Parallel robotics
EPFL – Dr M. Bouri, 2021

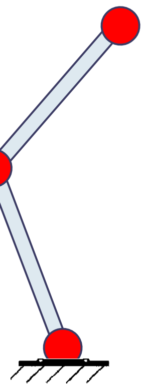
The course

- 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

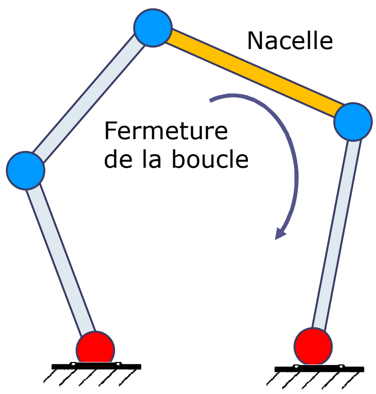
Serial robots

With **actuated segments in series**



Parallel robots

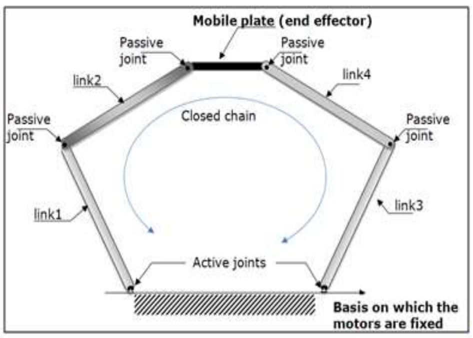
- ✓ Robots with closed kinematic chains
- ✓ All the motors are on the basis



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

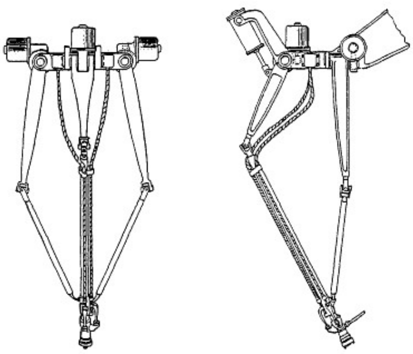


Close the chain and let us talk about parallel kinematics !

Parallel Robots

Since When?

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



[L. E. Rey, Environnement pour la conception de commandes de robots, PhD thesis, EPFL,1997]

Parallel link to <u>remote an actuator</u> and make the link stiffer

7

FANUC Robotics

Parallel kinematics….

8

The Most known

The flight simulator

The Gough Stewart platform

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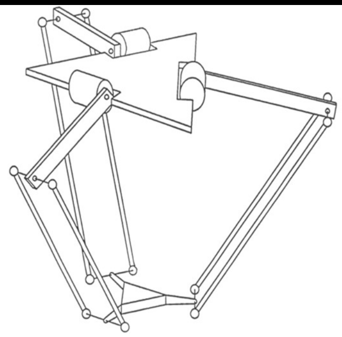
The robot "Delta" — 7 years : from the idea to the customer!

1985: Patented by R. Clavel (EPFL)

Principle



1988 – The patent is Sold to the Swiss company Demaurex SA (currently **Bosch Packaging Technology** Unit, Romanel).
1992– The first customer was Nestlé.

> Has been the **precursor** for the market of parallel robotics.

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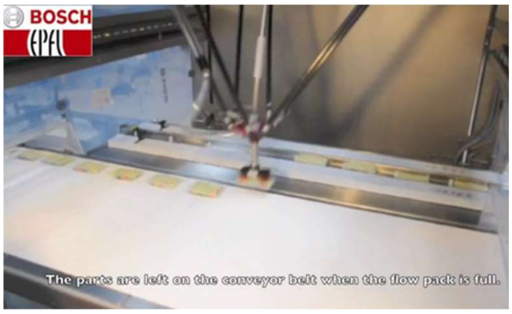
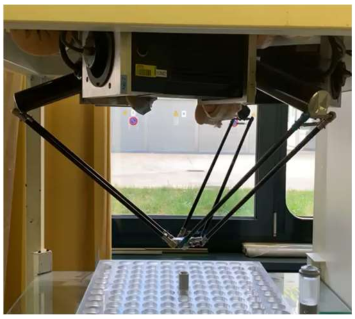
More than **200 companies** have adopted this kinematics since **2007** when the patent was in the public domain

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

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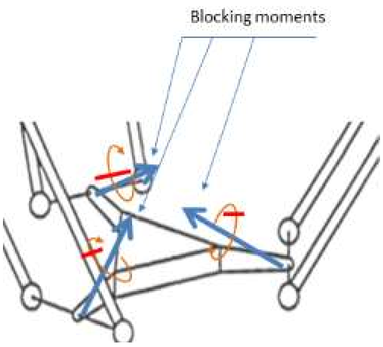
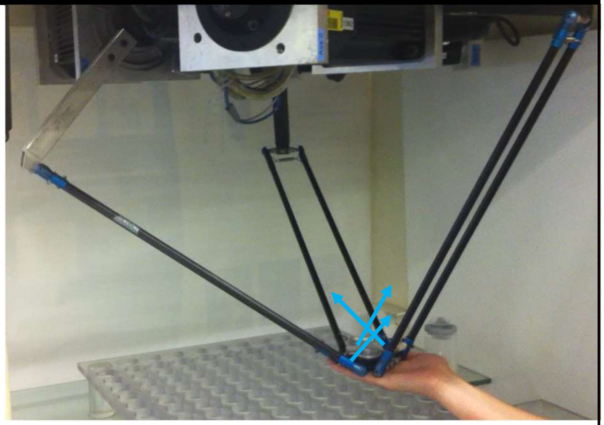
BOSCH Invented for life

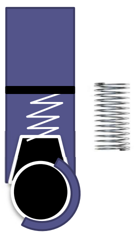
The robot "Delta"





- 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 spherical joints – The easiest way !



