A Few Guidelines for the Design of Surgical Robot Arms

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Surgical Robot Arms: Master & Slave

Outline

- A safety point of view
- Robot Arms
  - Classical Serial Arms
  - Not-so-classic Serial Arms
  - Parallel Arms
- Multi-purpose system?

A Safety Point of View

SURGEON

- Efficient natural sensors
- Dexterity
- Coordination
- Capacity in reasoning and learning
- Adapting his skills

~~- Subject to fatigue~~
~~- Stability~~
~~- Precision~~
~~- Unable to see through tissues~~
~~- Subject to radiations~~

ROBOT

- Geometric accuracy
- Precision in controlling forces
- Possibility to work in hostile environment
- Repeatability
- No fatigue
- Stationarity
- Rapidity

~~- Weak capacity in deciding, learning, adapting~~
~~- Incomplete models~~
~~- Reliability~~

Better accuracy
Safety increased
Trauma decreased
Decreasing number of interventions
Post operative comfort and fast recovering

So what ?

In contact with human body

- **Specific functionalities**
- **Easily movable**
- **Optimal size**
- **Manually controllable**

- **Unstructured environment,**
- **No repetitive tasks,**
- **Sterilization of the components…**

Specific safeties

Specific kinematics

Industrial *versus* medical robots

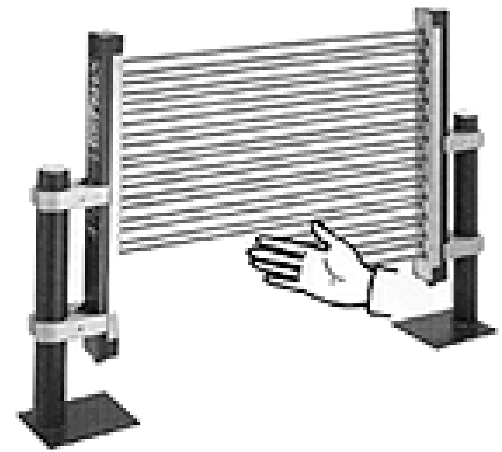
Industrial Robots

- Isolated from the workers (appropriate training to interact with them) by preventing machine workspace from human intrusion
- Possibility to enter in the workspace (for maintenance purpose or learning procedures) without stopping the machine:
  - Disconnecting of the protection devices
  - Activating the "manual mode" with limited speed

Medical Robots

- Medical robots cooperate with the human (surgeon and staff) and interact the patient
- Harsh constraints and specifications in the design itself, especially for active medical devices
- Influence of human factor and clinical constraints specific to mechanical devices for medical purpose

Typical Safety Tools in Industry



Safety: Human Factor

- Work done on human being:
  - Change in working conditions with each patient (characteristics of soft tissues, position of the patient on the operating table, size of the body and accessibility of the organs,…)
  - Task and execution specific to a patient: no “trial/error” nor “doing again” movements
- Robot directly in contact with the patient and staff:
  - Necessity of preoperative studies to plan the intervention
  - Modification of planning during the operation itself, according to the surgeon diagnostic, possible complications or patient organism behavior
- Surgeon is not “robotic specialists”:
  - Dedicated user-friendly HMI: task-oriented, allowing an easy manipulation of the system
  - Robot transparency: avoiding singularities, mechanical joint limits, reconfiguration procedures,…

Safety: Clinical Constraints

- Every component of the system in contact with the sterile field must be sterilized (generally, the robot is covered by a sterile sleeve while the tool is separately sterilized by an autoclave procedure);
- Environment is usually unstructured: operating rooms are cluttered with several other medical systems (radiology, anesthesia, surgery, etc.). The robot position with respect to the patient varies between two operations and even a single operation. Thus, its dimensions have to be reduced;
- The robot has to be easily and quickly transportable in and out of the operating room
- Required functionalities are defined according to each kind of clinical operations ➔ new medical robots have often been designed for specific operations;

Dependability

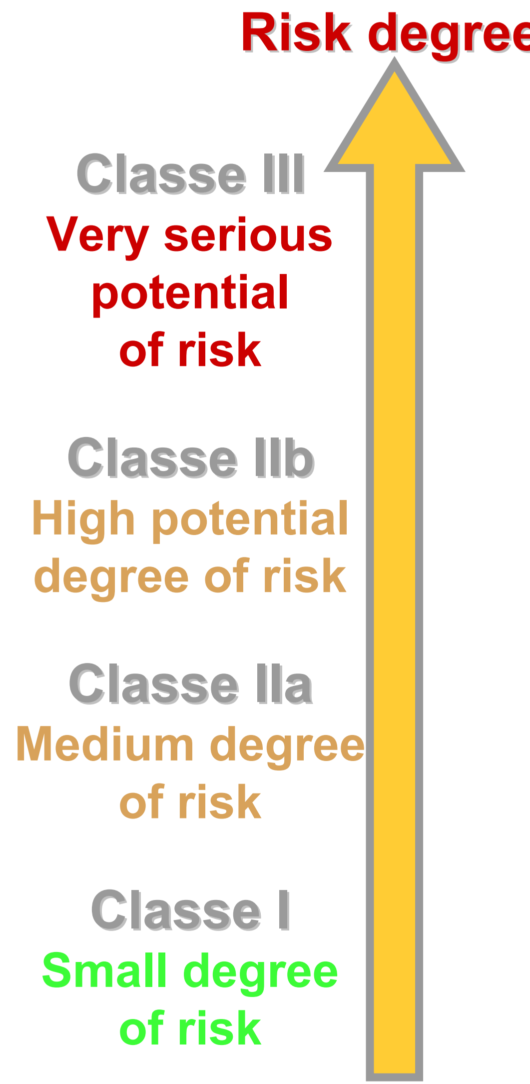
- Any failure $\Rightarrow$ very critical.
- Medical robots must function safely and with high reliability.
- 6 attributes of the concept of dependability :
  - Safety
  - Reliability
  - Availability,
  - Confidentiality,
  - Integrity,
  - Maintainability.

Safety rules: European Directives

- In European Community: ISO 9000 norm has been modified to comply with the specific constraints of medical devices in the European directive 93/42/CEE.

- CE marking: the EN 46000 certification enacts the various criteria necessary to classify all the medical devices according to four classes.

- Device classification depends on:
  1. its life span use: from a few minutes (temporary) to several years (implantable)
  2. its invasiveness or non-invasiveness
  3. its surgical or non-surgical use
  4. its activeness or inactiveness
  5. the vital or non-vital body parts concerned by the device



Emerging of a strategy ?

- In these directives, the “medical device” denomination includes several kinds of products such as drugs, compresses, electrical apparatus, mechanical devices, surgical or radiological tools,…

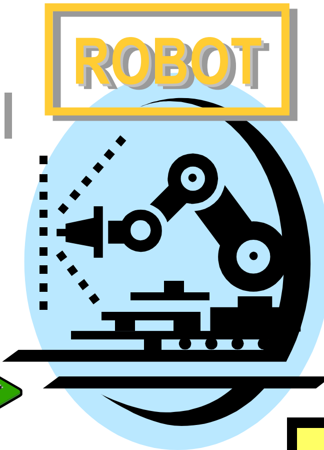
- Elementary rules for designing a “safe” surgical robot:
  - **No uncontrolled motions**
  - **No excessive force on patient**
  - **Keep the surgical tool in a predefine workspace**
  - **Supervision by the surgeon of any motion**

- To guarantee a high level of safety, a medical device such as a robot may be designed considering the main following principles:
  - The degree of redundancy in control and sensing
  - The possibility to design an intrinsically safe system (i.e. capacity to decrease the maximum level of risk by construction)
  - The tradeoff between reliability and safety. (… and cost)

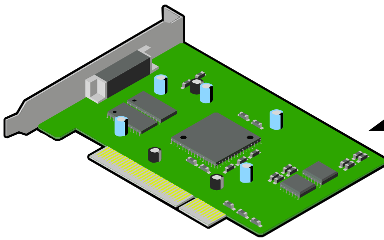
Emerging of a strategy ?

- Safety concepts based on three rules:
  1. Redundancy in sensor and control,
  2. Intrinsically safe components
  3. Reliability in design.

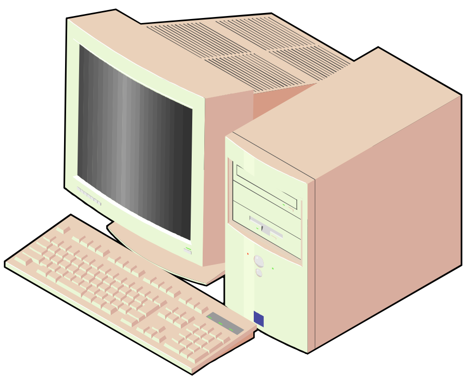
- Along three axis:
  1. At the electromechanical level
  2. At the hardware level
  3. At the software level



Hardware level (electrical)



Mechanical Level

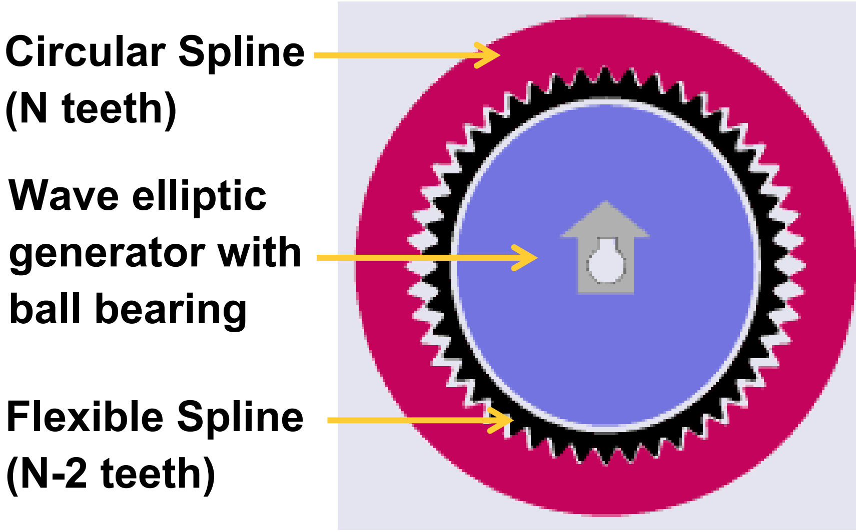


Software level

Electromechanical concepts of safety: Intrinsically safe components (1)

- Limitation of actuator power to satisfy only the required tasks better than simply using software thresholds to restrict payload, forces, torques, velocity and acceleration.

- Use of high reduction gears such as harmonic drives (high efficiency and low backlash) reduces the robot's velocity. But high reduction ratios $\Rightarrow$ non back-drivable structures :
  - Required (in neurosurgery for instance)
  - Unacceptable (in remote MIS applications).



Electromechanical concepts of safety: Intrinsically safe components (2)

- For systems applying effort: when the robot force becomes too important, a mechanical system ("mechanical fuse") enables to quickly drop the tool. (On AESOP, the collar linking the endoscope and the arm is quickly disconnected thanks to a magnetic connection).

- Joints may also be equipped with mechanical torque limiters mounted on the motor shaft (e.g. Neurobot or Hippocrate): when a link collides with an obstacle during a motion, it stops moving while the motor shaft still rotates.

Electromechanical concepts of safety: Intrinsically safe components (3)

- In case of power breakdown or emergency stop, parking brakes mounted on selected joints prevent the robot from falling down under gravity effect.
- However, this technical choice presents a main drawback: when the user has to manually move the arm without actuator control, the brakes have to be released. Besides, many robots tend to vibrate a bit when brakes are applied.
- As an alternative to this solution, gravity compensation may be fulfilled by a passive counterbalancing payload or by a full irreversible structure

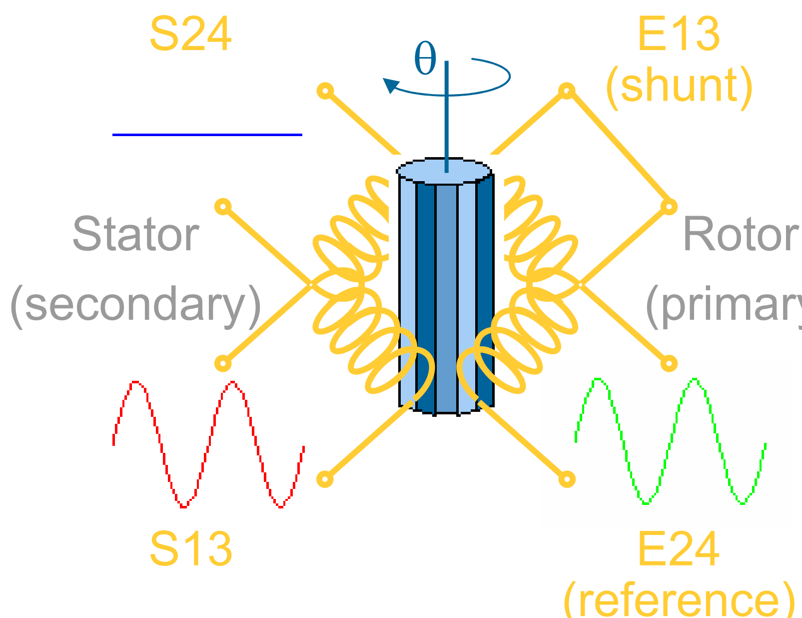
Electromechanical concepts of safety: Redundancy of sensors (1)

- Decreasing the hazard rating ⇒ Increasing information and improving control by using redundant and independent components.

- Examples:
  - Stereotactic neurosurgery during the needle insertion phase ⇒ duplication of joint brakes to prevent any breakdown effect
  - In Image Guided Surgery applications ⇒ using both independent active and passive marker-based tools to improve the reliability of the tracking system (e.g. cameras coupled with a Computed Tomography system)

Electromechanical concepts of safety: Redundancy of sensors (2)

- Avoided time consuming and potentially hazardous initialization procedures by using:
  - one absolute joint position sensor
  - a combination of two relative encoders (one sensor mounted on the motor output shaft and the other mounted on the joint axis)
- Examples:
  - two resolvers (Hippocrate, SCALPP,…)
  - one incremental encoder associated with an absolute encoder (Robodoc)
  - one incremental encoder associated with potentiometer (NeuroSkill robot, SCALPP,…).
- Redundancy of sensors also used for the arm control: e.g. information on the joint velocity deduced thanks to the coarse sensor.



Electromechanical concepts of safety: Mechanical design (1)

- Avoid the risk of wrenching or cutting wires, by shielding and integrating all leads inside the links of the robot arm.
- Limiting the working envelope by using mechanical joint limits: physical threshold (+ software threshold).
- Computer Aided Design analysis for selecting robot location
- Kinematics concept:
  - Adapting the number of dof to the required task workspace
  - … or use redundant kinematics to avoid collision and increase dexterity (for instance, in MIS or in neurosurgery)
  - Fit link dimensions to preserve patient and clinical staff safety
  - Kinematic models:
    - Avoid numerical or polynomial resolution methods and prefer analytical ones
    - Reject wrist and shoulder singularity configurations out of the workspace as much as possible

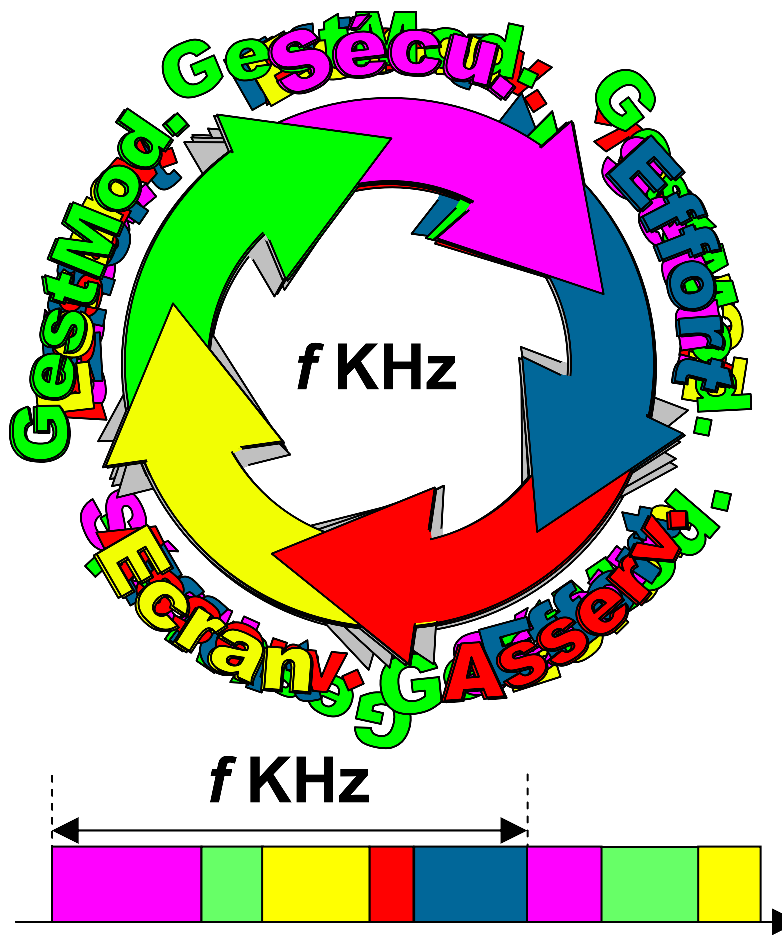
… Many other issues in …

- Safety at “electrical level”
  - Intrinsically safe components
  - Redundancy
  - Wiring techniques
  - EMC … and so on
- Safety at software level
- Safety at system monitoring level

(see IEEE Magazine for more on that …)

Software concepts of safety: Real-time controller

- Design the controller as concurrent processes dedicated to specific tasks: security, Cartesian control, joint control, communication with peripheral units and sensors, HMI communication,…
- By tuning the process and variable priorities, an appropriate emergency procedure is switched on as soon as an error is detected. For instance, the dedicated security process may have the higher priority.
- ➔Stable computation time ➔closed-form solutions for models.



