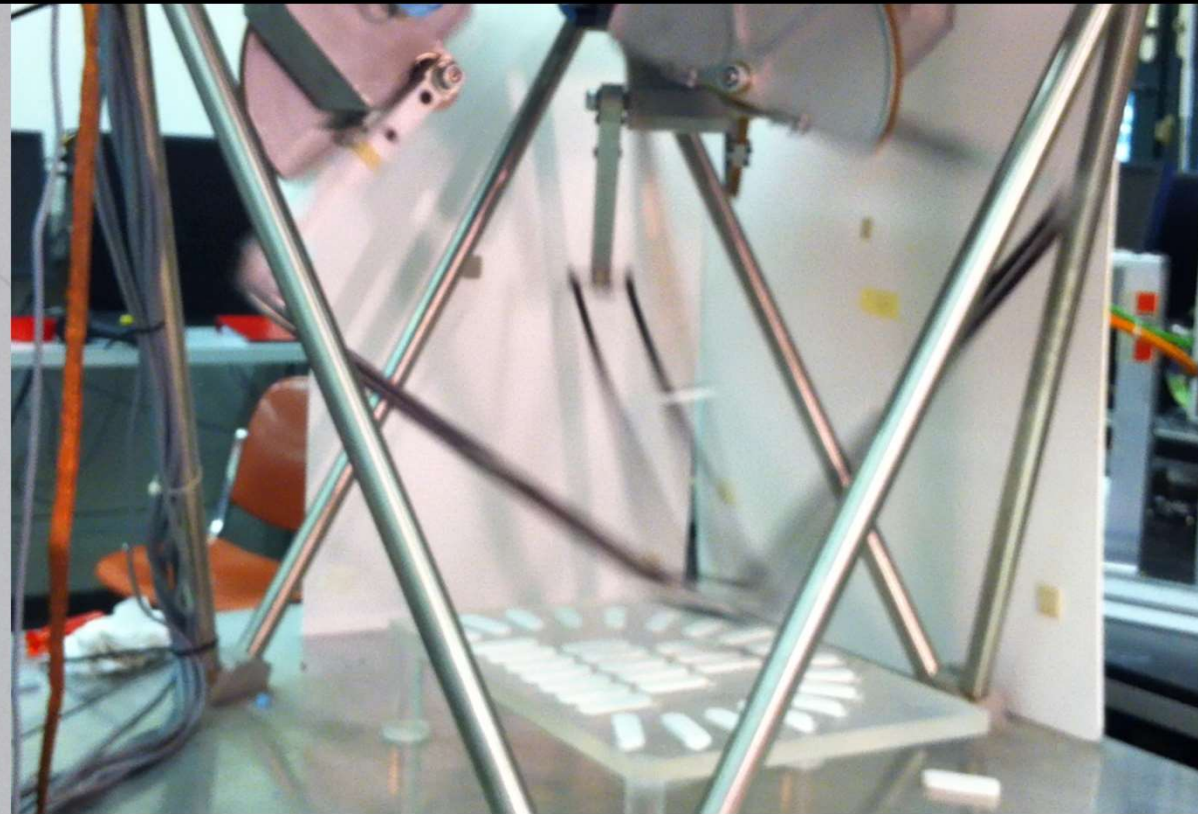


- The family of Delta robots
- More DOFs
- The Hexapods

The Delta 4, with 4 DOFs



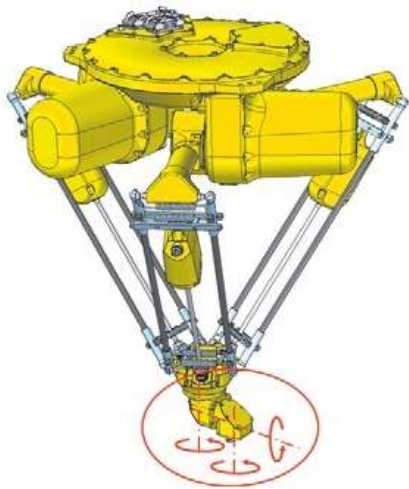
Angular Delta with **4 DOFs**



Additional DOF : **Serial or Parallel?**

Other companies are proposing parallel robots in their catalog:

1. **Mitsubishi** that proposes the double Scara robot.
2. **ABB** (Delta FlexPicker).
3. **Demaurex** at Ecublens, VD/ CH
4. **Adept** that is proposing the Quattro robot
5. **Fanuc** that proposes different variants of the Delta robot.