Another implementation

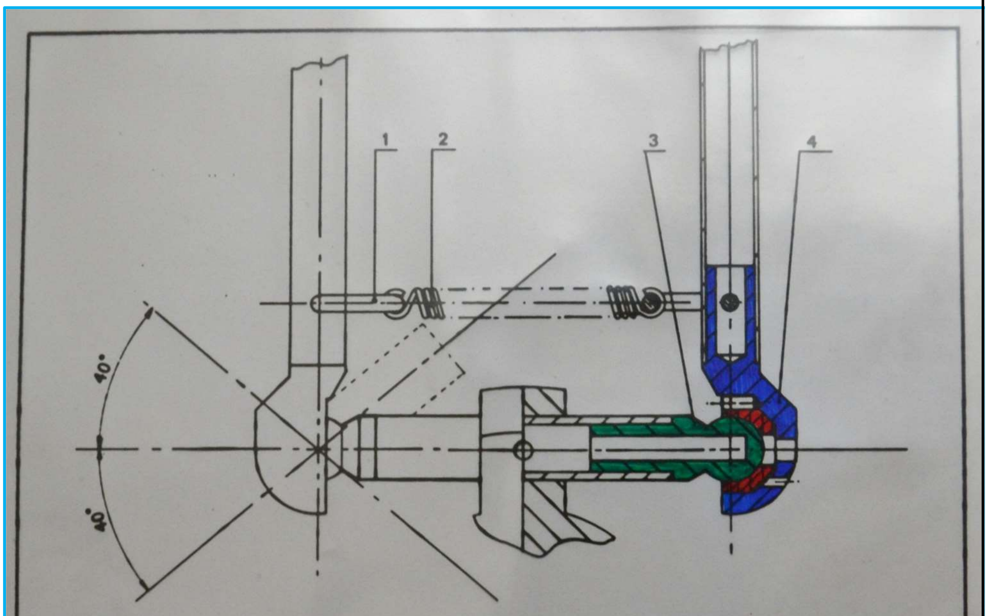


Fig.5. Detail of the construction of the arm - parallelogram joint.

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 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 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 allows 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 $\boldsymbol{MO = 6.n}$ (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:

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

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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.

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Mobility of parallel robots

Reminder: Representations of kinematic links

Pivot

Pivot (fr)
Pivot joint / Rotary joint (en)

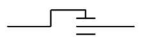
Cardan

Cardan (fr)
Universal joint / cardan joint (en)

Spherical joint

Rotule (fr)
Spherical joint (en)

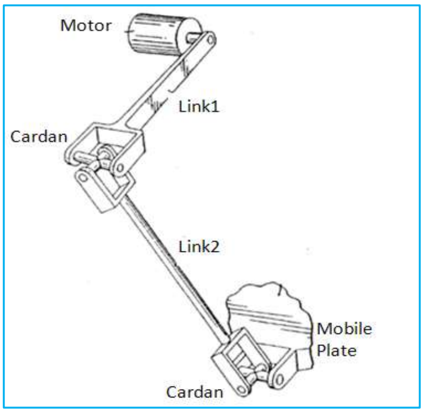
Prismatic joint



Example 1: Delta with cardans / universal joints): Exercise ☺

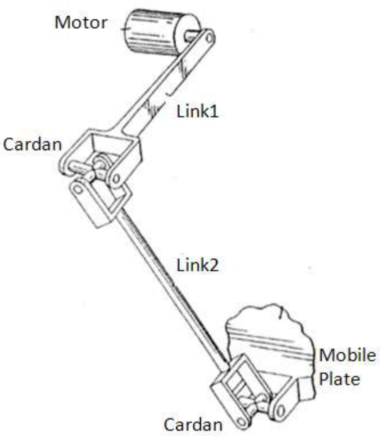
Example 1,

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

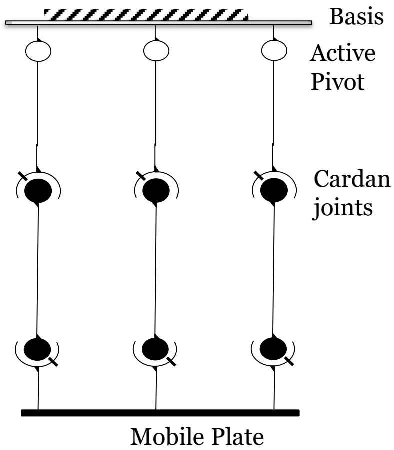


Representation of one kinematic chain of the cardan based Delta

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



Representation of one kinematic chain



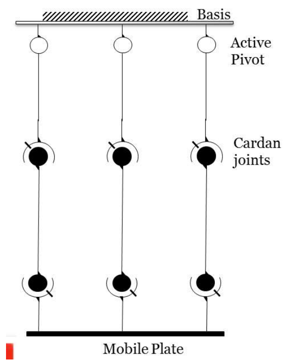
Delta with cardans: Calculation of the Mobility ☺

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:

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

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



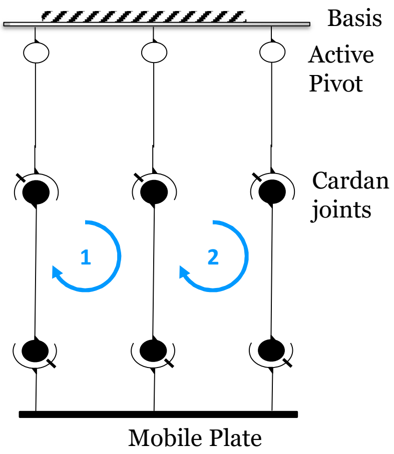
Delta with cardans: Calculation of the Mobility using the the llop formula ☺

Formula of kinematic loops

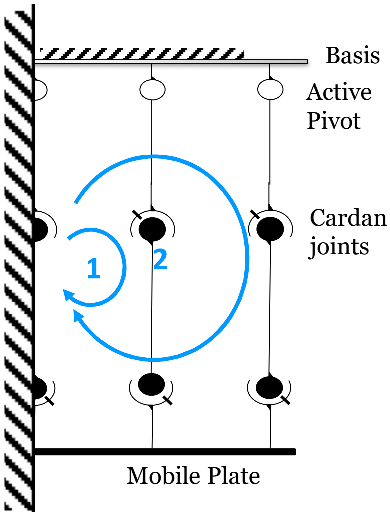
$$MO = \sum_{i=1}^{k} MO_i - 6bo$$

How to count the loops ?