Safety … then what ?

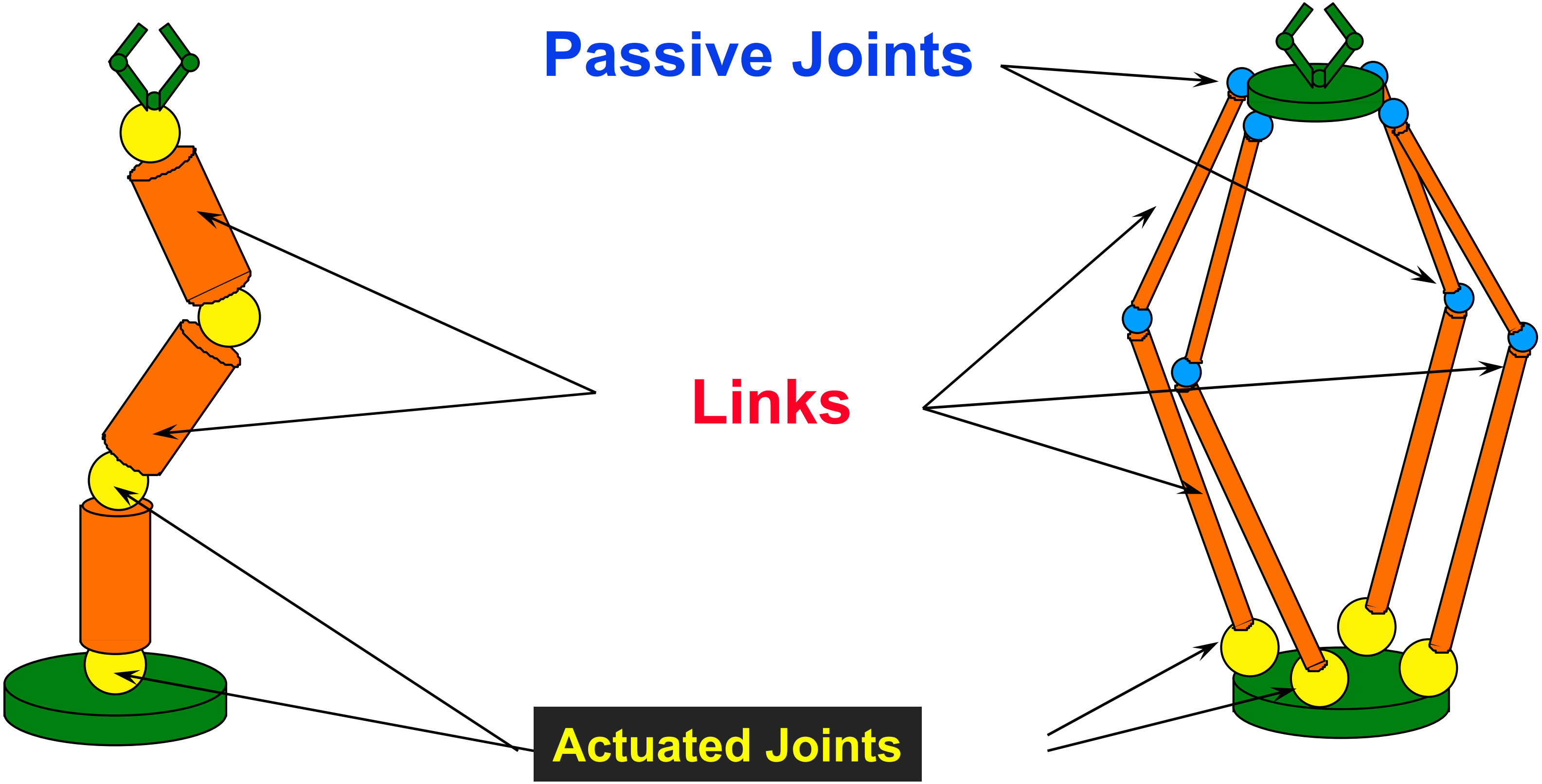
With safety in mind, you still have to select which arm to use…

A classic (means: serial)?

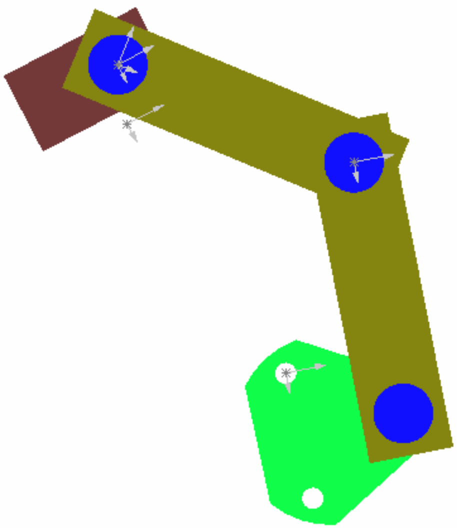
A not-so-classic?

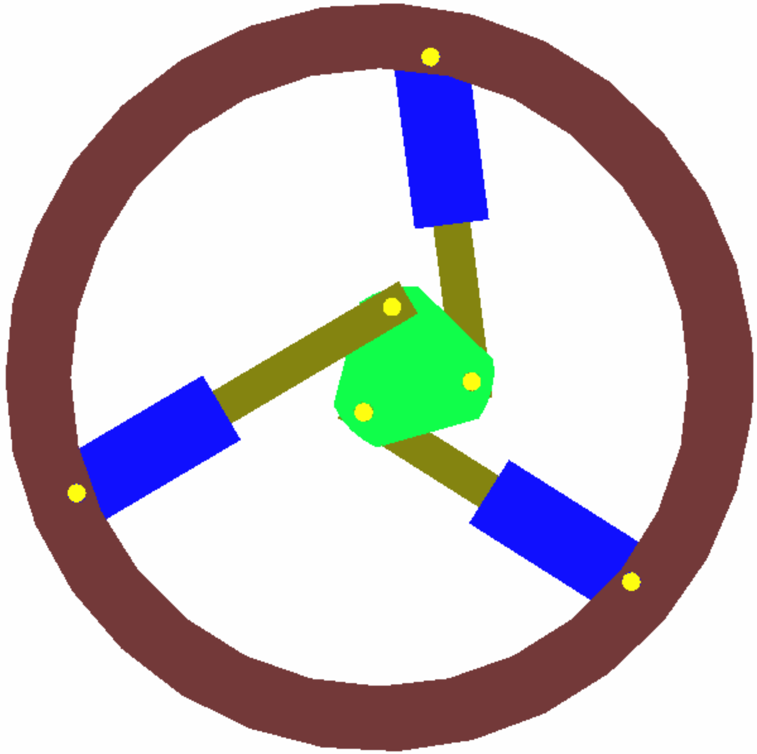
A PKM?

PKM versus Serial

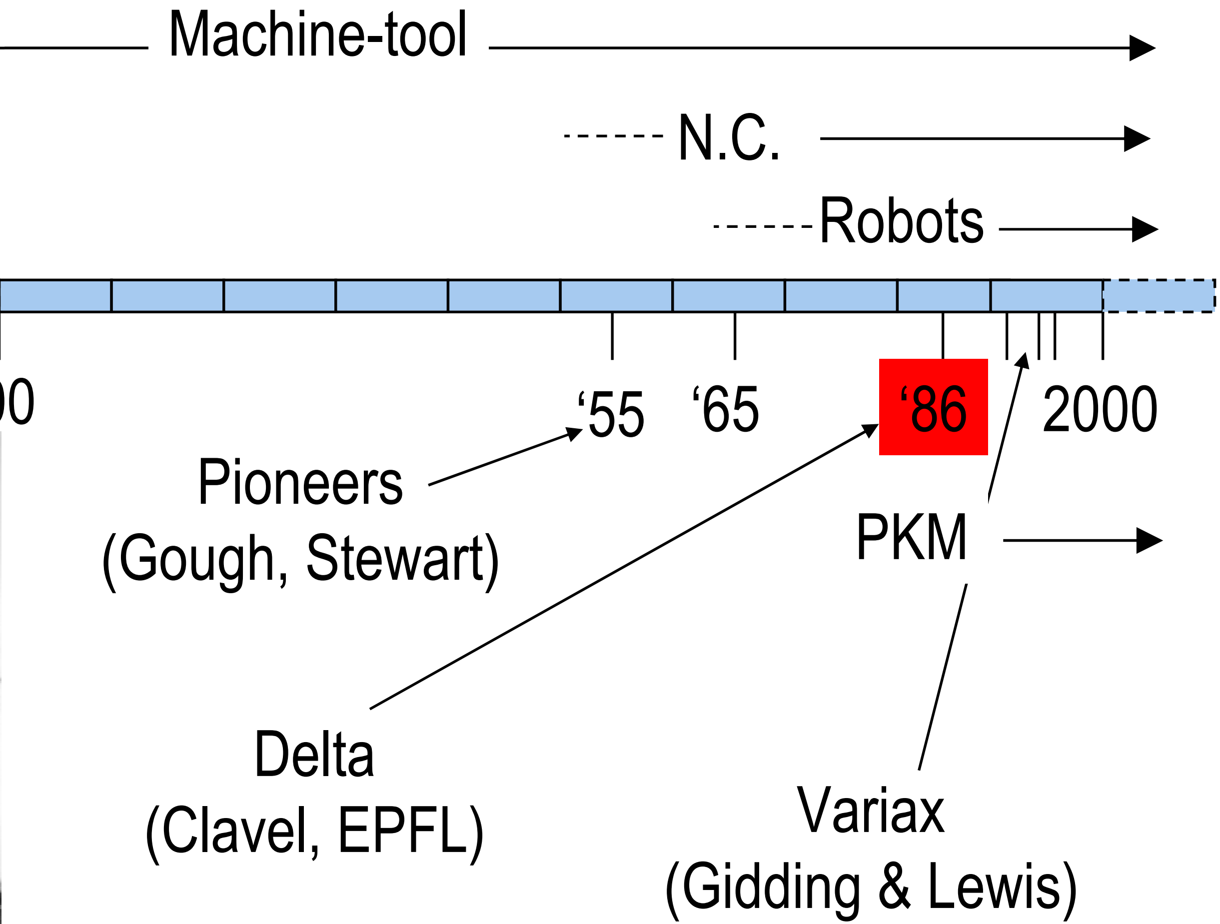


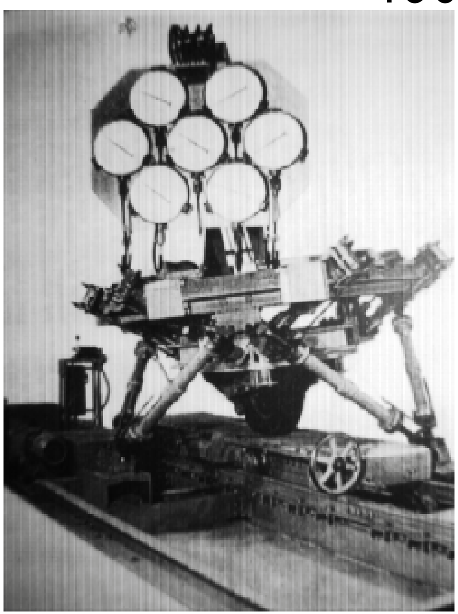
PKM & Serial in Motion





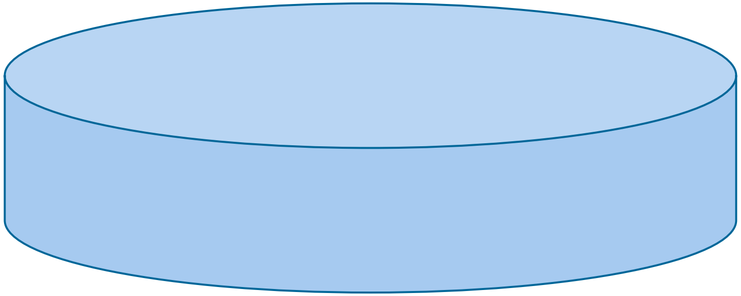
Historical Perspective

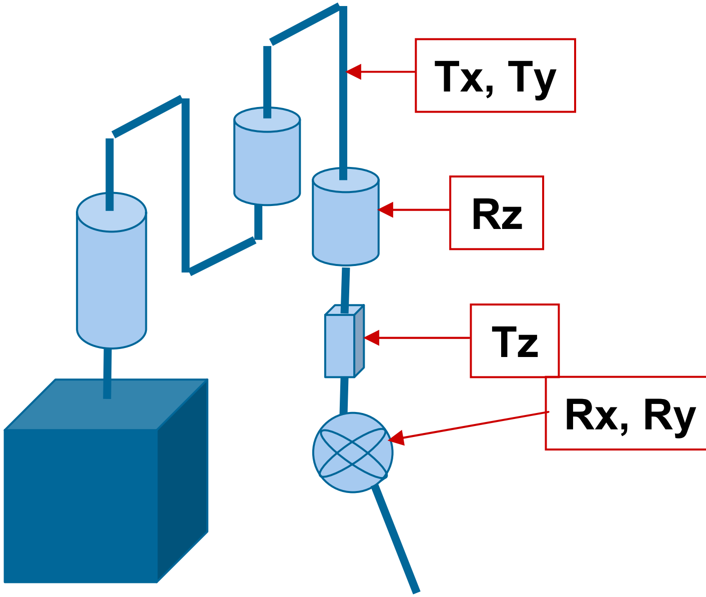




Classical Serial Arms

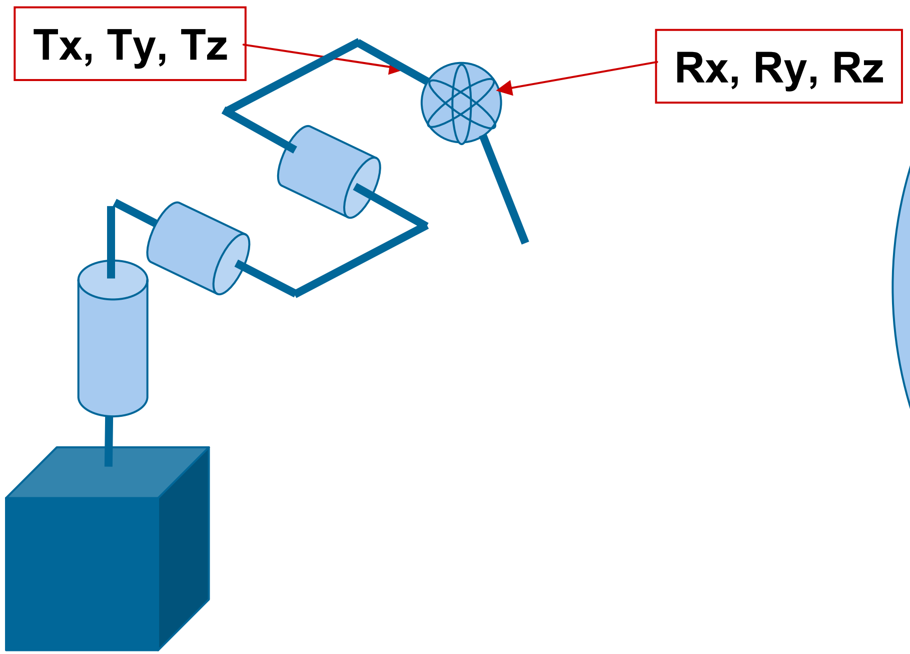
- Two important "families":
  - Scara
  - Anthropomorphic
- Scara:
  - Comes from "pick-and-place" applications
  - 4 dof + possible 1~2 dof "wrist"
  - Workspace ⇔ "flat" cylinder