EPFL Fanuc 6DOFs



ABB Flexpicker 4DOFs (Delta)



Delta Demaurex 4DOFs (the first manufacturer of the Delta)

Other companies are proposing parallel robots in their catalog:

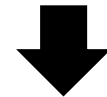


Fanuc Delta robots

6 axes ↓



Omron robots



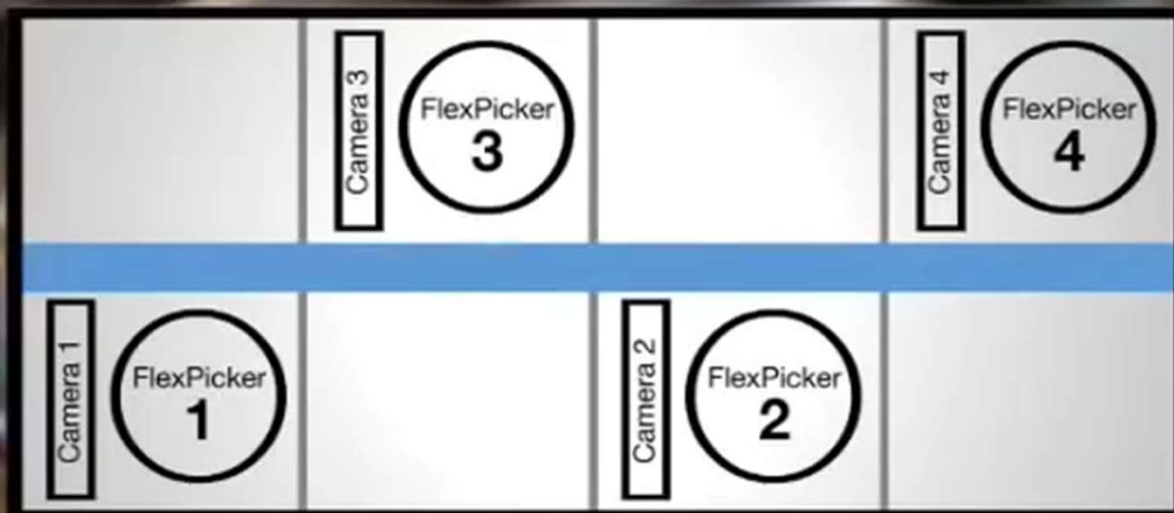
IP67



ABB - example



4 axes – Delta robot



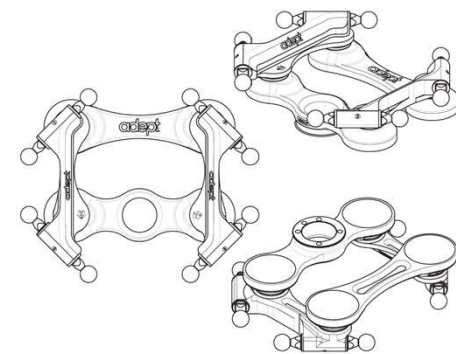
The Quattro – 4 DOFs from Omron (prev. Adept)

Parallel Robot (Delta Robot): Adept Quattro s650H

The Adept Quattro™ s650H parallel robot is specifically designed for high-speed applications in packaging, manufacturing, assembly, and material handling. The Adept Quattro robot is the only parallel robot (or "delta robot") in the world that features a patented four-arm design, advanced control algorithms, and large work envelope make the Adept Quattro the ideal overhead-mount robot for smooth motion, high-throughput applications. The Adept Quattro is powered by ultra-compact controls and embedded amplifiers, which reduces the cycle time and improves footprint efficiency.