1- Disjointed loops



2- Closed loops with same reference



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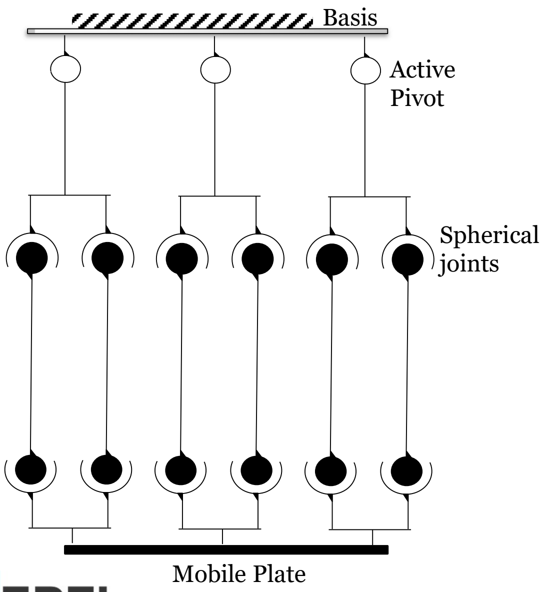
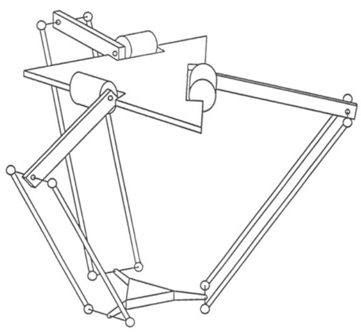
Example 2: The most common realization, Delta with parallel bars and spherical joints





- **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}.

$$MO = 6.(11 - 15 - 1) + \{1 + 4.3\}.3$$
$$= -30 + 39 = 9$$

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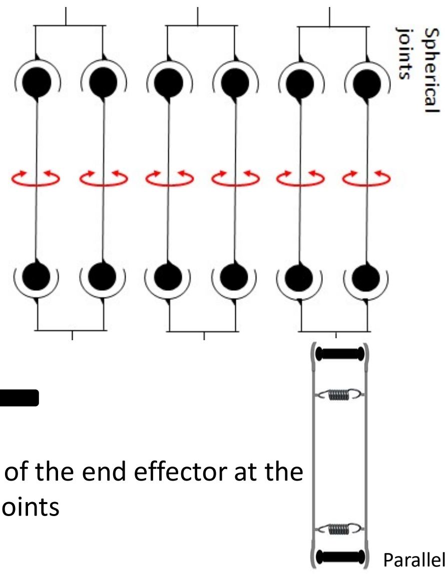
Observation

- 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

Delta with cardans ☺

Using cardans instead of a 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 ….

More DOFs

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

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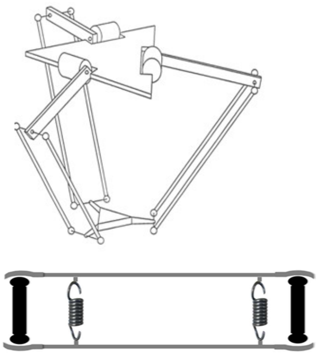
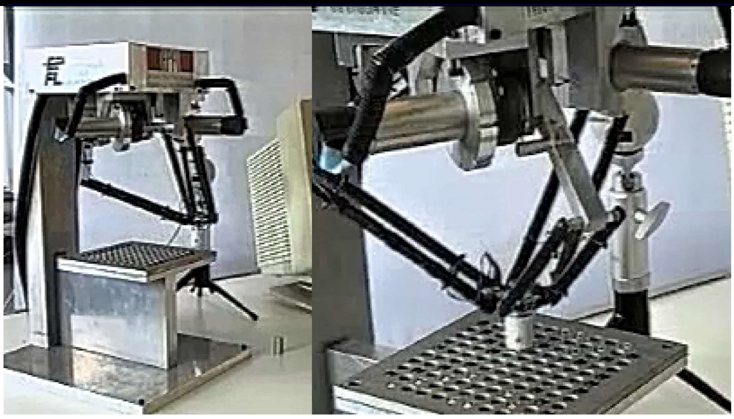
Simplicity of the Delta