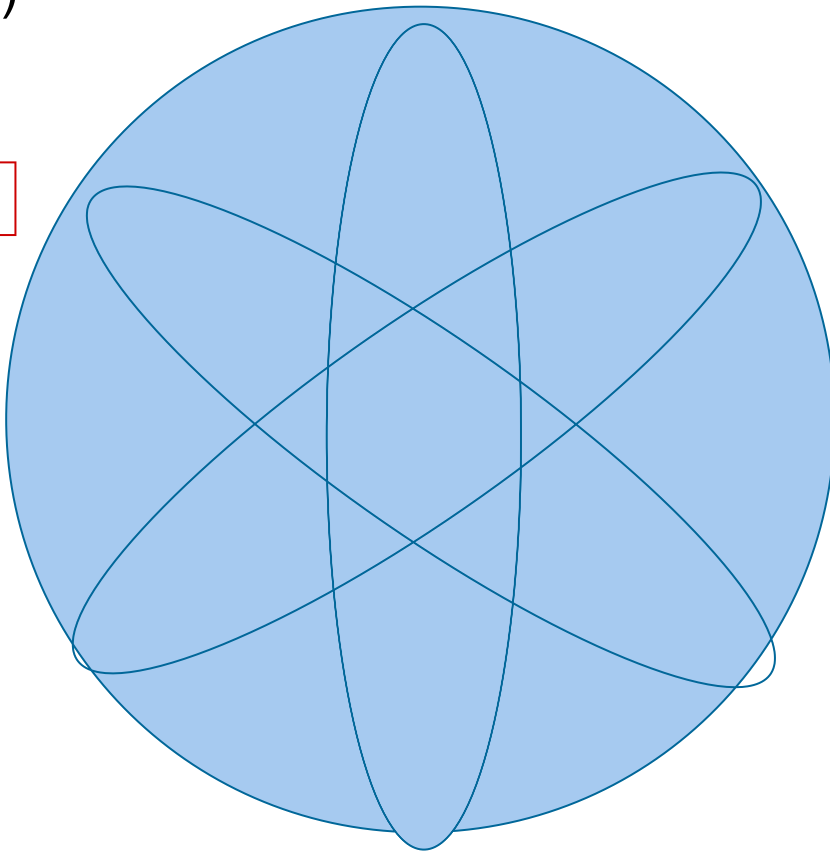




Anthropomorphic

- Anthropomorphic Arm
  - Comes from automotive industry applications (painting, welding)
  - A carrier (3dof) + a “wrist” (2~3dof)
  - Workspace ⇔ a sphere



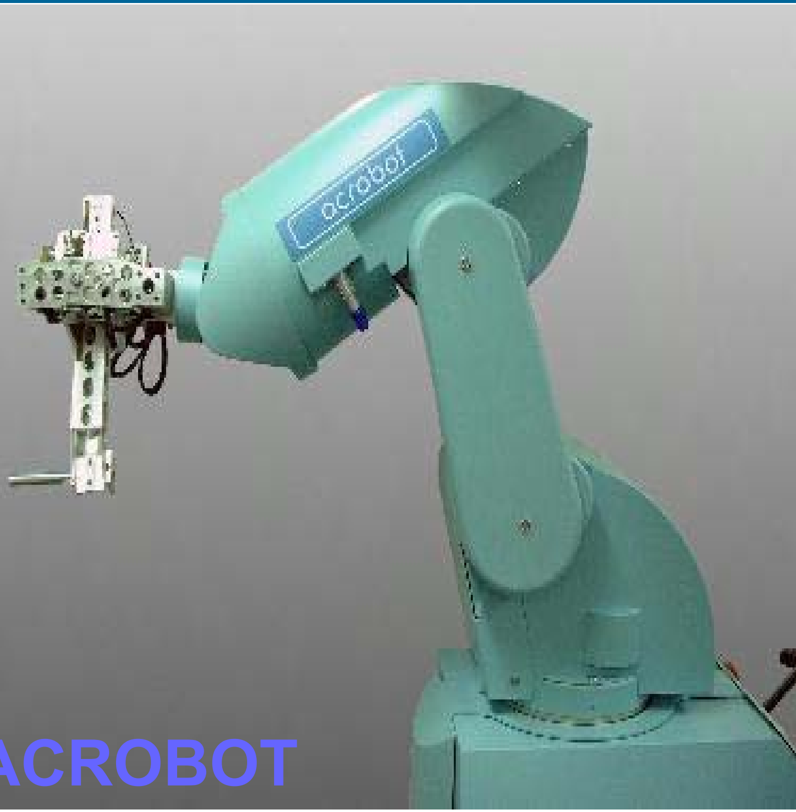


Scara & Anthropomorphic in Surgery

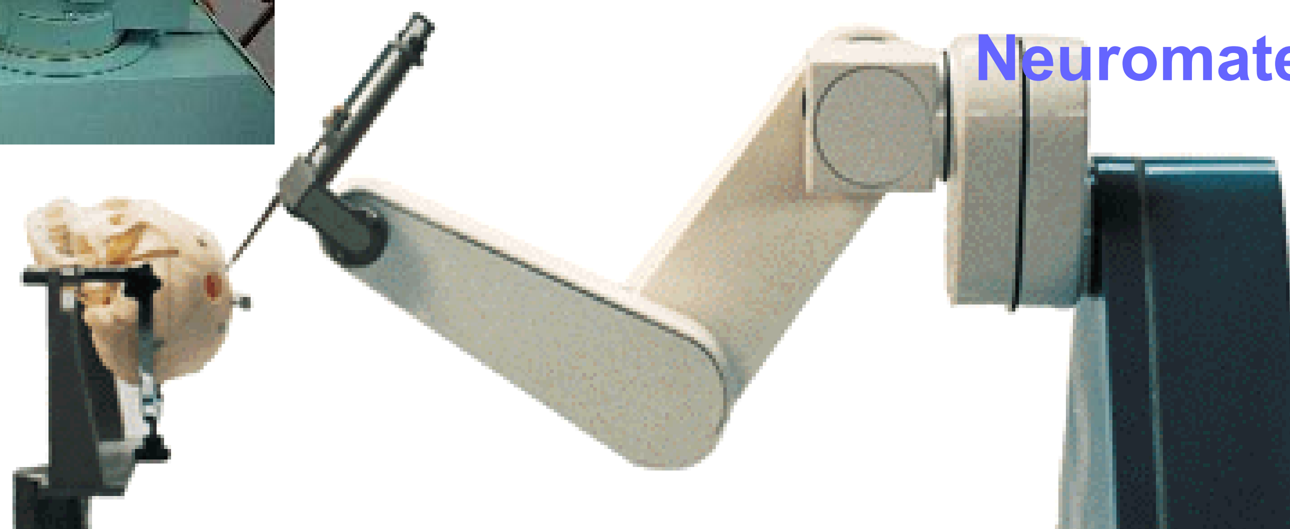
Scara

Anthropomorphic

Scara & Anthropomorphic in Surgery

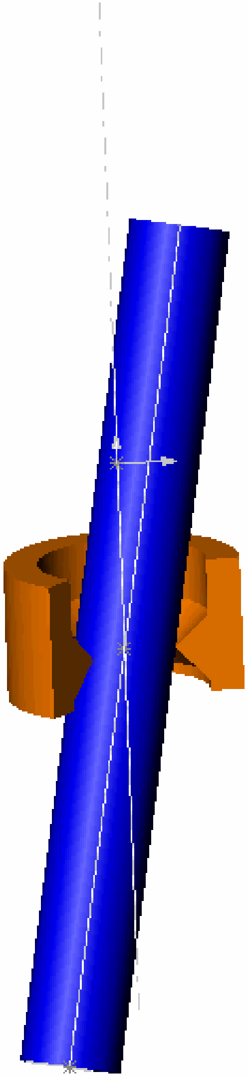


Anthropomorphic
Or
Anthropomorphic-like



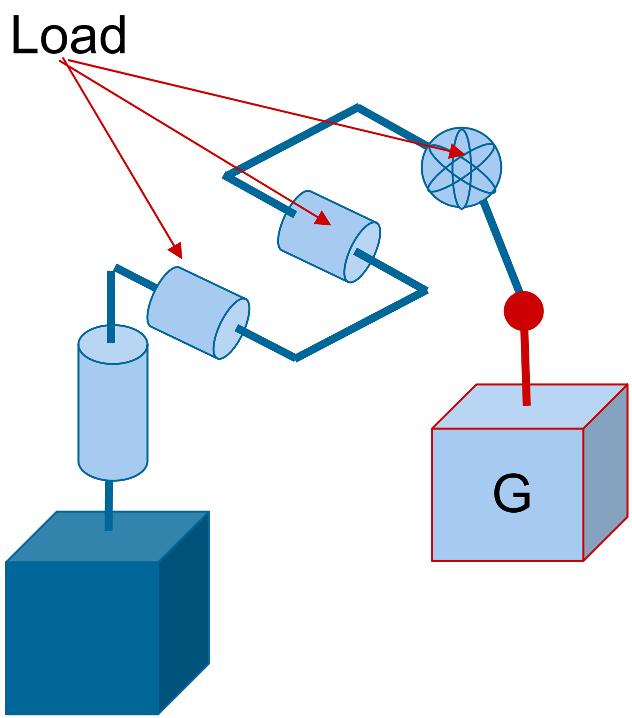
Classical Arms Key Features

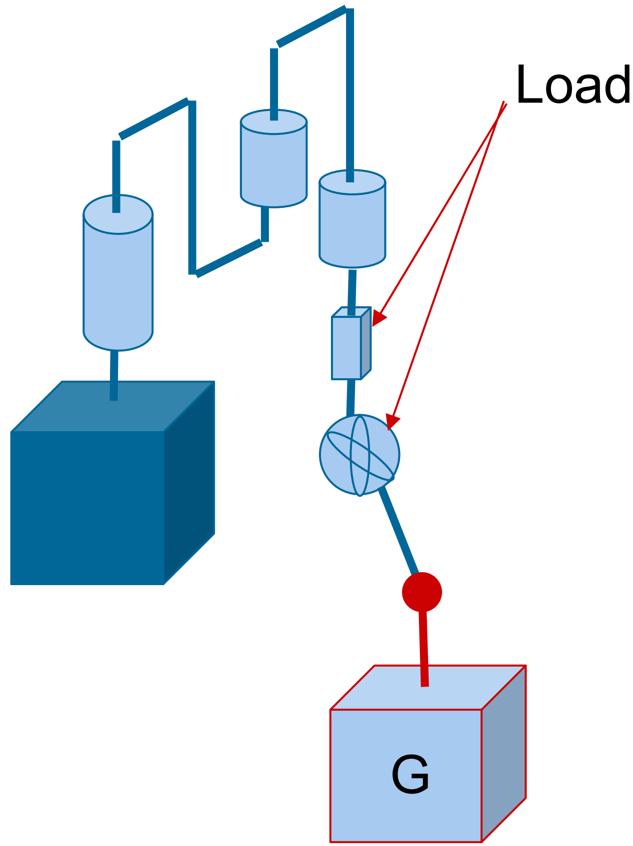
- Scara & A-R ⇔ the "foundation" of robotics (100% mastered)
- Transformation models are OK
  - F.K. is straightforward
  - I.K. just a bit more tricky
- Singular positions exist



Scara *vs* Anthropomorphic

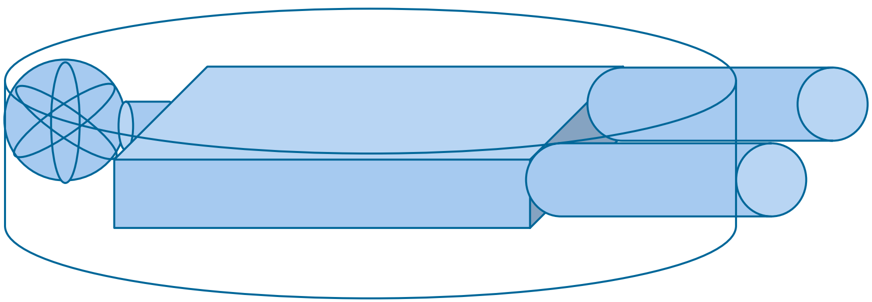
- Scara presents less problem with Gravity effects

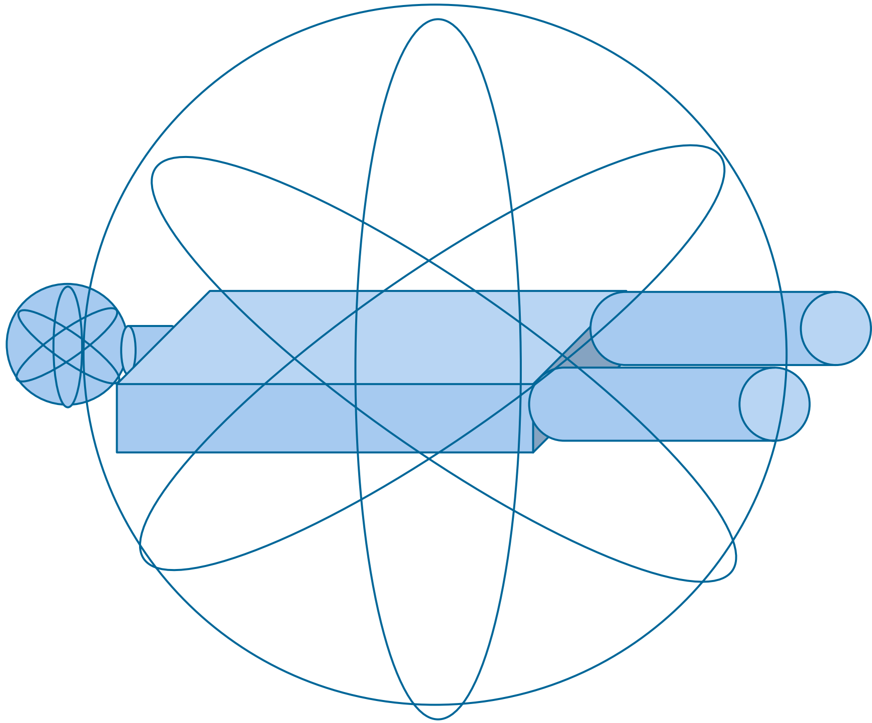




Scara *vs* Anthropomorphic

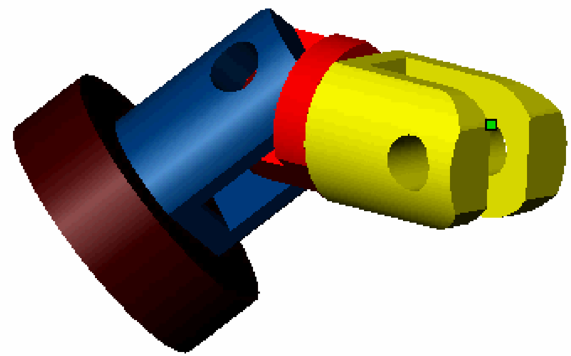
- Scara's workspace is more likely to suit to the volume of a human body lying on a surgical table

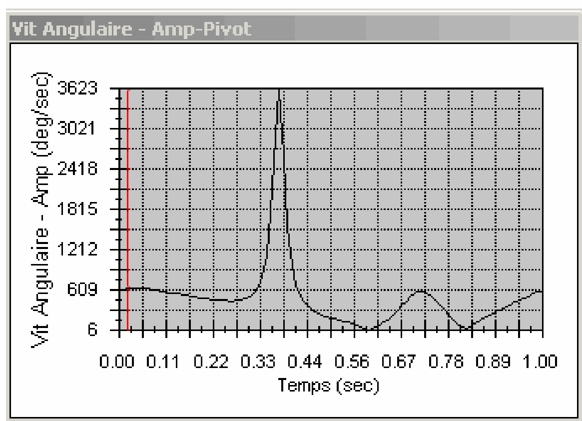


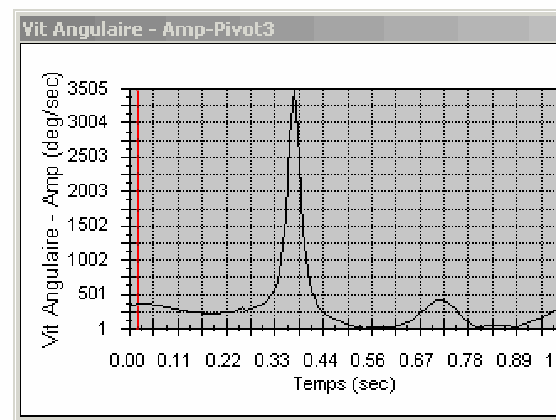


Scara *vs* Anthropomorphic

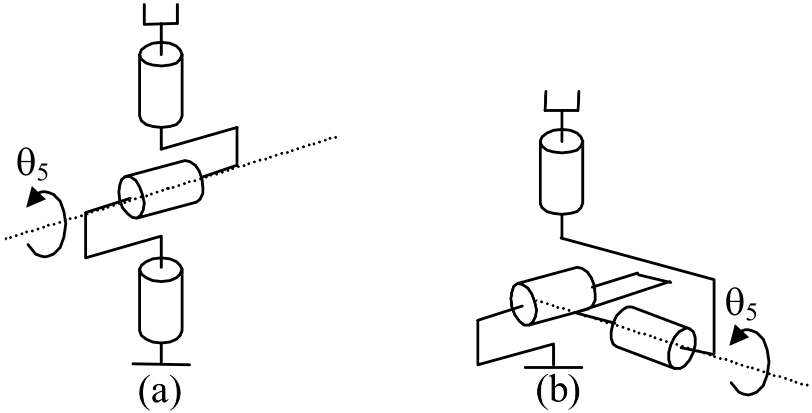
- It is possible to design an almost-singularity-free Scara arm
  - Most problems come from “wrist singularity”
  - Typical case: axis 4 and 6 aligned
  - One way out of this problem: non spherical wrists
  - New problem: I.K. in closed form?