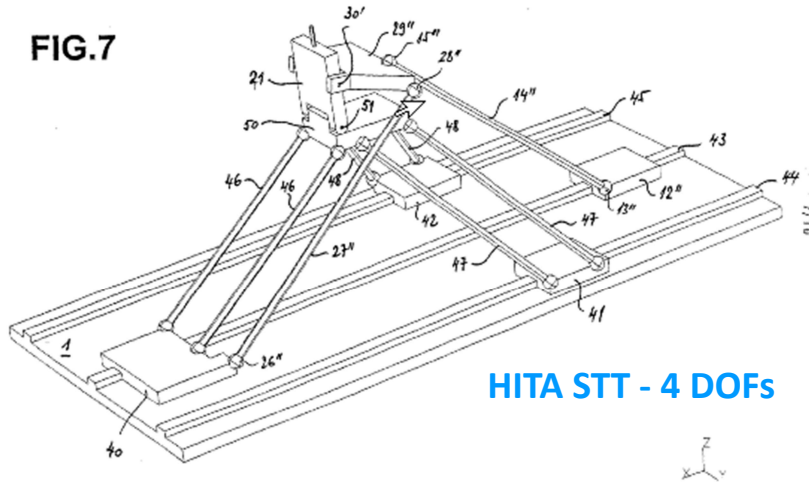


Figure 1-1. Adept Quattro s650H Robot



The Horizontal family - Tool Machining

FIG.7



HITA STT - 4 DOFs

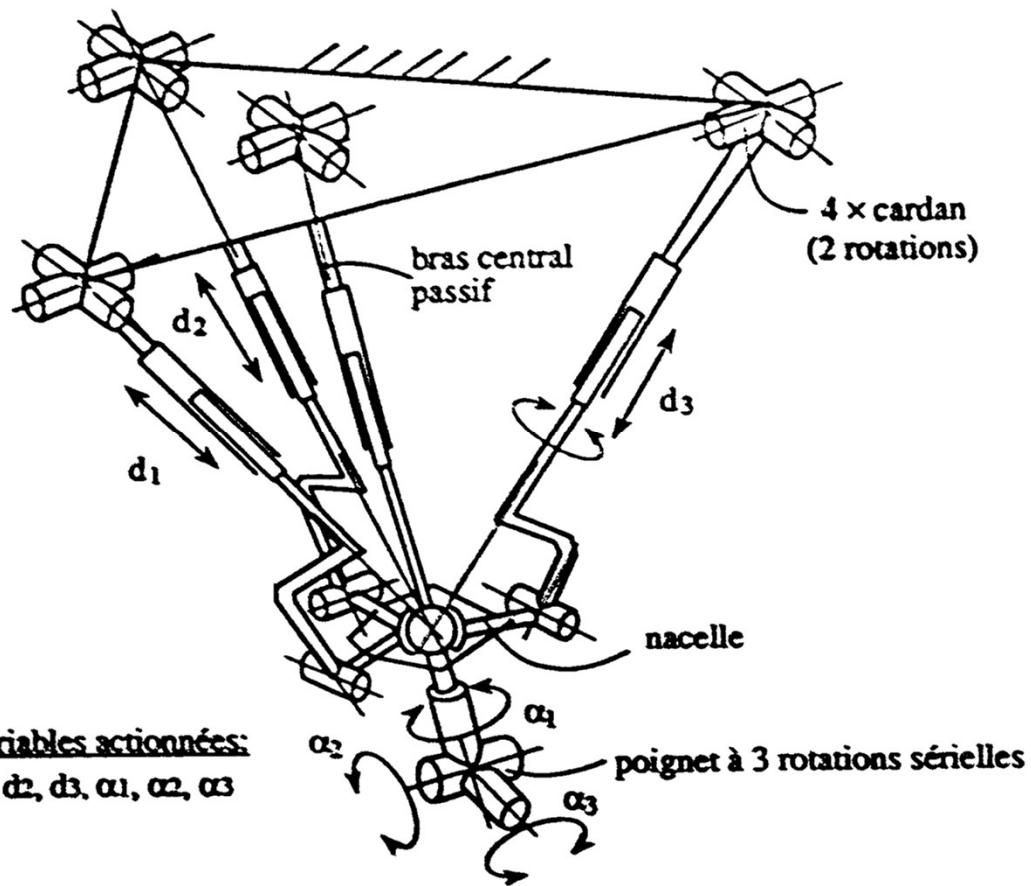
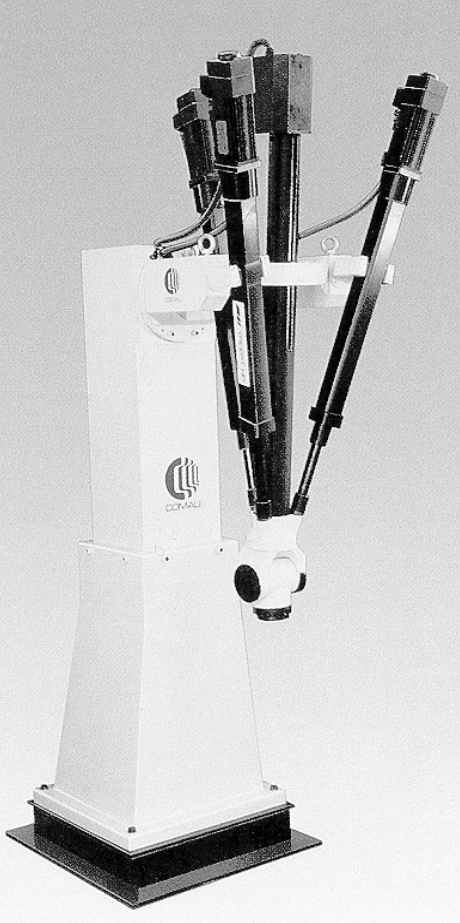
Extension of the linear horizontal Delta to have one additional degree of freedom.