Parallel bars



Motor + Gear Box+ Arm + Fore arms

Motor + Gear Box+ Arm + Fore arms

Motor + Gear Box+ Arm + Fore arms

+

Mobile plate

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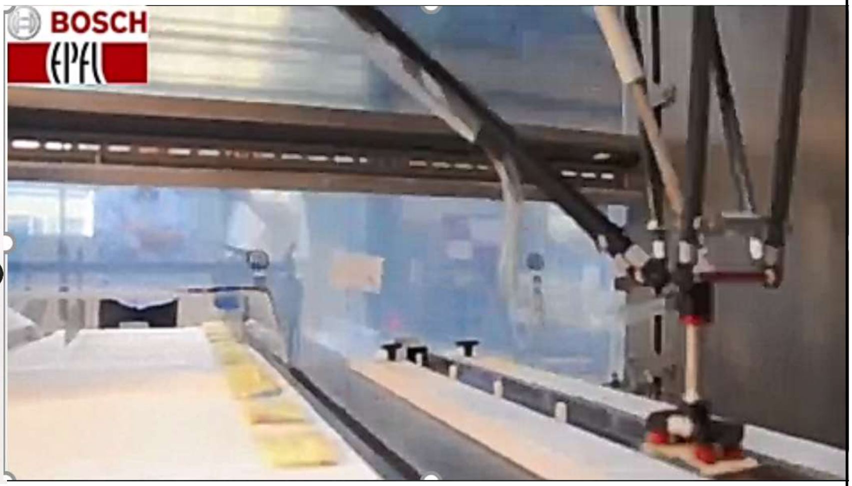
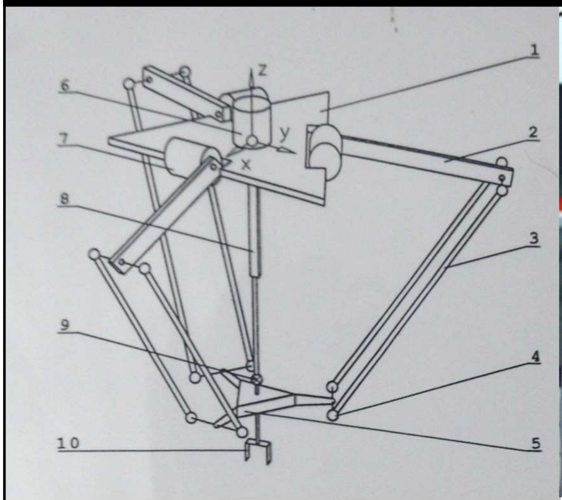
Even simpler without gearboxes : the trend

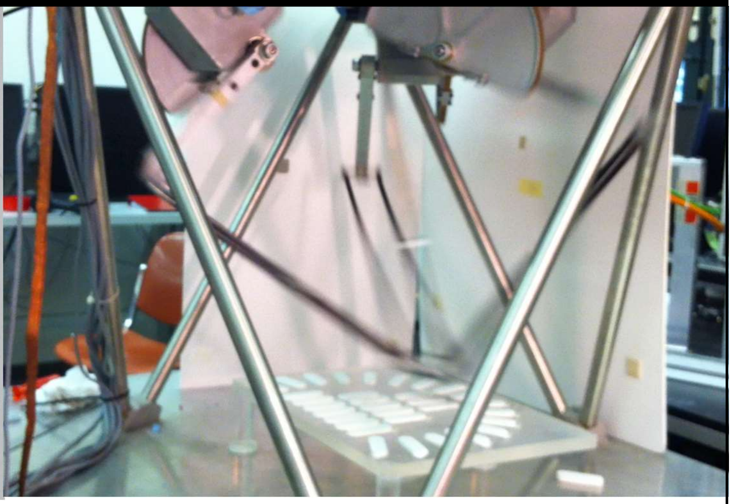
Direct Drive Actuated Delta realized for **BOSCH Packaging Technology**



[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

The Delta 4, with 4 DOFs



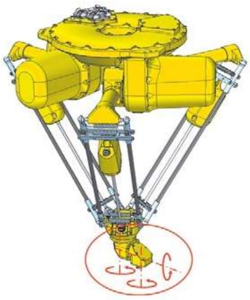


Angular Delta with **4 DOFs**

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.



Fanuc

ABB

Demaurex (the first manufacturer of the Delta)

Other companies are proposing parallel robots in their catalog:

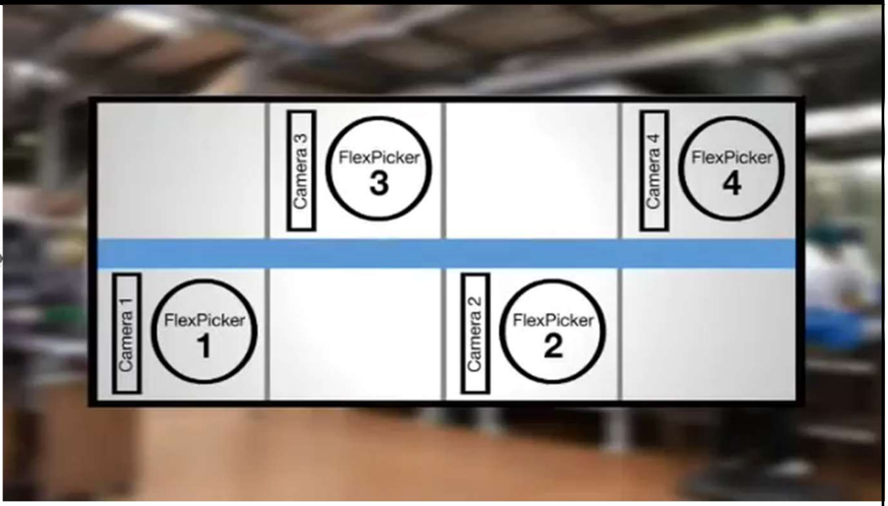
Fanuc Delta robots

6 axes

Omron robots

IP67

ABB - example



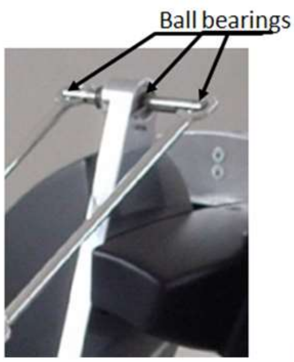
4 axes – Delta robot

Delta Omega: Parallel robotics for haptic feedback

How to reduce friction ? Bearings in series instead of spherical joints

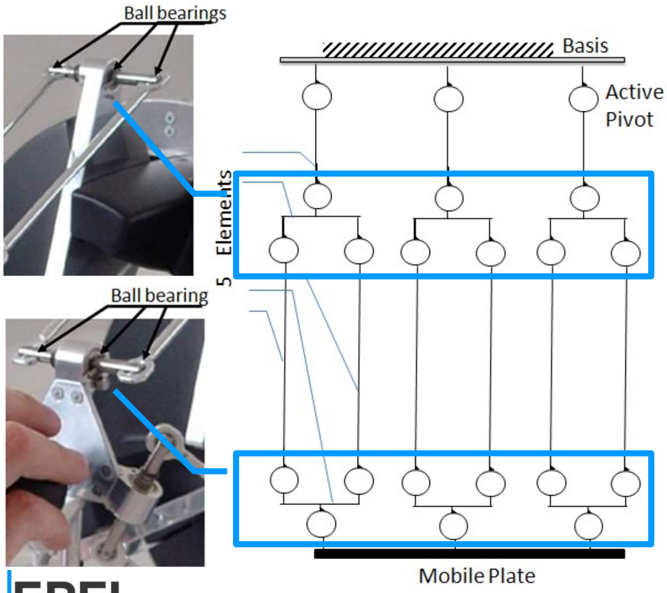
How to reduce friction while keeping big torques ? Cable transmission instead of gears

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



[Force dimension, CH, http://www.forcedimension.com/]

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}.

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

Over-constraint of order 12

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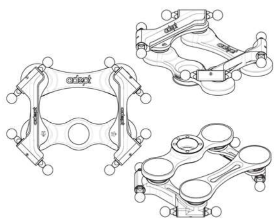
The Quattro – 4 DOFs from Omron (prev. Adept)

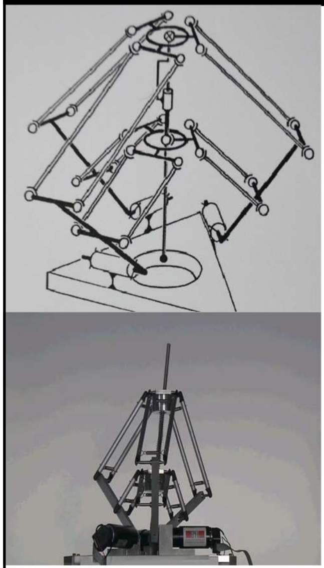
Parallel Robot (Delta Robot): Adept Quattro s650H

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.

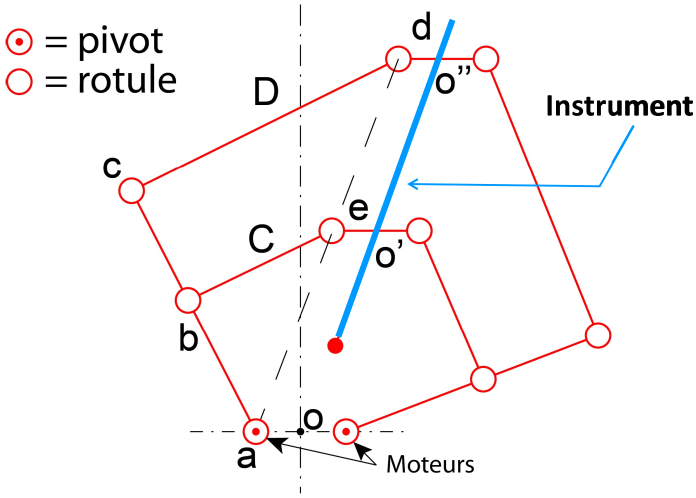
Figure 1-1. Adept Quattro s650H Robot



Thales … idea found an application !

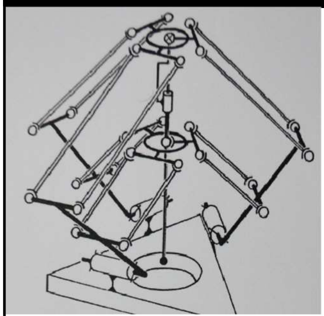


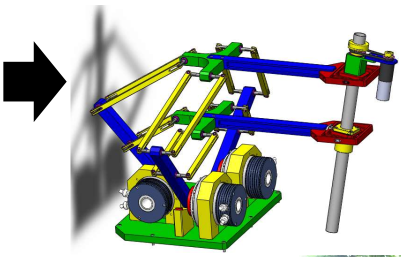
Initial kinematics



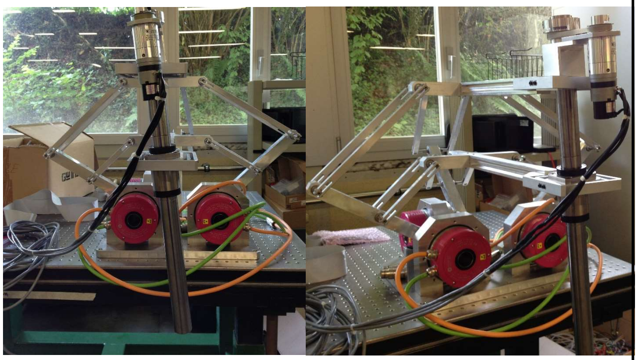
A spherical robot…..
1 translation (insertion) of the instrument
2 tilts (orientations) of the instrument

Thales … idea found an application for surgery!