One offset is not enough

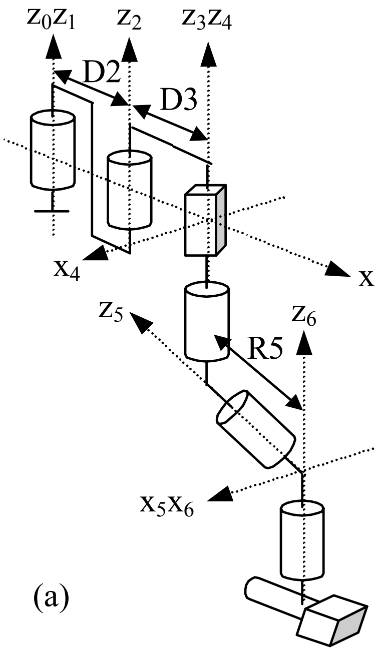


$$\Theta_5 = 0$$

$$\Theta_5 = \pm\frac{\pi}{2}$$

- Symmetric joint limits?
- Ranges of motion?

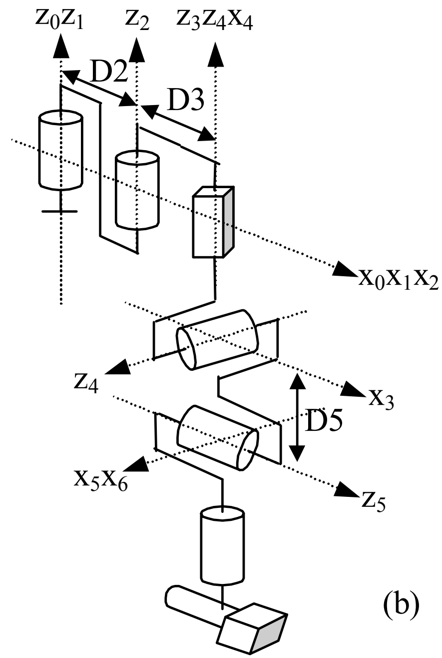
Most non-spherical wrists aren't OK



(a)

$$\Theta_2 = 0$$

$$\Theta_5 = 0$$



(b)

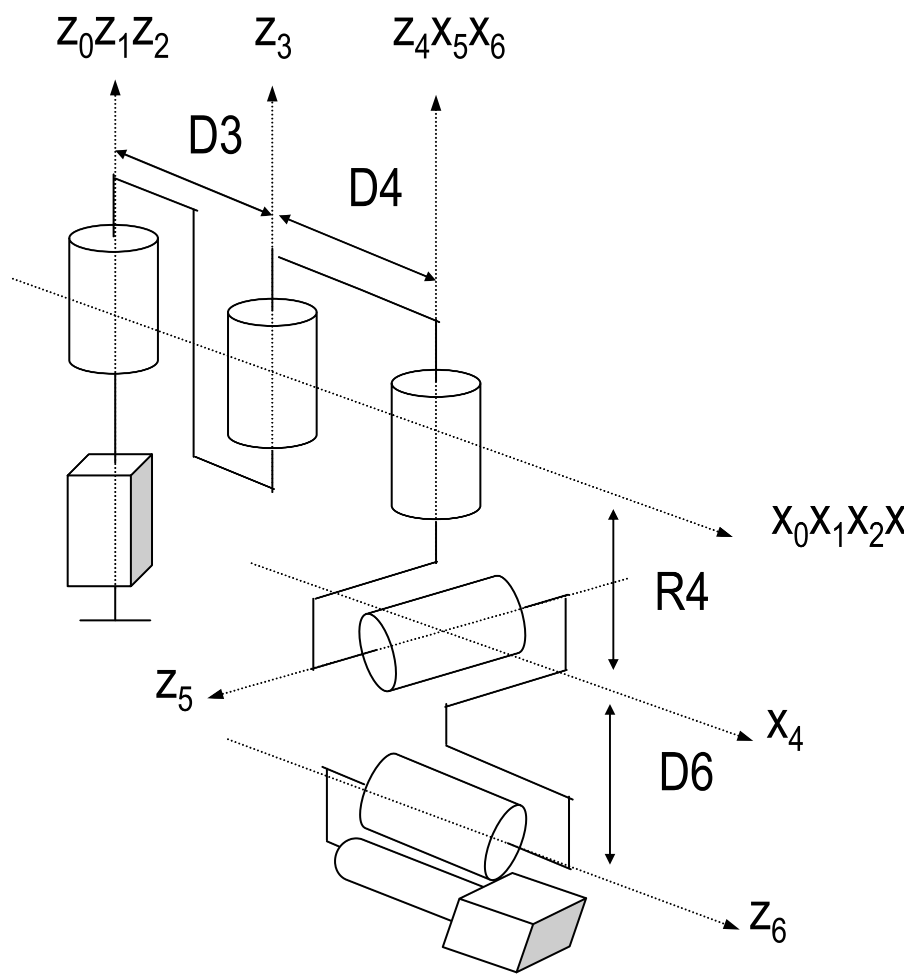
$$\Theta_2 = 0$$

$$\Theta_4 = \pm\frac{\pi}{2}$$

$$\Theta_5 = \arctan\left(\tan(\Theta_2)\frac{D_5\sin(\Theta_4) - D_3}{D_5\cos^2(\Theta_4)}\right)$$

… but one design does it all

- 6-degree-of-freedom Scara Robot,
- No wrist-singularity,
- One classical singularity on the elbow,
- Inverse Kinematics Model,
- Non-spherical wrist,
- Large Workspace.



Easy singularity check + I.K. in closed form

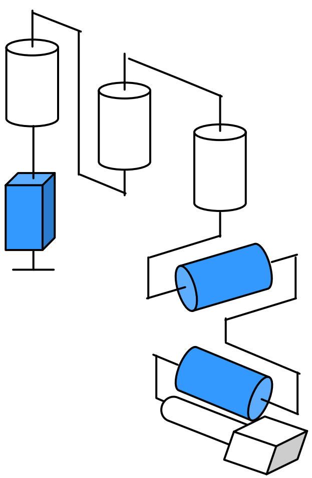
- $\det(\boldsymbol{J}) = D_3 D_4 \sin(\Theta_3)\cos(\Theta_5)$

- $$U_0 = \begin{bmatrix} s_x & n_x & a_x & p_x \\ s_y & n_y & a_y & p_y \\ s_z & n_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

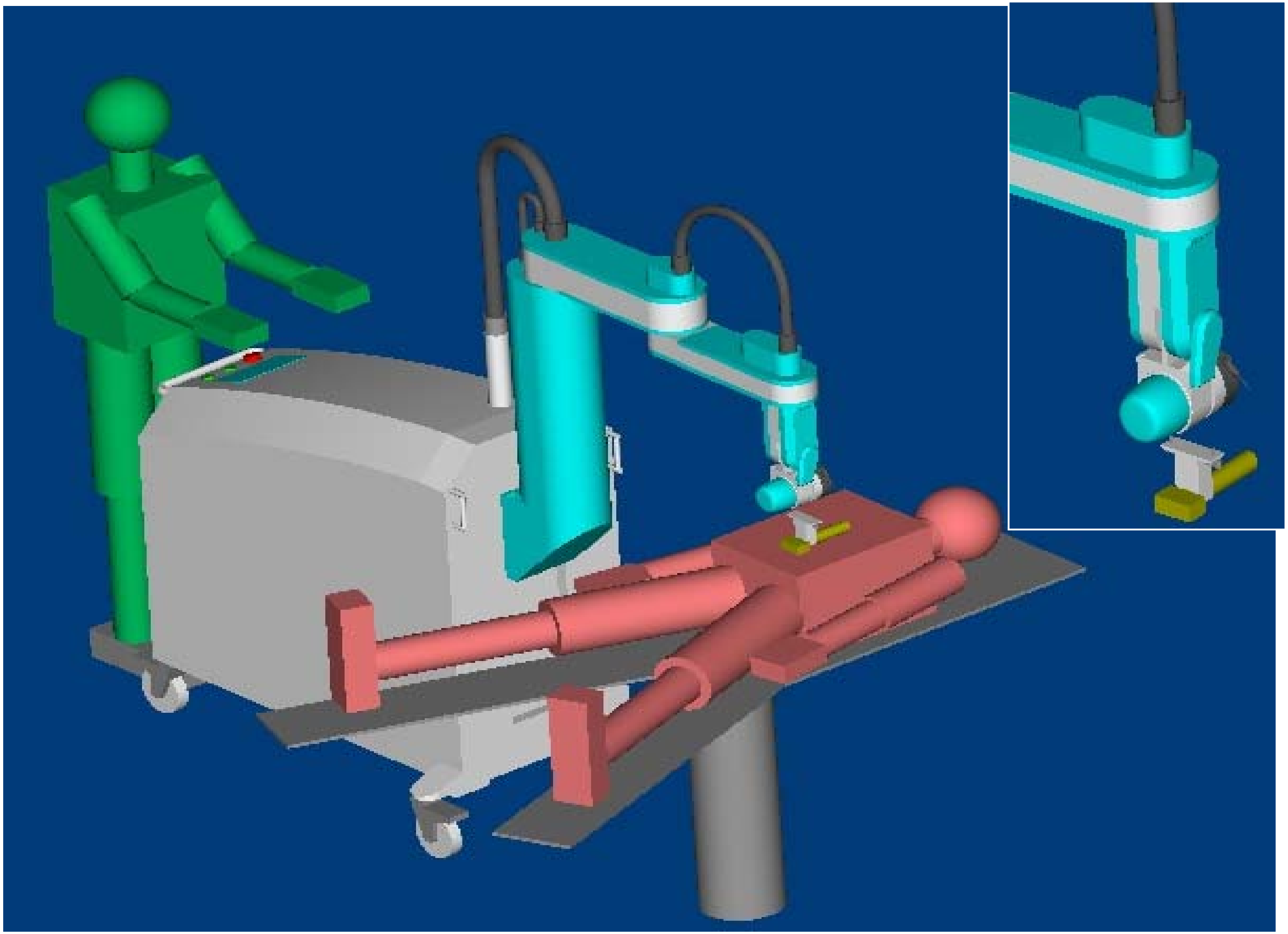
$$\theta_5 = \text{atan2}\left(a_z, \pm\sqrt{n_z^2 + s_z^2}\right)$$

$$\theta_6 = \text{atan2}\left(\frac{-n_z}{C_5}, \frac{s_z}{C_5}\right)$$

$$r_1 = p_z - R_4 - D_6 C_5$$

- 

Scalpp Kinematics



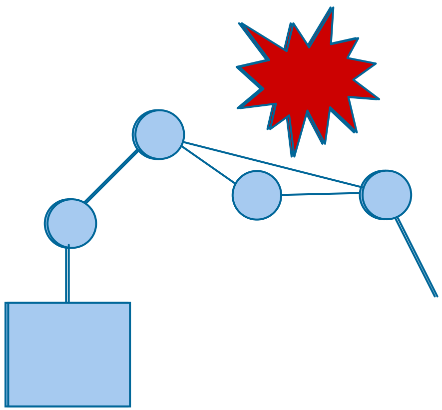
Scara *vs* Anthropomorphic: Two Examples

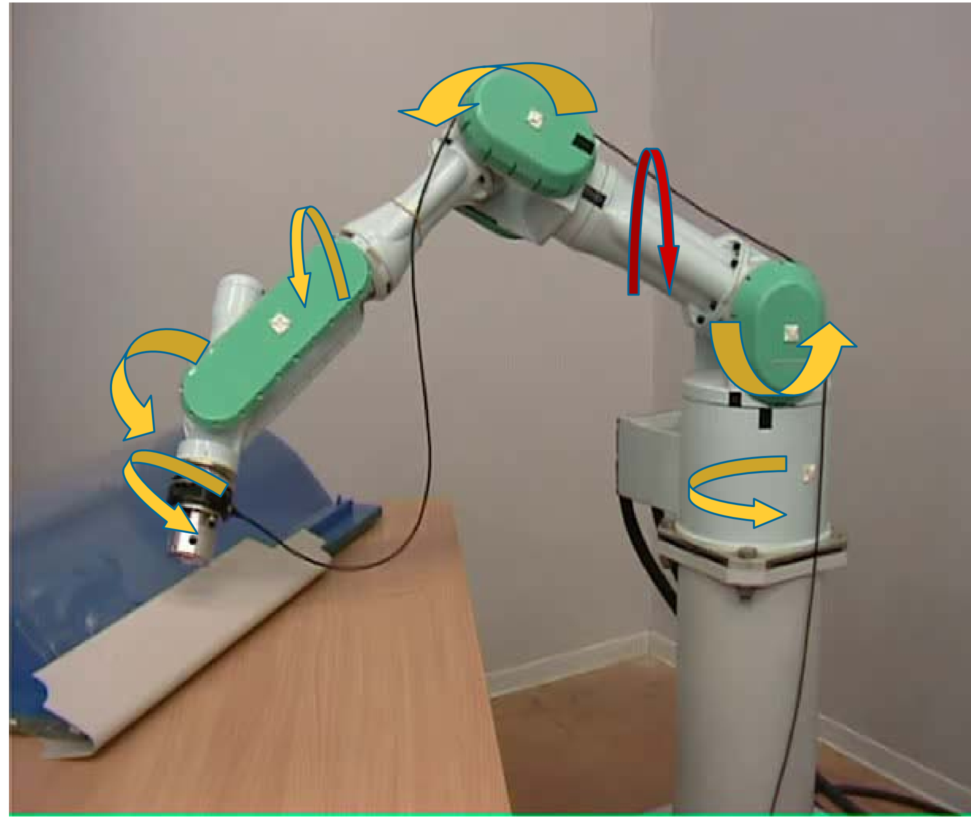
Not-so-classic Serial Arms

Redundant Arms

- Offer more dof than strictly needed

- May help to avoid collisions





- “Numerically tricky” (The I.K. is not solvable in closed form)

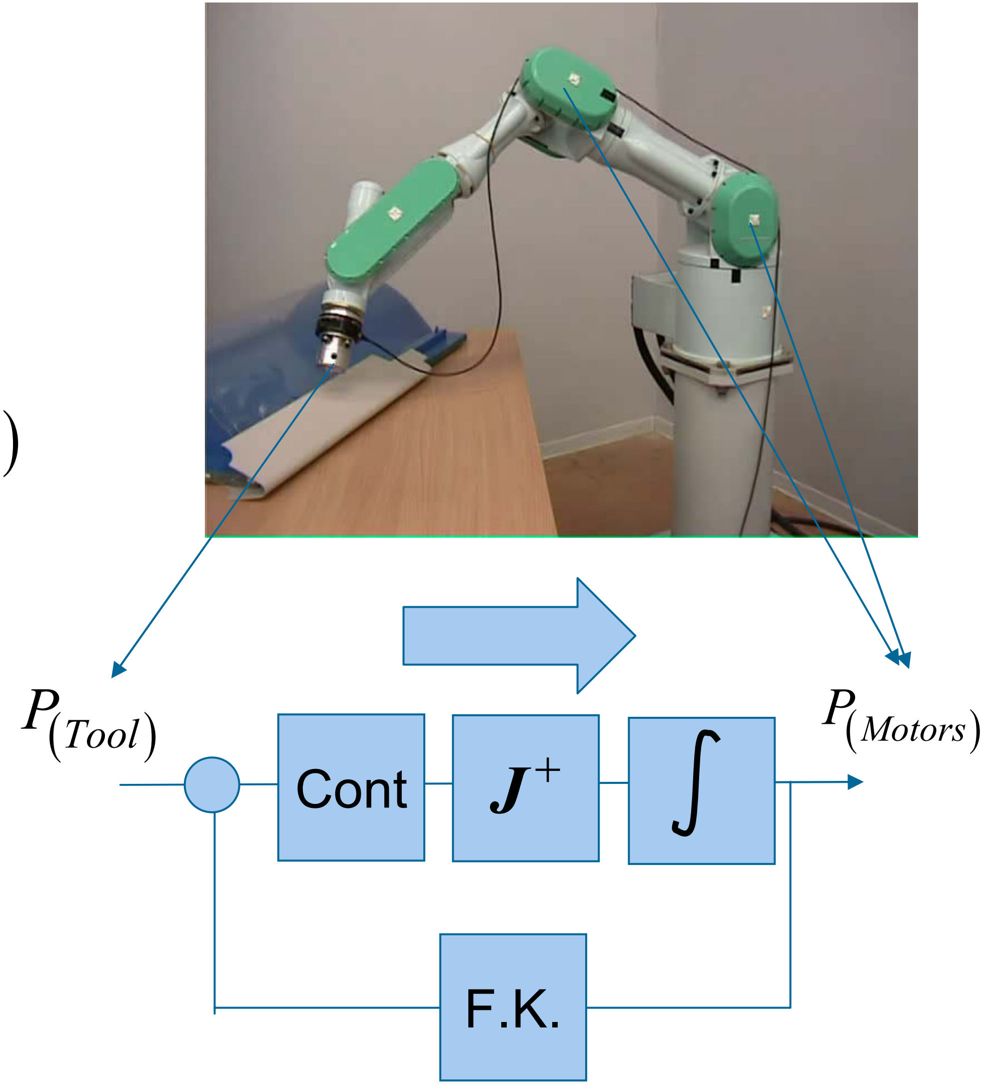
Solving I.K. for Redundant Arm

$$V_{(Tool)} = \boldsymbol{J}\, V_{(Motors)}$$

Not a SQUARE matrix!