STT: Stiffness Tracking Technology.



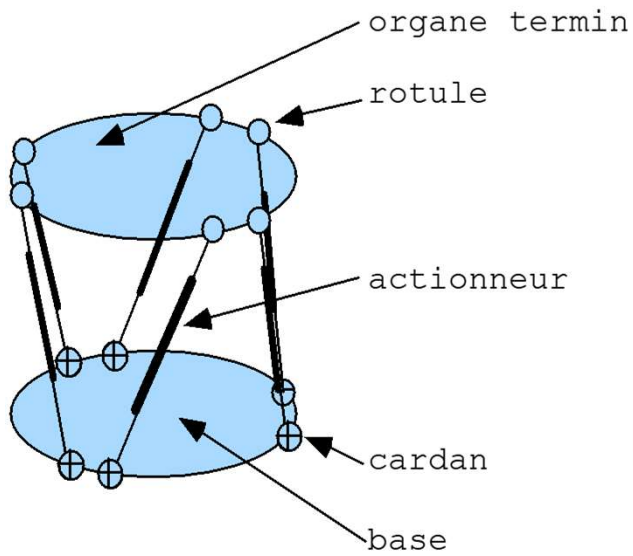
HITA STT, EPFL, 4 DOFS / XYZ and one tilt
[ref Willemin Macodel]

The Tricept (Tetrabot)

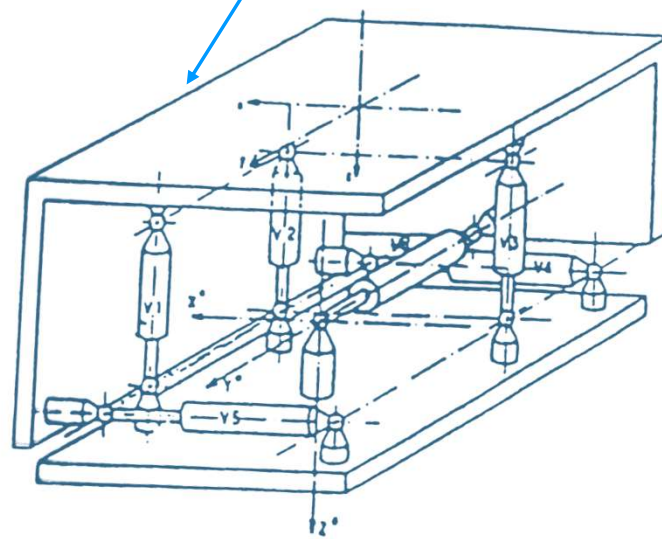


Variables actionn es:
 $d_1, d_2, d_3, \alpha_1, \alpha_2, \alpha_3$

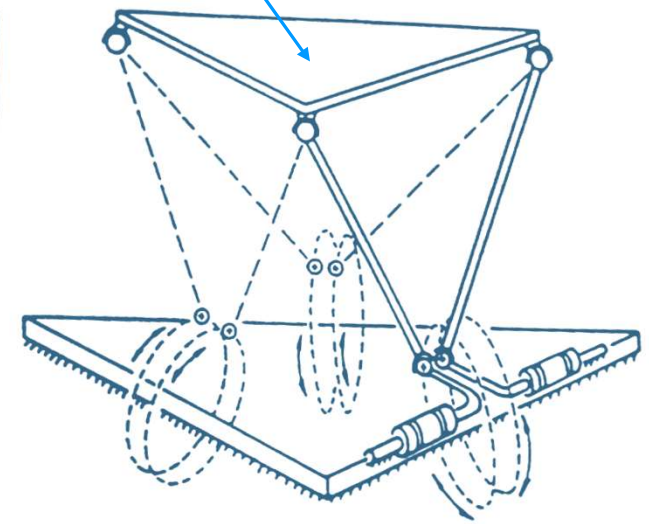
GOUGH-STEWART (1962)