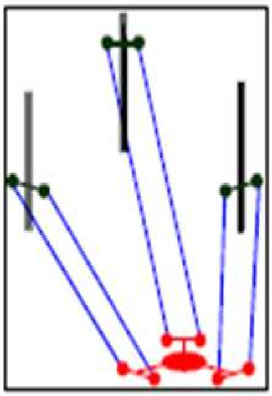
……for laparoscopic surgery with an **ex-centered** tool

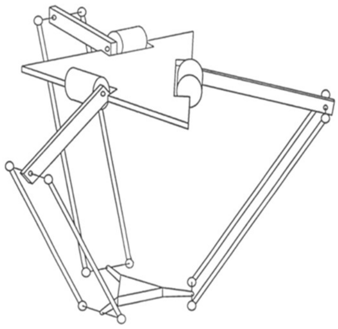


Linear Variants

Variants with linear movements

- for applications requiring stiffness.
- For applications requiring precision

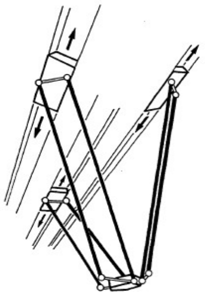


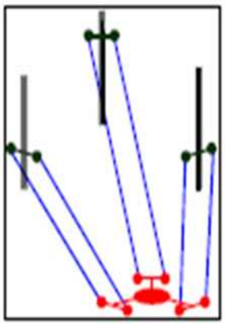


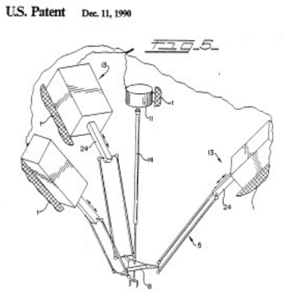
Linear versus Angular

- The speed of the linear variants **is only limited by the actuators**
- The stiffness of the 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.

Types of the linear Delta





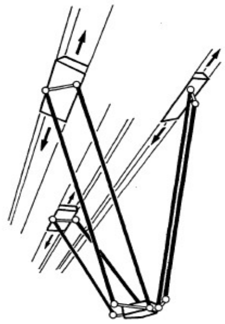


- Horizontal linear structure,
- Vertical structures,
- Orthogonal,
- Inclined guided

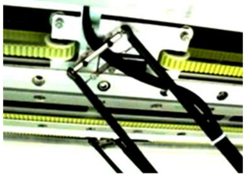
EPFL Bouri, M, and Clavel, R, "The linear delta: Developments and applications." *ISR 2010*

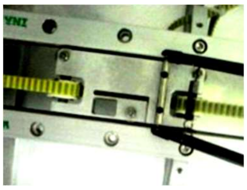
Developments and applications

The Horizontal family



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





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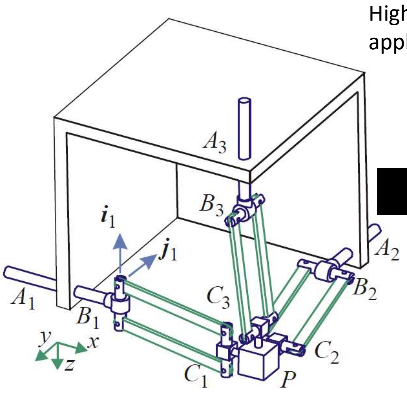
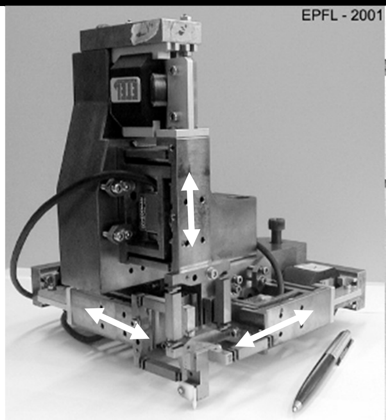
The orthogonal family



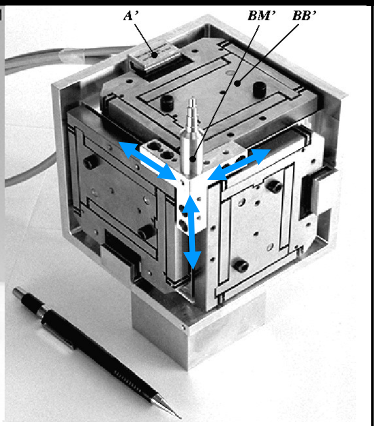
The orthoglide from IRCCyN

[!] Problem of the orthogonality of the three plans

High precision applications



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

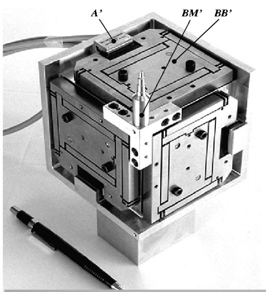
The orthogonal family

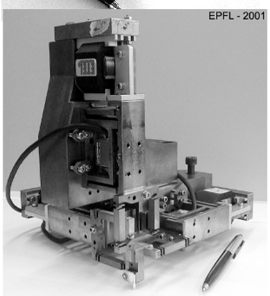
More details

This Delta structures called "**Delta Cube**" reach a repeatability of **+/-10nm**.

"**Delta Cube I**" that has a travel of +/- 1mm in each direction.

"**Delta** Cube II" has a travel of +/-4 mm in each direction with a proper frequency of 350Hz.



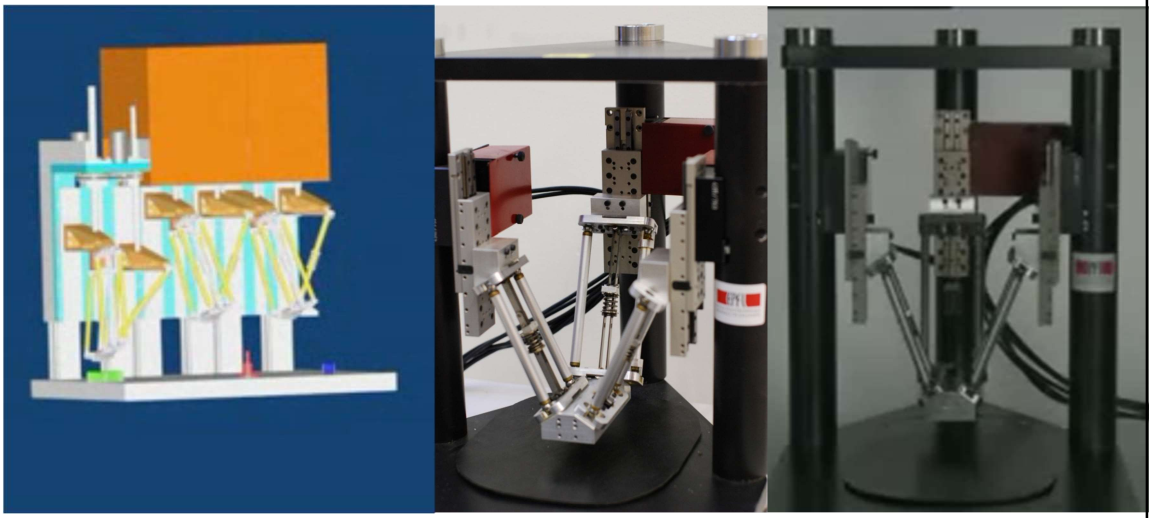


EPFL M. Bouri, R. Clavel [ISR 2010]