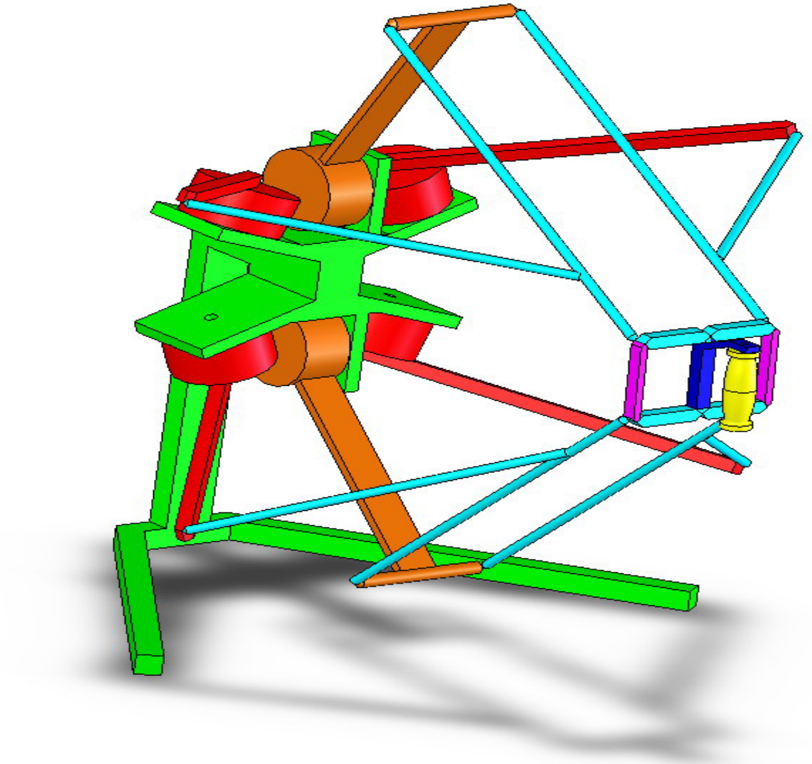
$$V_{(Motors)} = \boldsymbol{J}^{+}\, V_{(Tool)}$$

Pseudo-inverse

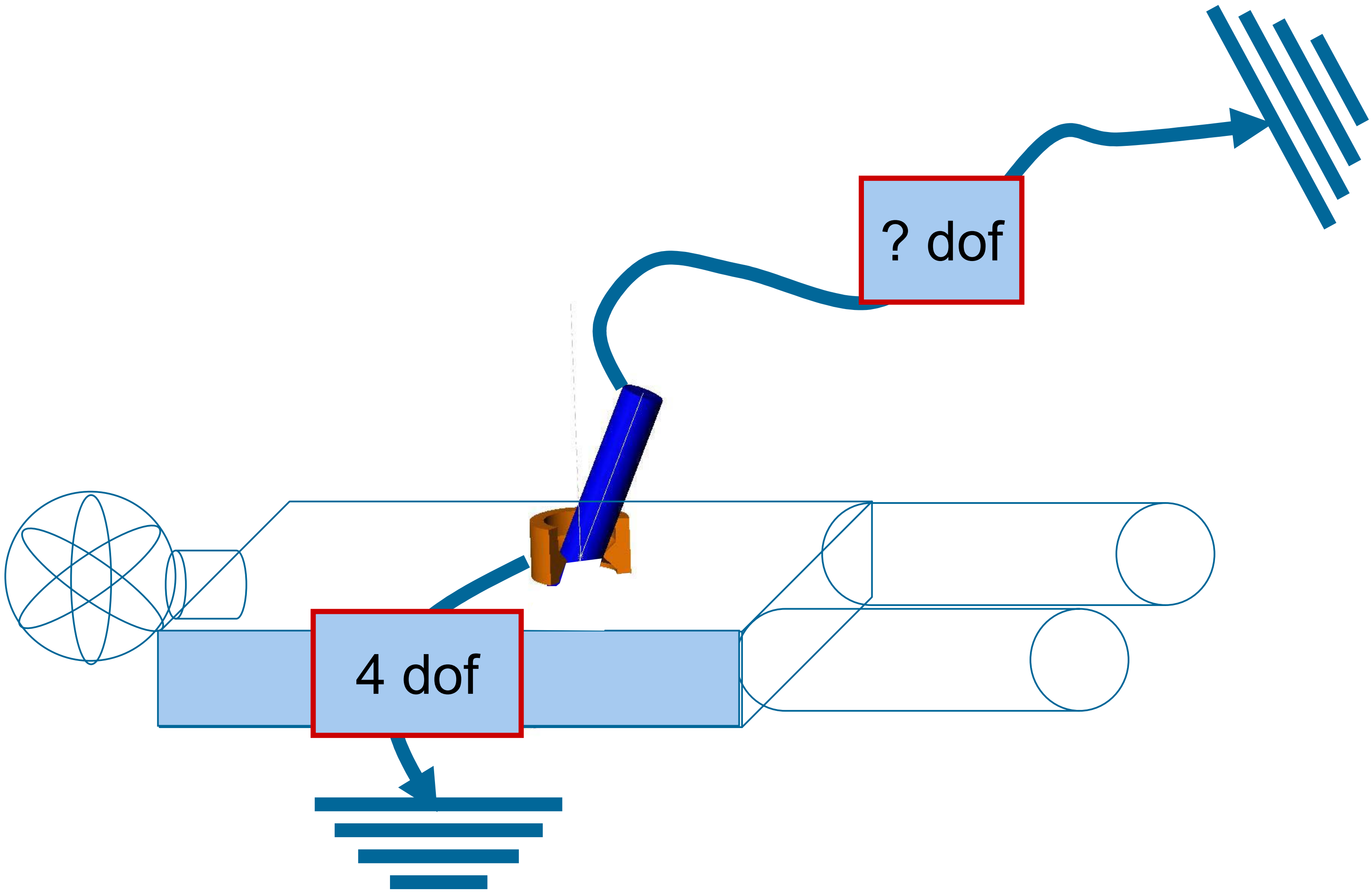


Not-so-classic Serial Arms

- Arms with kinematics constraint
  - The idea is to create a mechanical structure able to give the tool one SPECIFIC type of motion
  - Mostly applied to mini-invasive surgery
- M.I.S. ➔ a tool (shape ⇔ cylinder) passes through a trocar (shape ⇔ annulus ??)
- The tool axis always passes in one “fixed” point
- ➔Two constraints (translation is constrained in two directions)

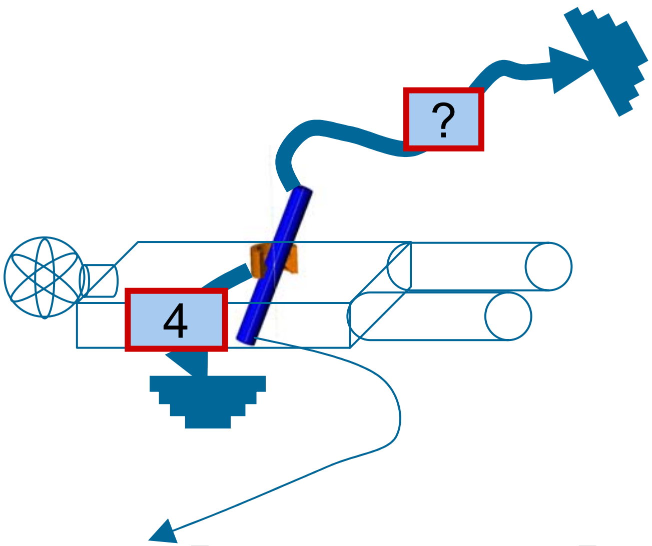


How many dof for respecting the constraints?



How many dof for respecting the constraints?

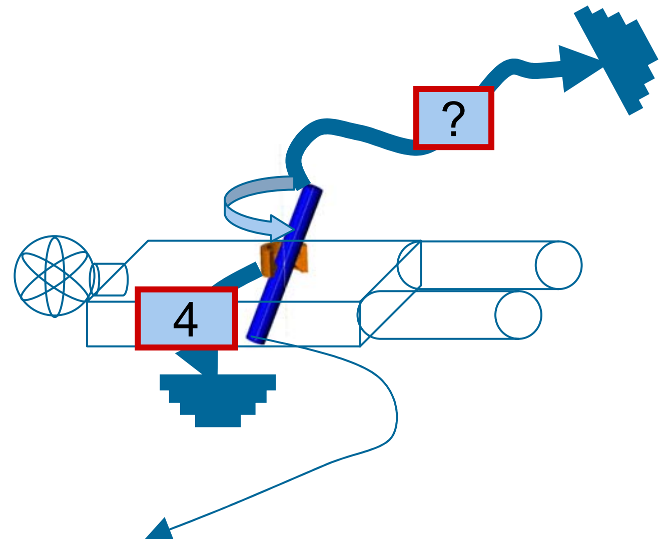
- Gruebler formula: Mobility = (Total dof) – (6 x Nb of loops)



Mobility ➔ Tx, Ty, Tz ➔ **3**

3 = (4 + ?) – (6 x 1)

➔ ? = 5



Mobility ➔ Tx, Ty, Tz, Rz ➔ **4**

4 = (4 + ?) – (6 x 1)

➔ ? = 6

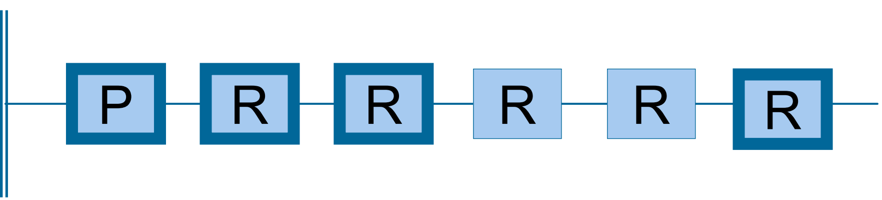
Option 1: passive joints

- Mobility → Tx, Ty, Tz → 3
- 3 = (4 + 5) – (6 x 1)

5 joints
\-
3 motors

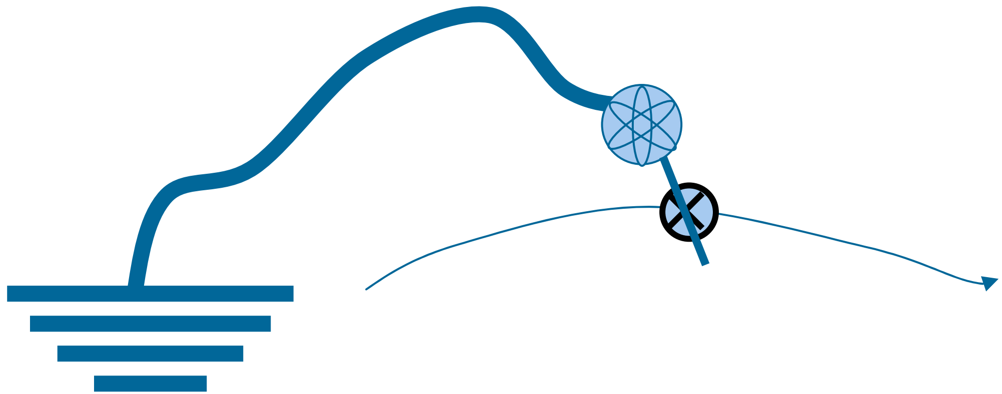
2 passive joints

Zeus



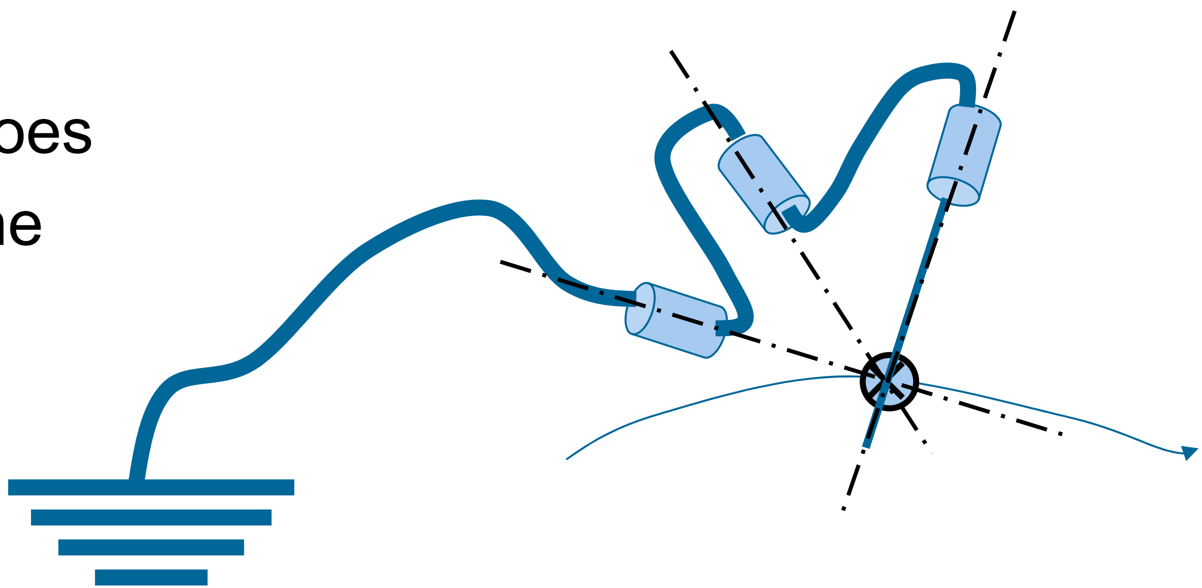
Option 2: Remote Rotation Center

- A classical spherical wrist does not rotate at the “right” point



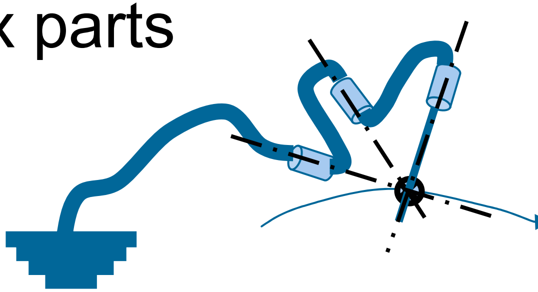
- A RRC system does and thus “cancel” the Constraint