ARTIGUE (1984) and HUNT (1983)

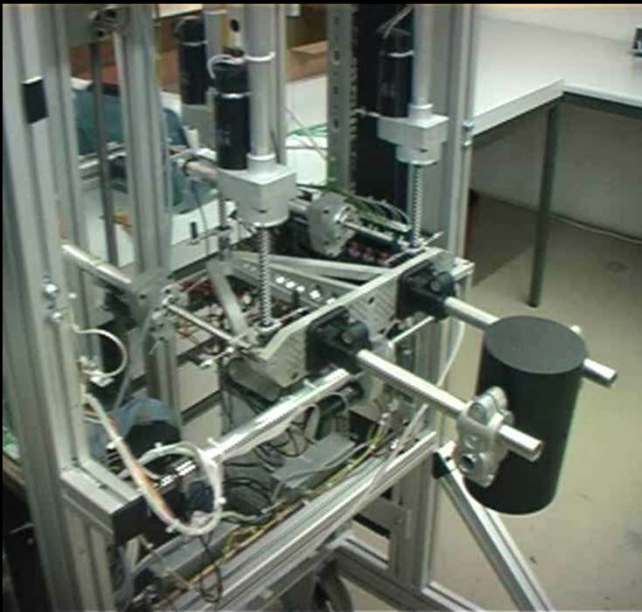


- Decoupled for small motions

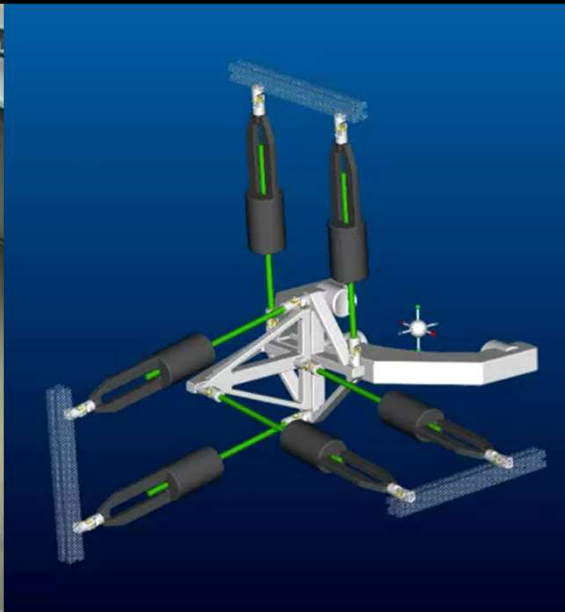


- Actuators fixed to base

Gough-Stewart vs Hunt vs Artigue



Artigue 3x2x1



Artigue 2x2x2



Gough-Stewart
Hexapod [ref. Symetrie]