Developments and applications

The Vertical family

1. Assembly for microEngineering



Developments and applications

The Vertical family

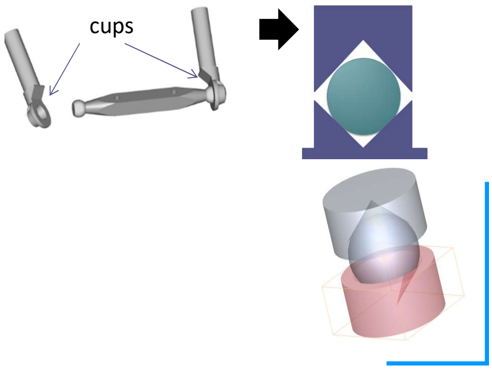
2. Towards PIN insertion for watch industry

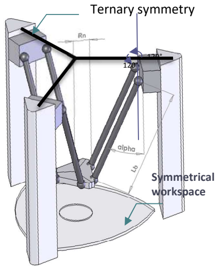
- Stiffnes
- Speed
- Simplicity

Modify the spherical joints

Adapt the parallel bars

Use ball screw to increase insertion forces up to 300N



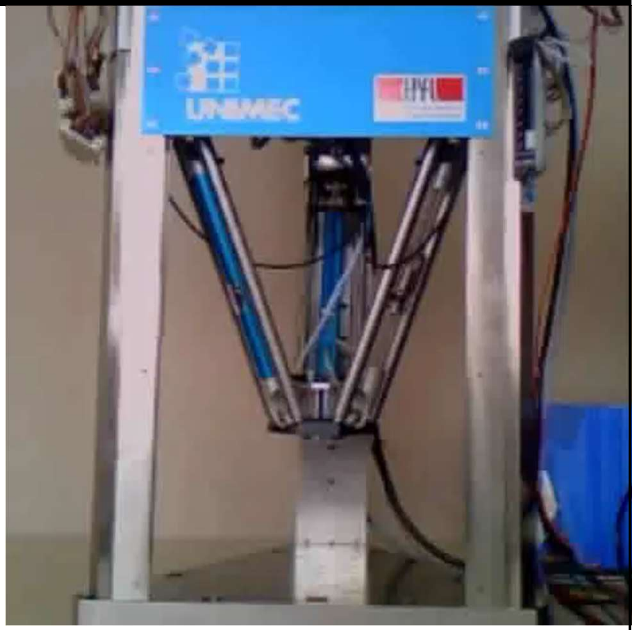


Developments and applications

The Vertical family

2. Towards Pin insertion for Watch Industry

Length of parallel bars:	*300 **mm***
Space resolution:	*0.1-0,25 **µm***
Vertical resolution (center):	*0.1 **µm***
Velocity:	*0.4 **m/s***
Acceleration:	50 ***m/s²***
Vertical force:	≤ 350***N***
Stiffness:	50***N/mm*** ***(5.10⁷N/m)***
Working space:	ϕ = *240 – 280 **mm*** H = *80 **mm***



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Developments and applications

The Vertical family

The Inclined **Keops-** Advantage 1

Workspace .vs. robot size

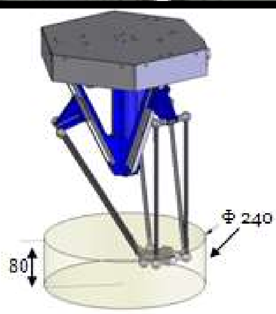
Resolution on the linear axis is **7.5 µm**;

the worst resolution in the workspace is

better than **20µm**;

the velocity can easily reach **3.5m/s** at

the acceleration value of **3.5g**.



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Developments and applications

The Vertical family

The Inclined **Keops-** Advantage 2

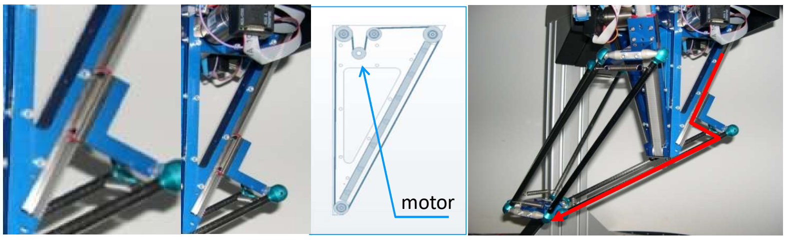
Simplicity

The Inclined **Keops-** Advantage 3

Stiffness at the **extremity** of the volume

What else…

1µm - sensors integrated to Schneeberger guideways.