$\color{red}{3} = (6 + \color{blue}{3}) - (6 \times 1)$

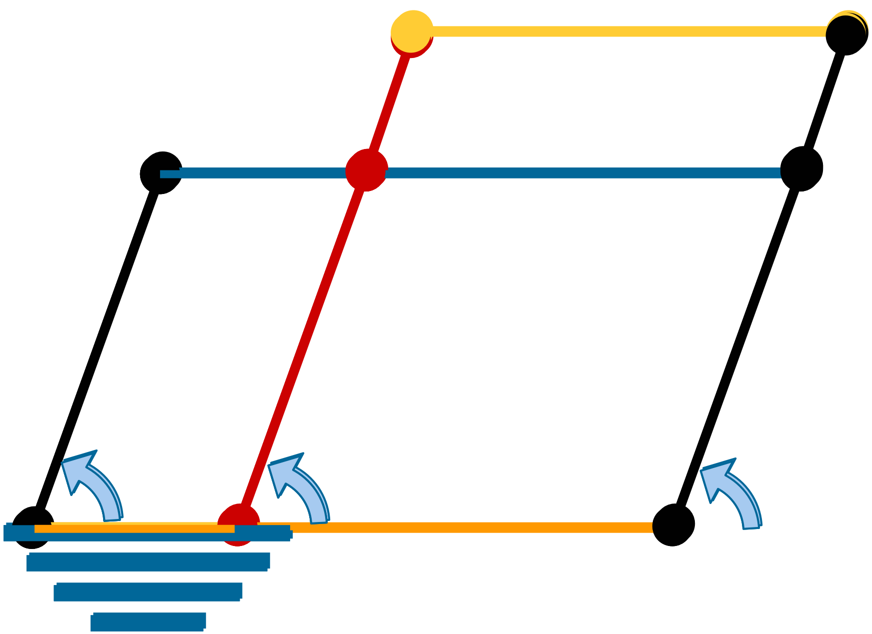


RRC or "The Magical Parallelogram"

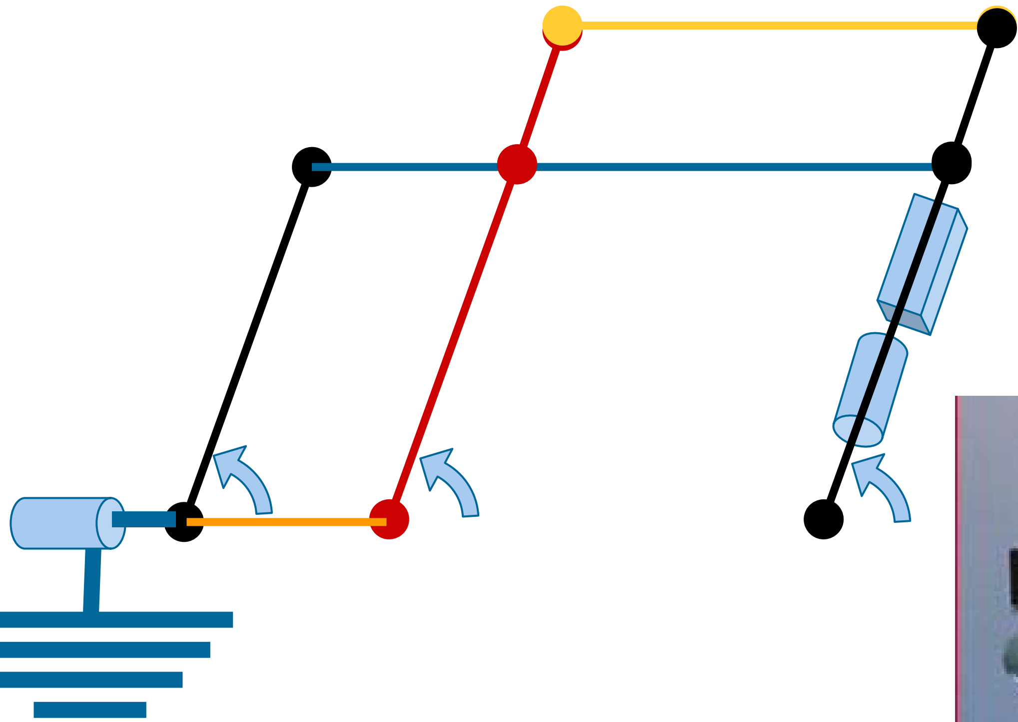
- RRC with spherical links requires complex parts



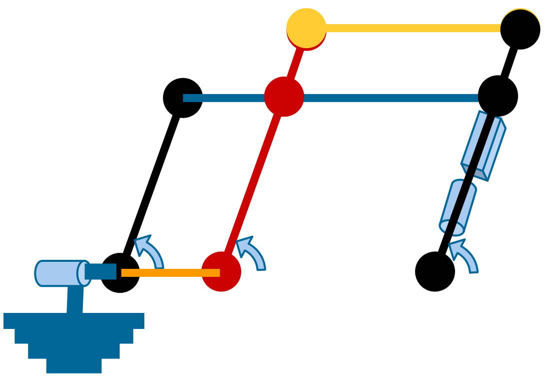
- … while a basic parallelogram may do the job as well

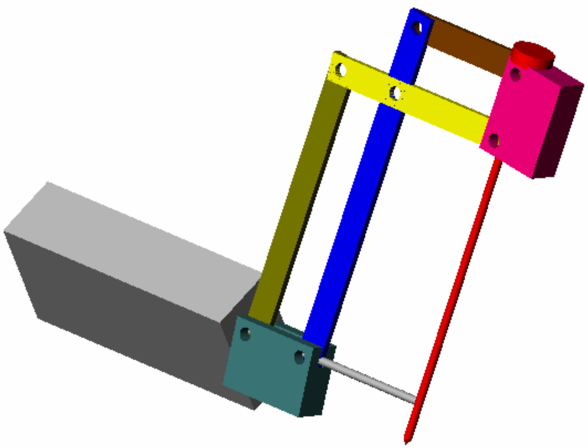


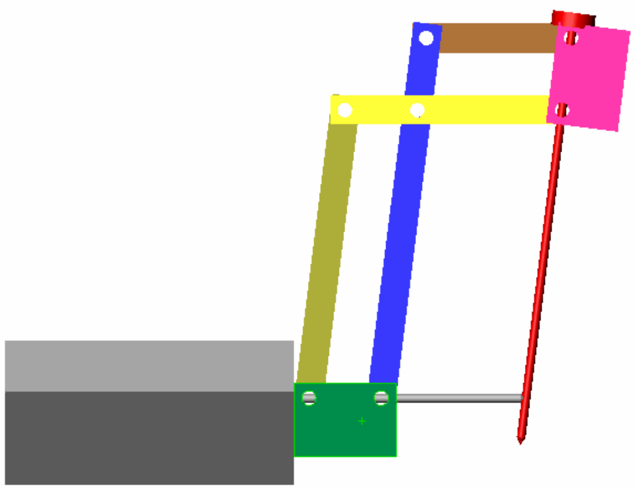
Implementation of RRC



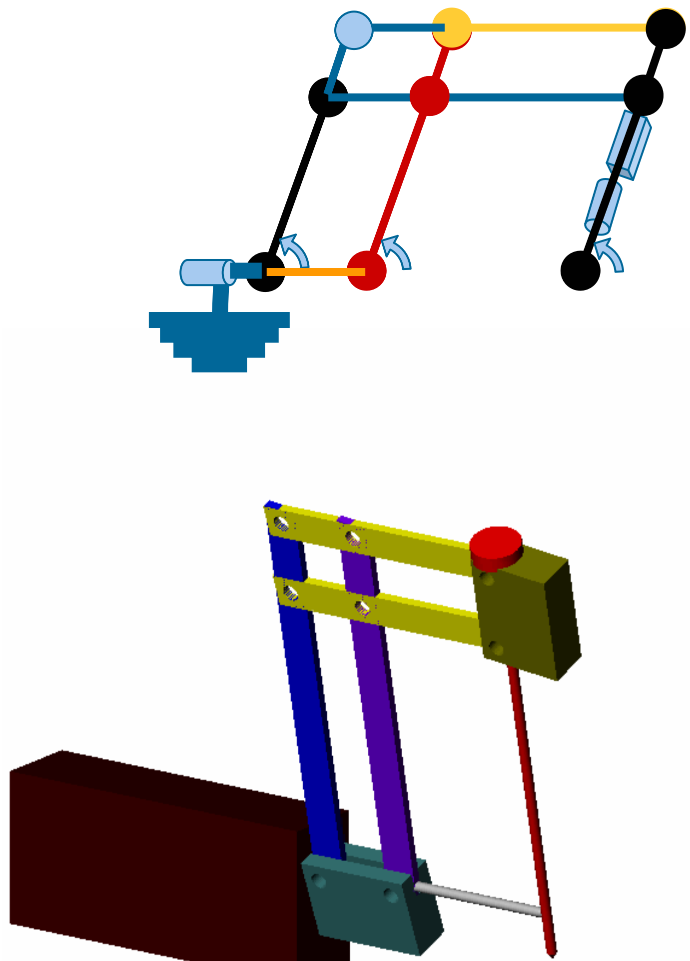
RRC in motion

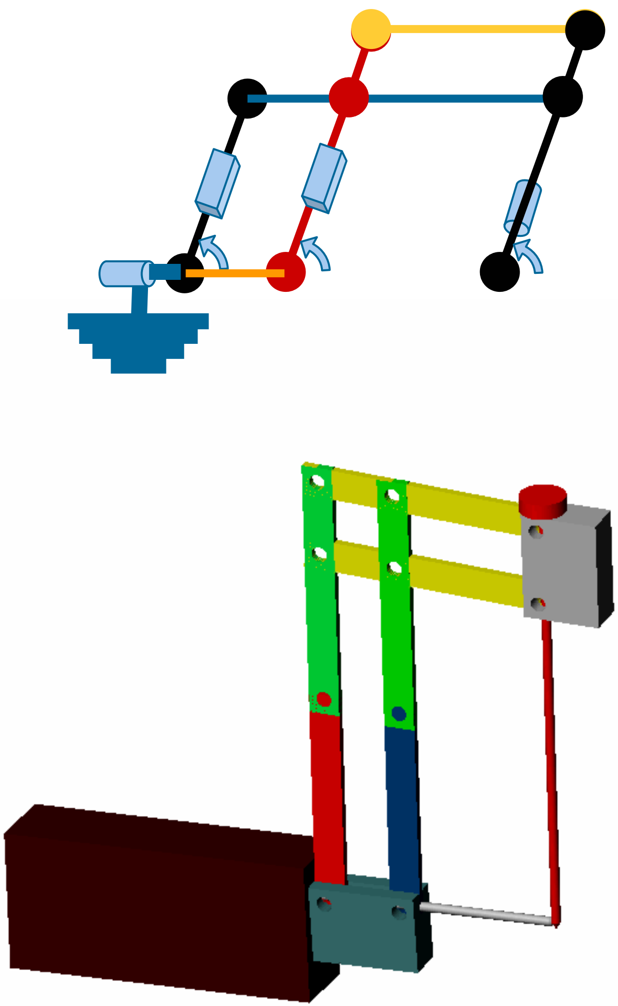




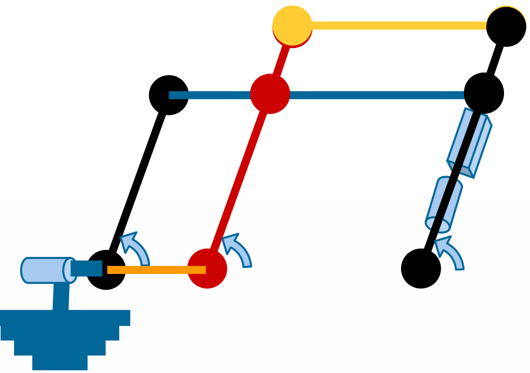


RRC: other “unique” solutions…

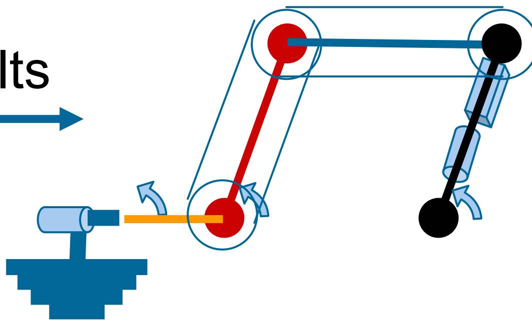


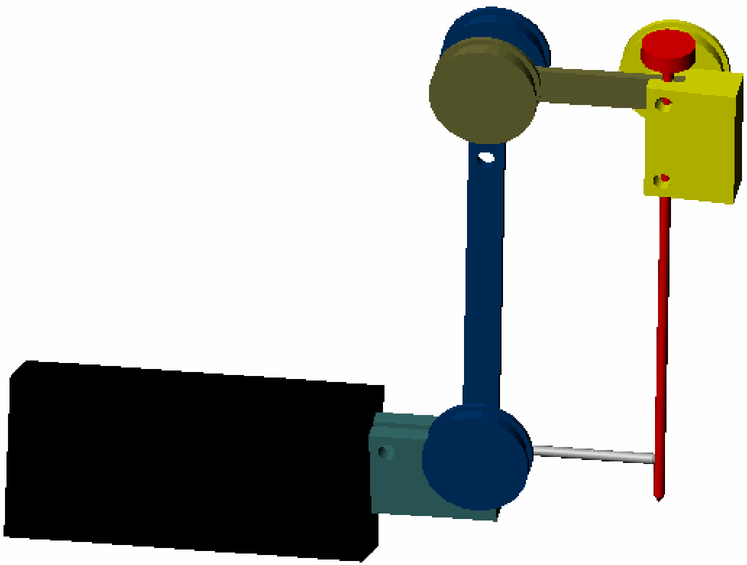


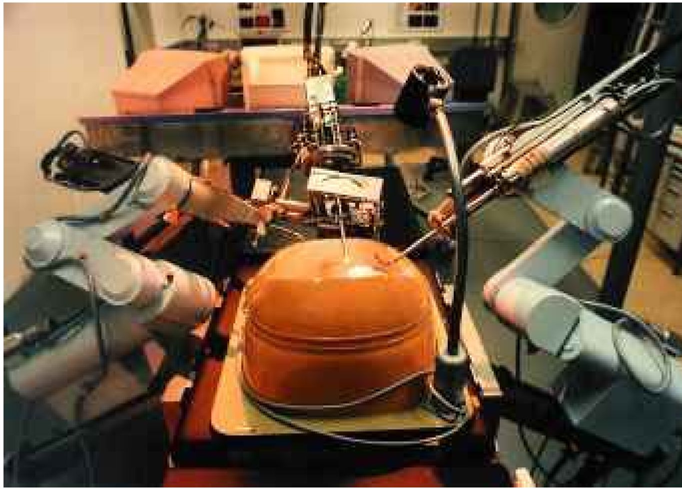
RRC: other “unique” solutions…



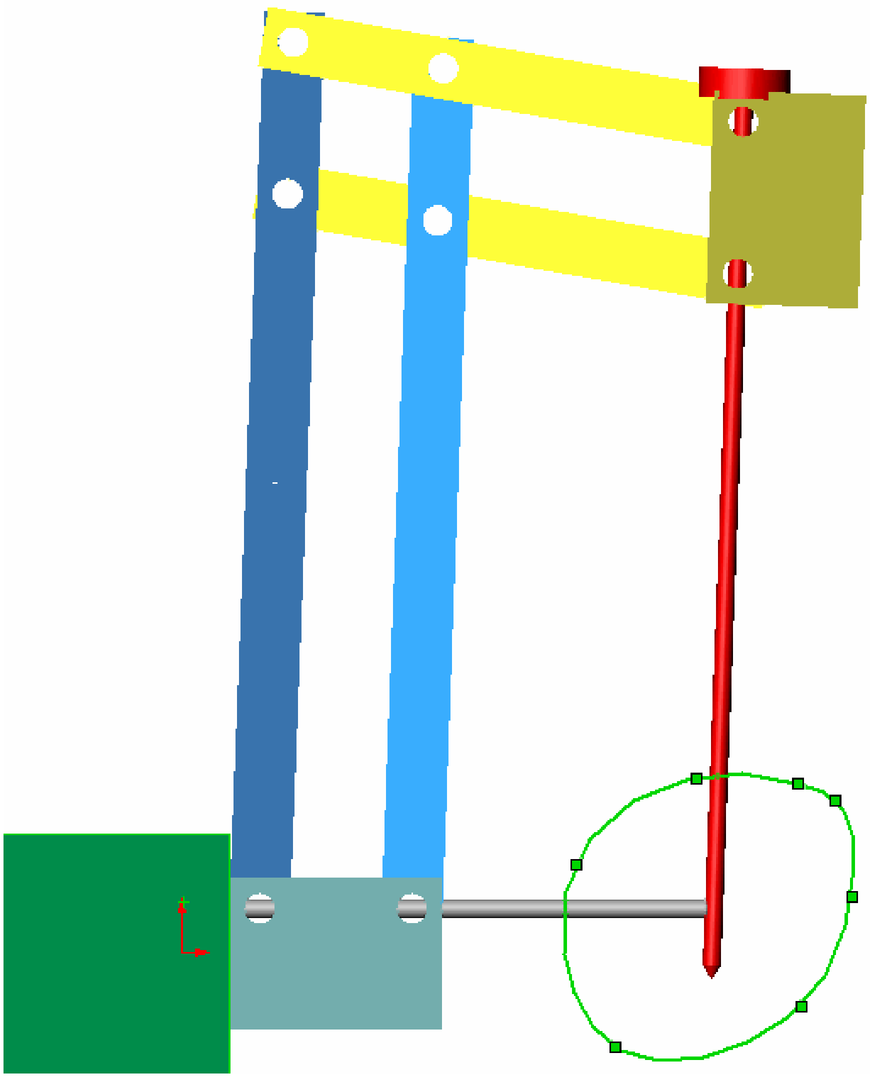
From solid links to timing belts







Remark: the parallelogram must be a real one!