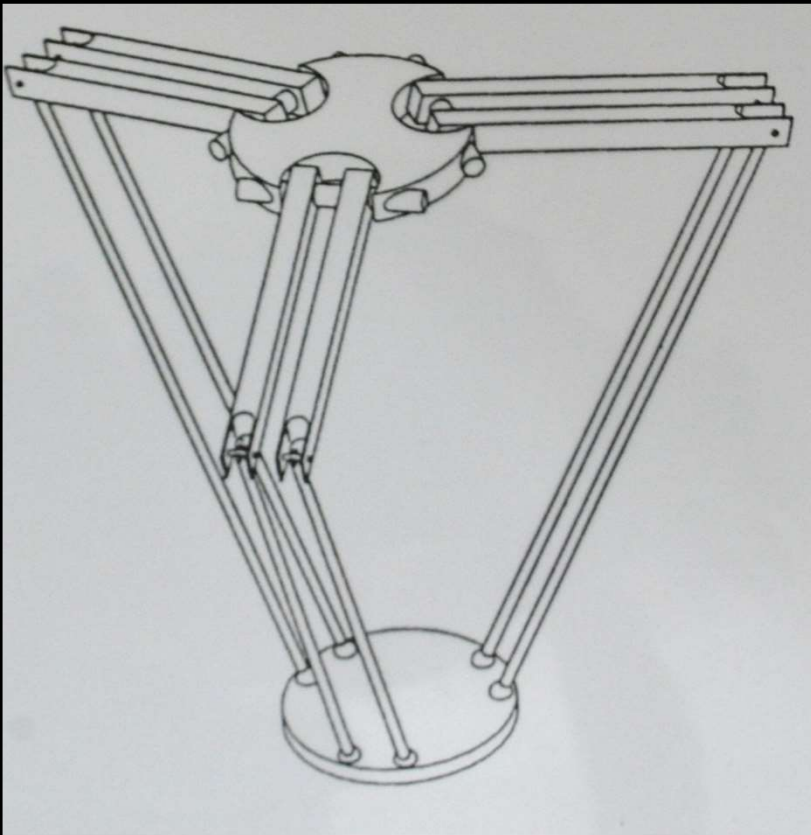


Hunt
Rotational Stewart

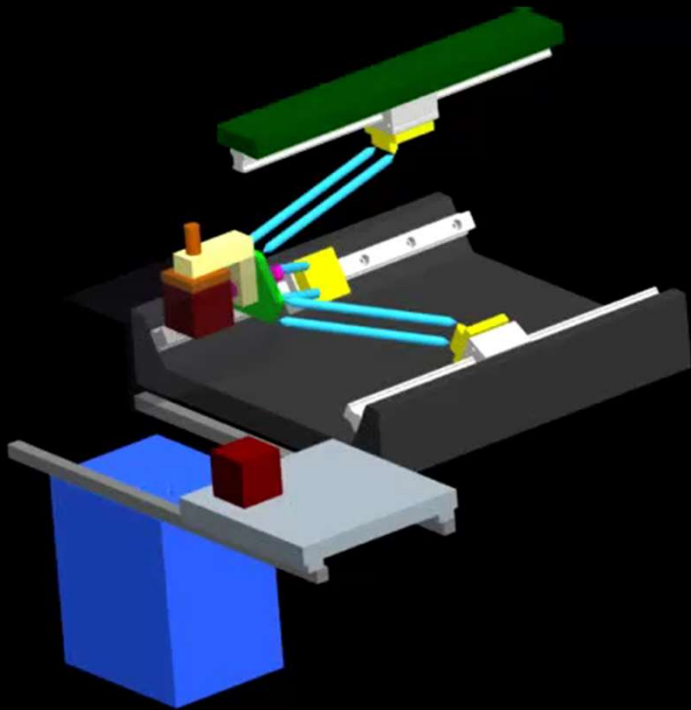
- «Artigue» has more **decoupled movements** than «Gough-Stewart» and «Hunt»
- «Artigue 2x2x2» is **even more decoupled** than «Artigue 3x2x1»
- All the **linear variants are stiffer** than the Rotational «Hunt»
- «Hunt» is **more dynamic**, has a **bigger workspace** than «Gough-Stewart»

Platform 6 DOFs inspired from the Delta

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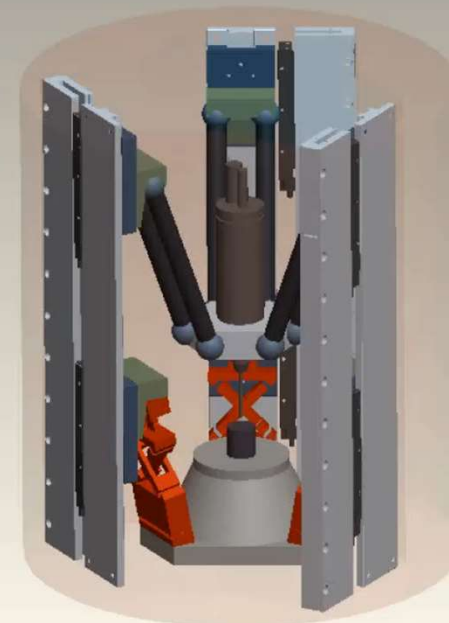


Hybrid solutions to obtain more DOFs



Parallel + serial

XYZ using the Delta linear + serial double-tilt
Ref. Unitechnology SA / Laser polishing



Right and Left Hand combination

XYZ using the Delta linear + Orion double-tilt + Z
Ref. Mecartex SA /Micro EDM