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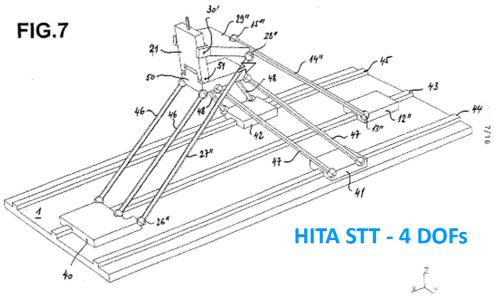
Developments and applications

The Horizontal family - Tool Machining

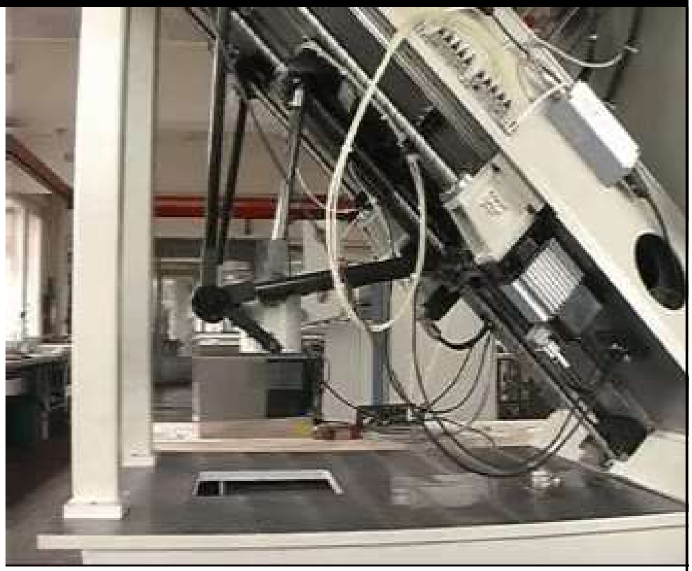
FIG.7



HITA STT - 4 DOFs

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

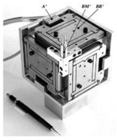
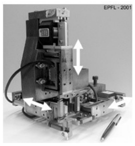
STT: Stiffness Tracking Technology.



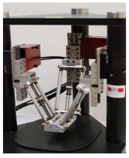
HITA STT, EPFL, 4 DOFS / XYZ and one tilt
[ref Willemin Macodel]

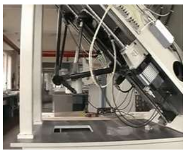
EPFL

Plenty of Δ -structures…..

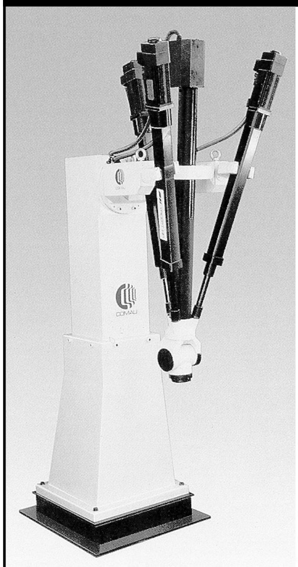



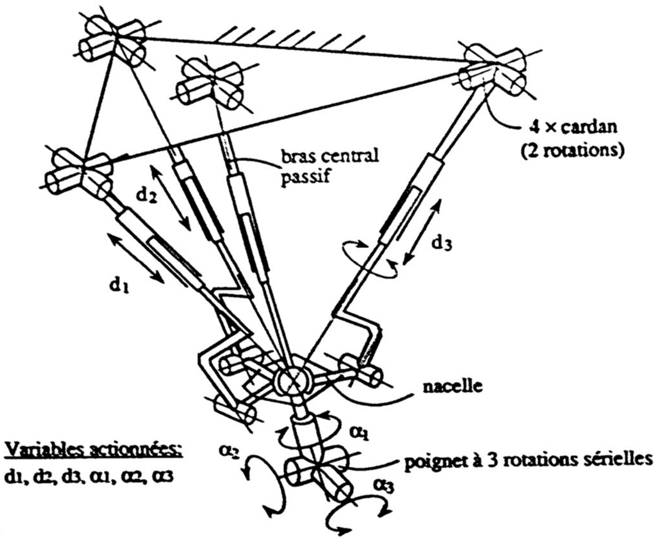






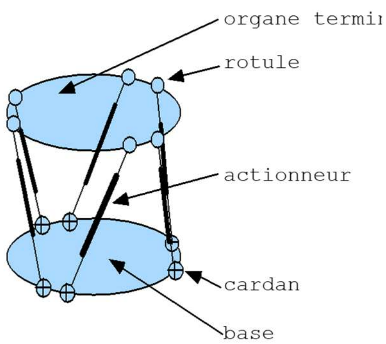

The Tricept (Tetrabot)



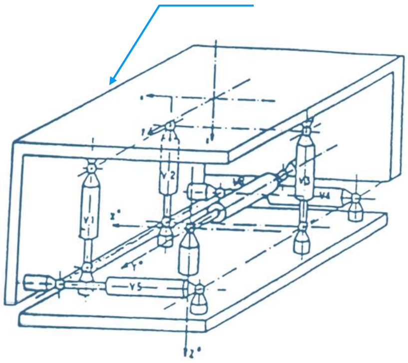


Platforms 6 DOFs

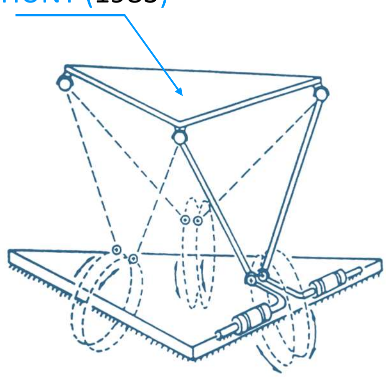
GOUGH-STEWART (1962)



ARTIGUE (1984) and HUNT (1983)



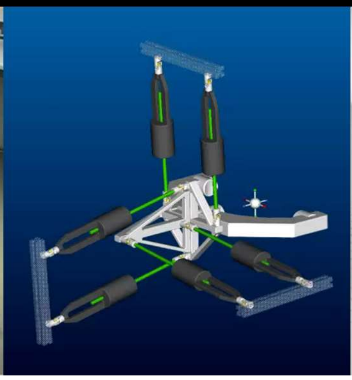
- Decoupled for small motions



- 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