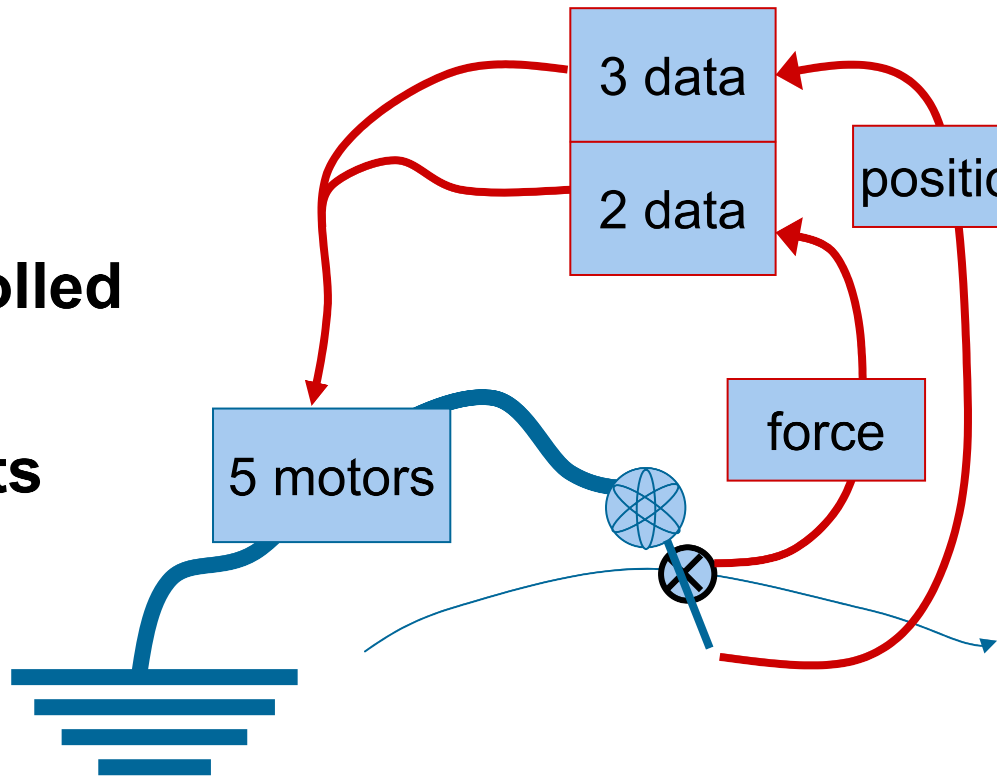


Option 3: force control

- Mobility ➔ Tx, Ty, Tz ➔ 3
- 3 = (4 + 5) – (6 x 1)

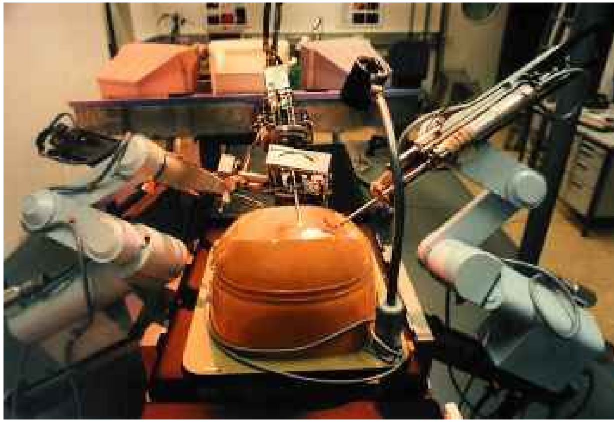
5 joints
&
5 motors

2 dof controlled with force measurements



Overview of arms with kinematics constraint

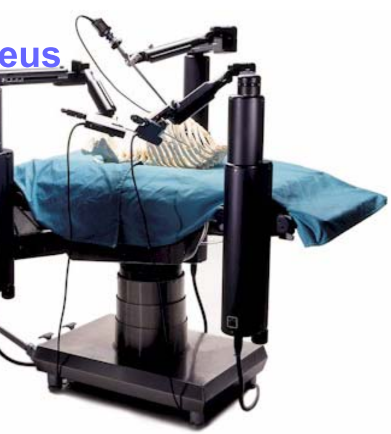
- Option 1 (passive joints)
  - Few motors
  - The trocar "forces" the passive joint to adapt "mechanically"
  - No accurate positioning is needed
- Option 2 (RRC)
  - Few joints and motors
  - The trocar has no influence on the arm motion
  - BUT, the arm MUST be precisely located (positioning device + procedure)
- Option 3 (force control)
  - The trocar "forces" the passive joint to adapt by means of measures + control software
  - A bit more complex
  - May open a path to "multi-purpose" systems



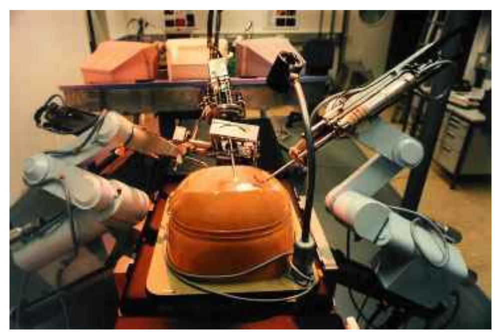
Overview of Serial Arms

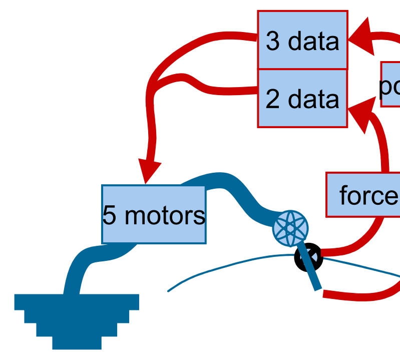
ROBODOC

CASPAR

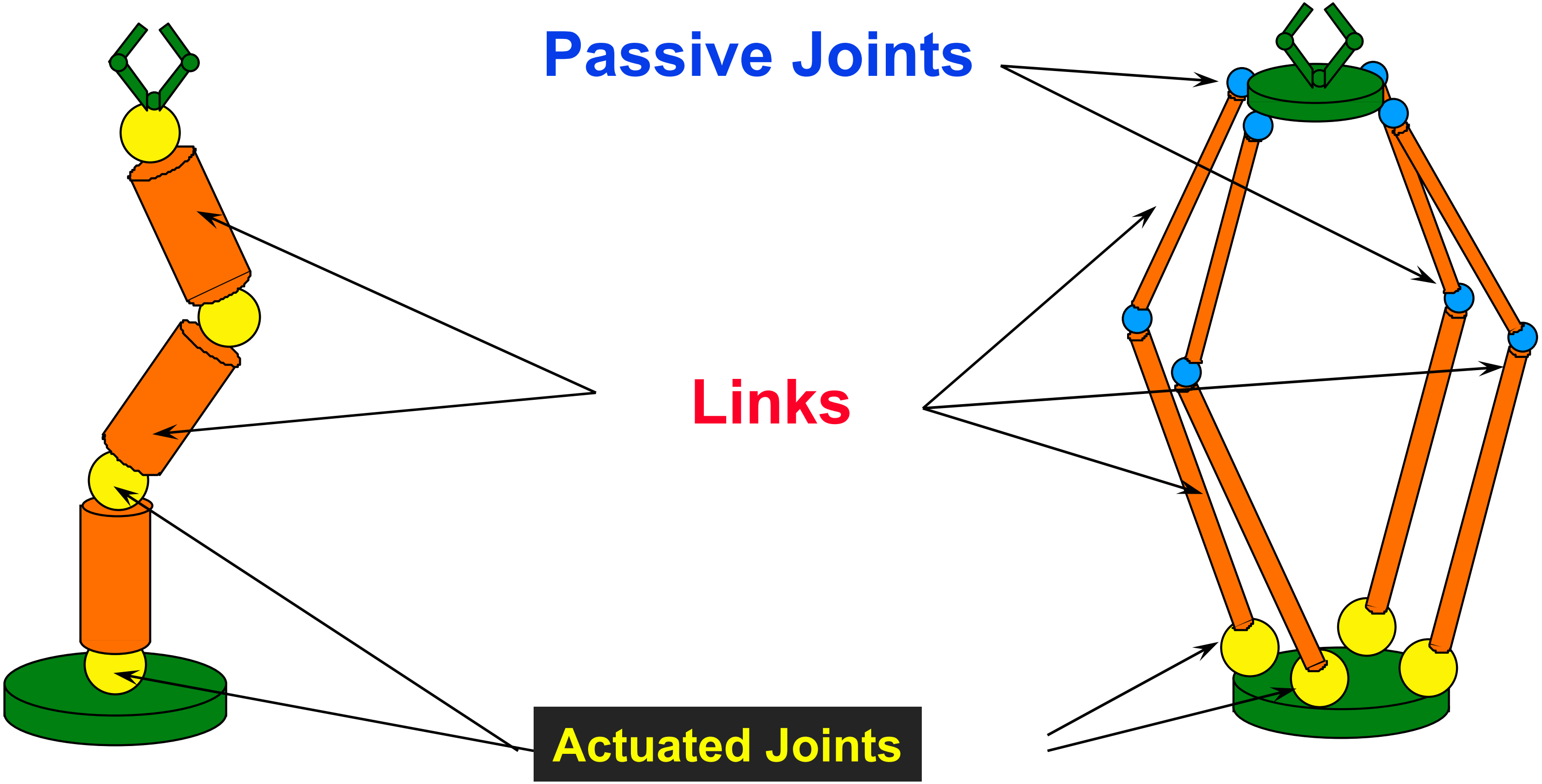


eus





… Still half the way to go …



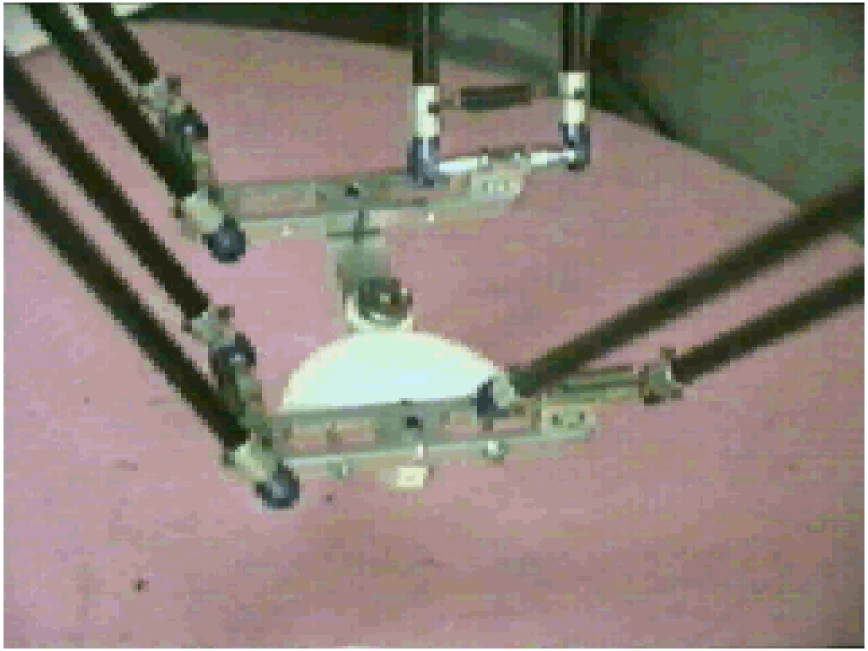
A Convention to Describe PKM

	Revolute	Prismatic	Universal	Spherical
Passive	R	P	U	S
Passive + measurement	R	P	U	S
Actuated	R	P	U	S
Actuated + measurement	R	P	U	S

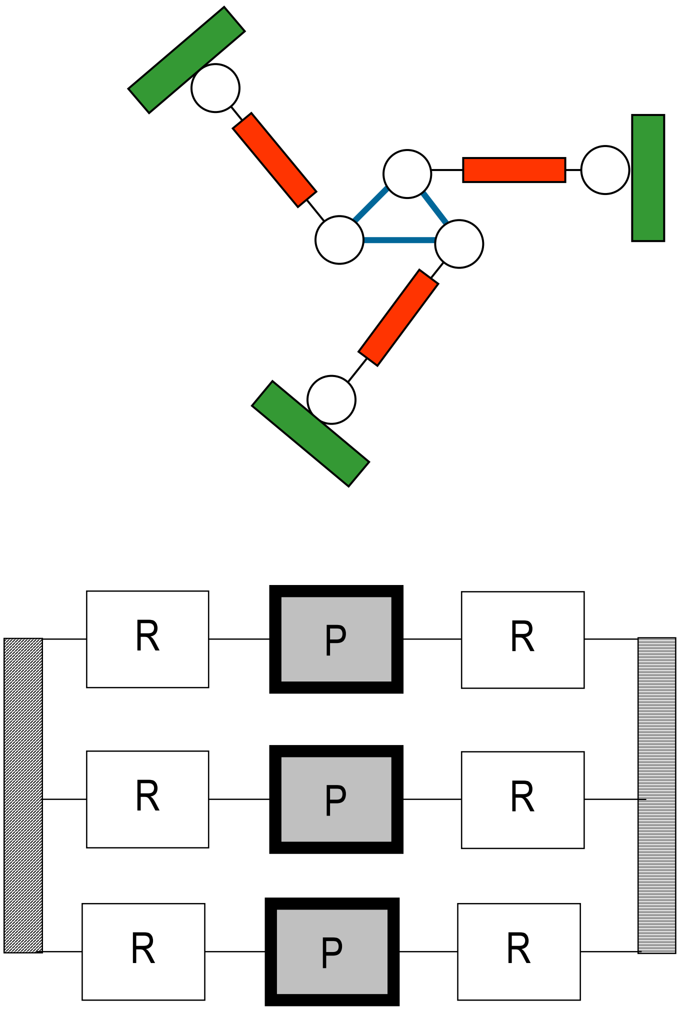
table 1. Symbols for Joint-and-Loop graphs.

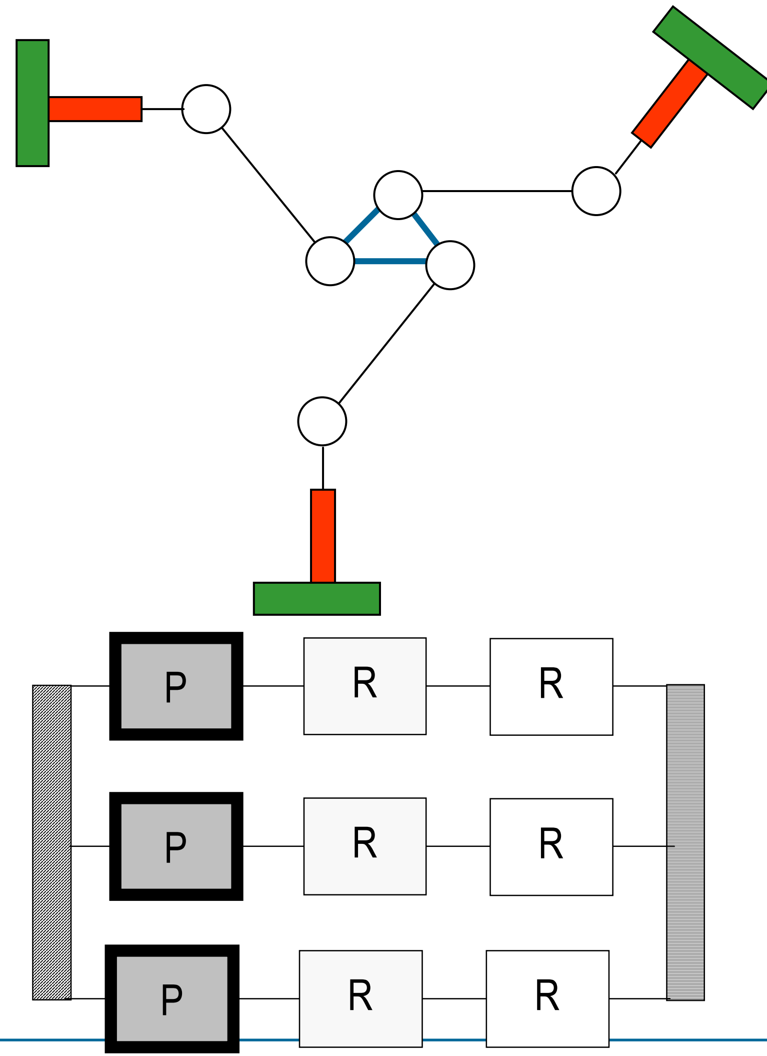
(not easy to implement)

An example (H4)

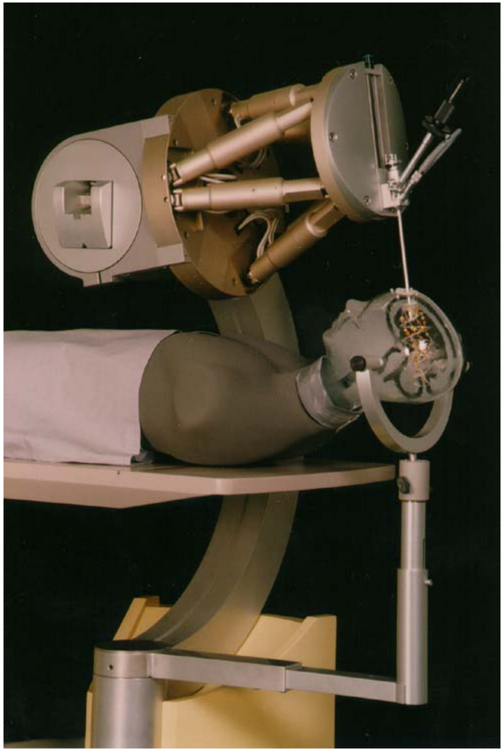


Telescopic Legs or Fixed-Length Legs

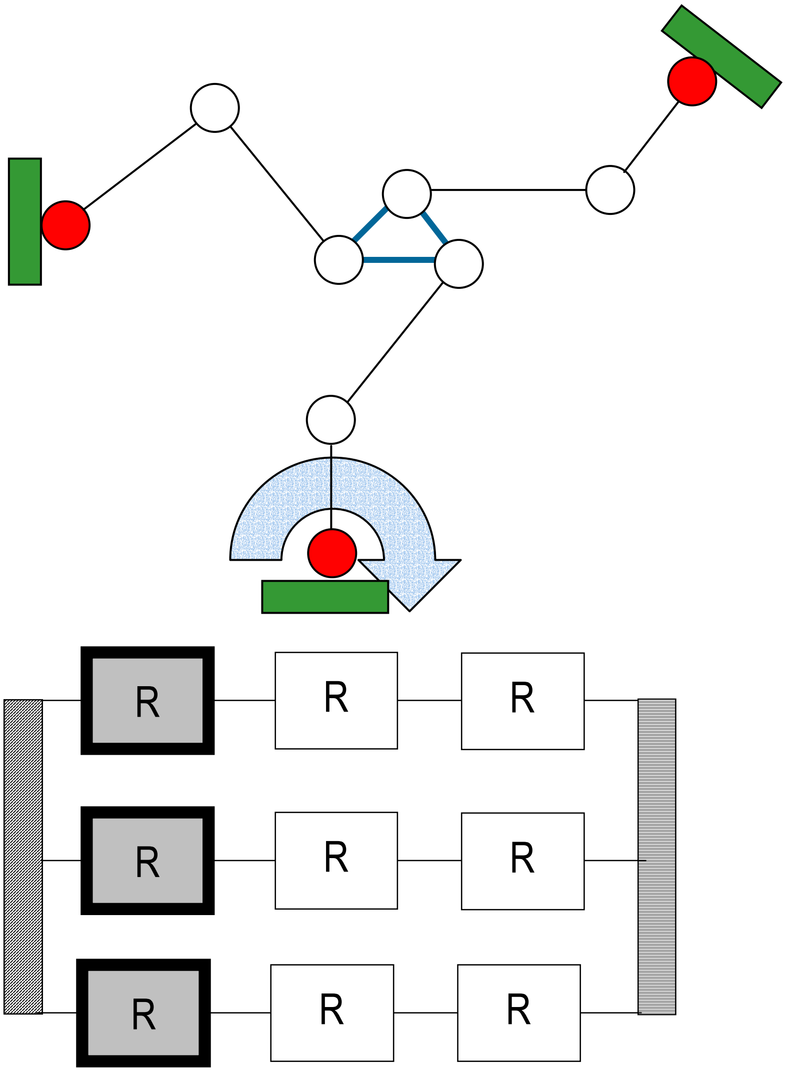


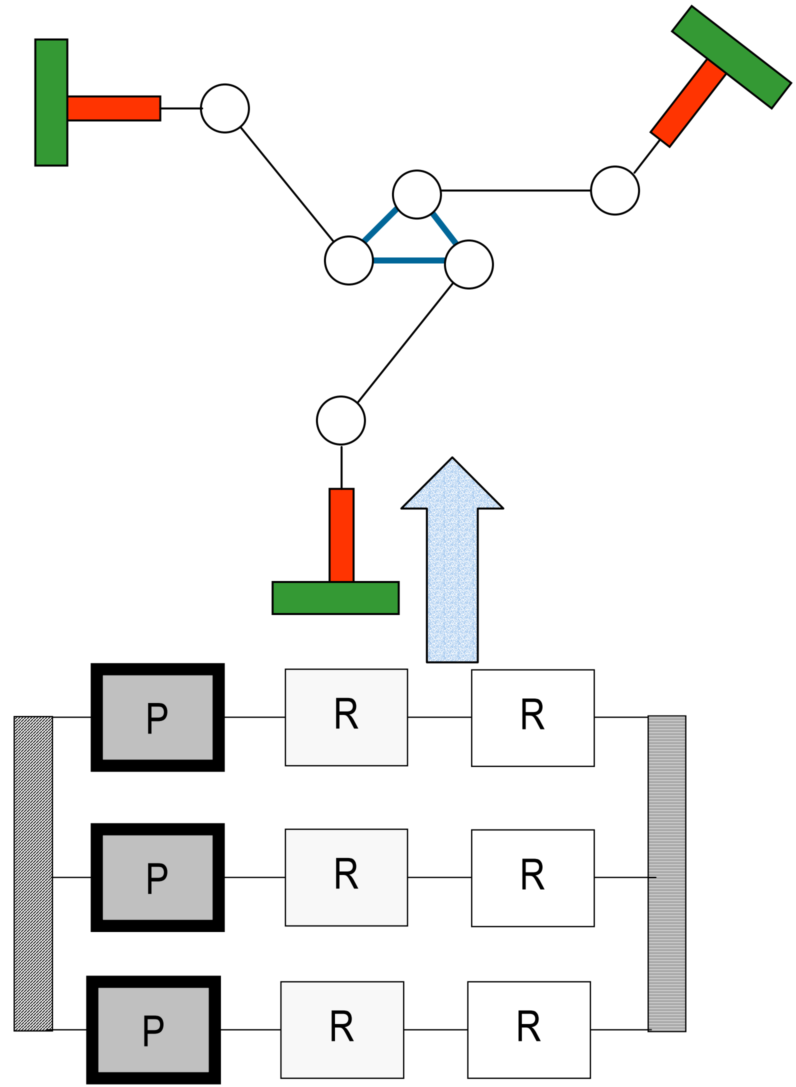


Telescopic Legs or Fixed-Length Legs

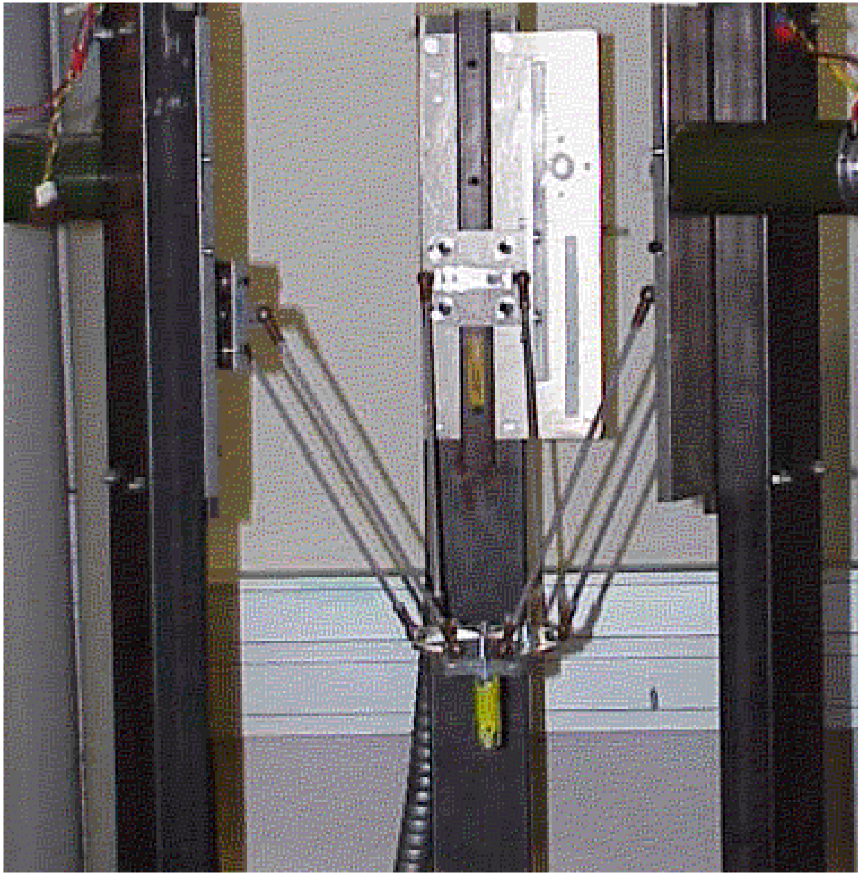


Rotational or Linear Drives

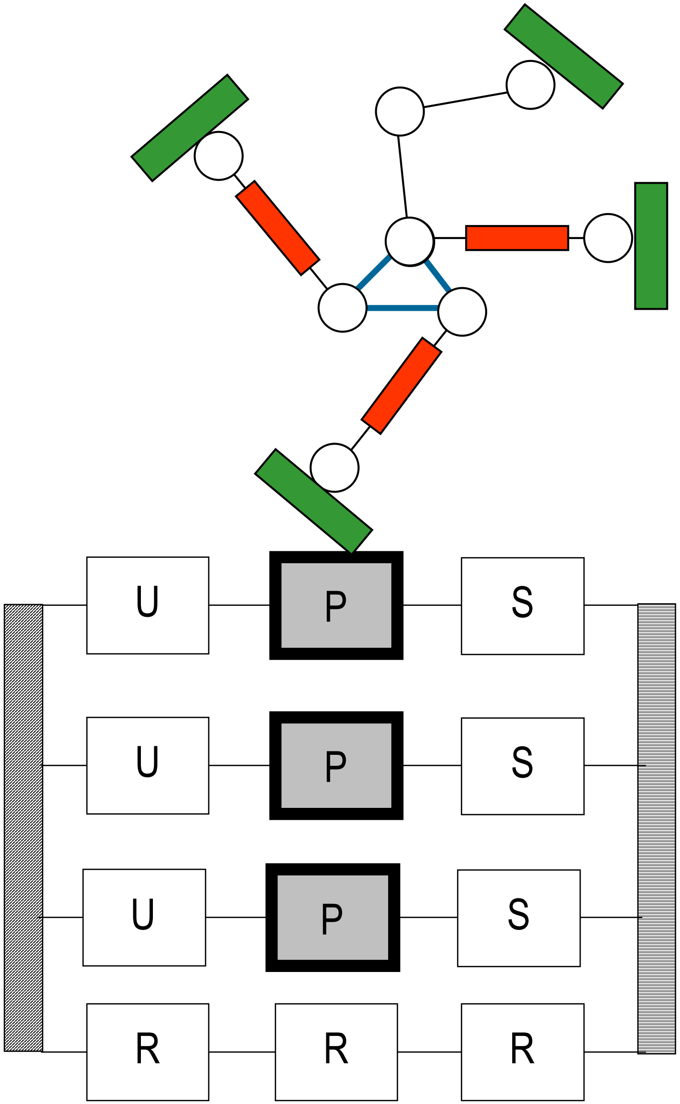




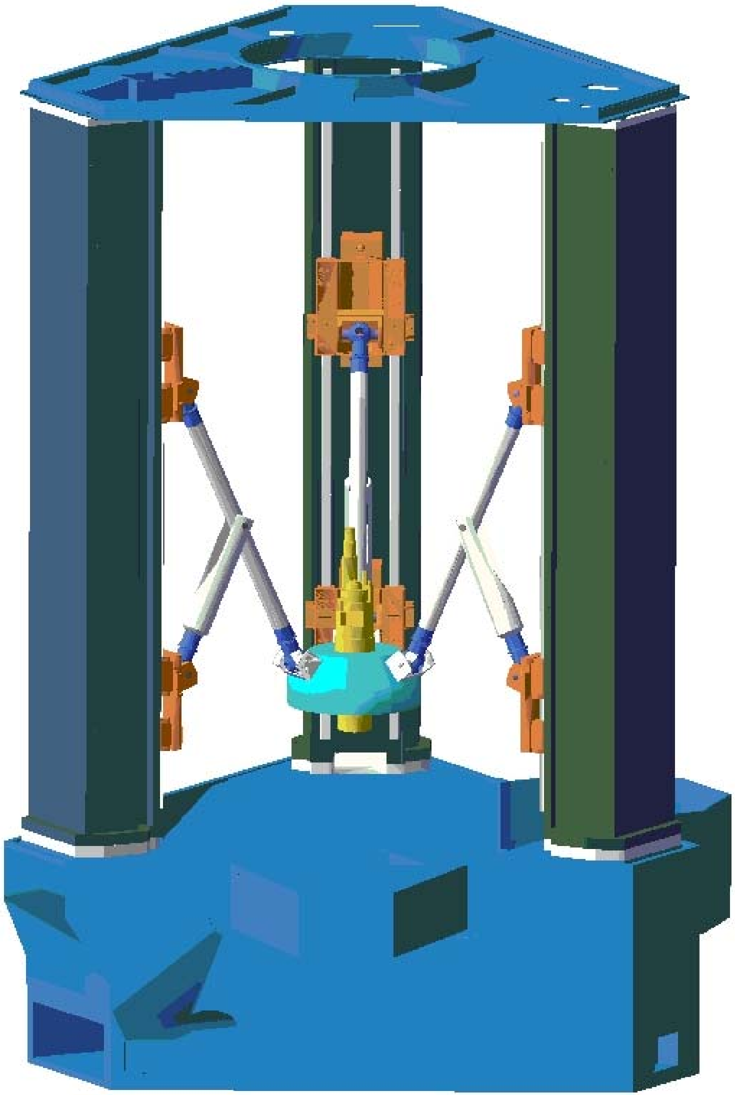
Rotational or Linear Drives

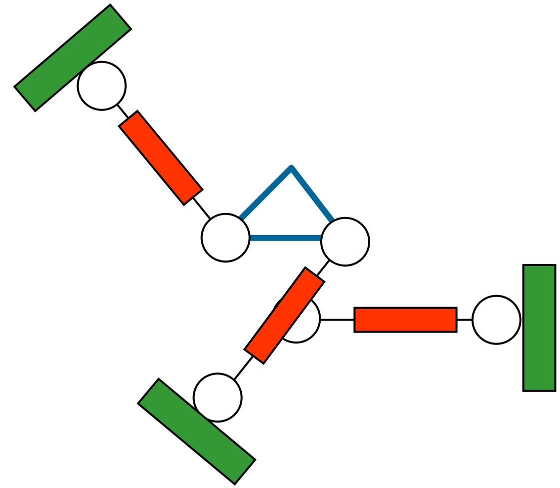


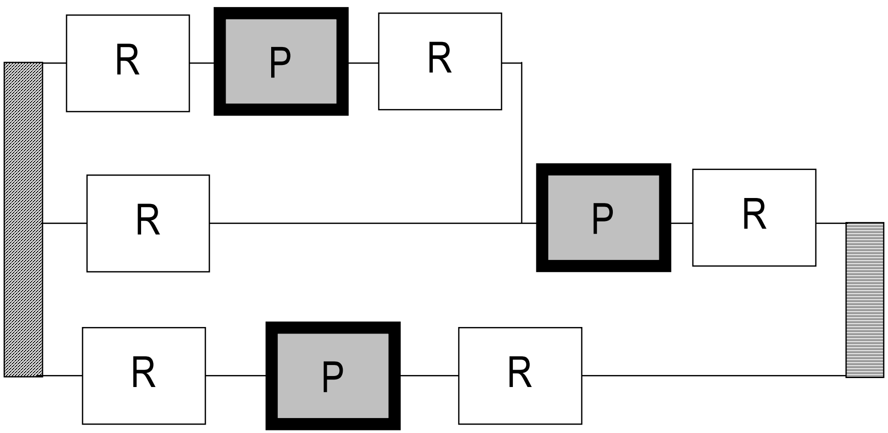
With or Without a Passive Leg



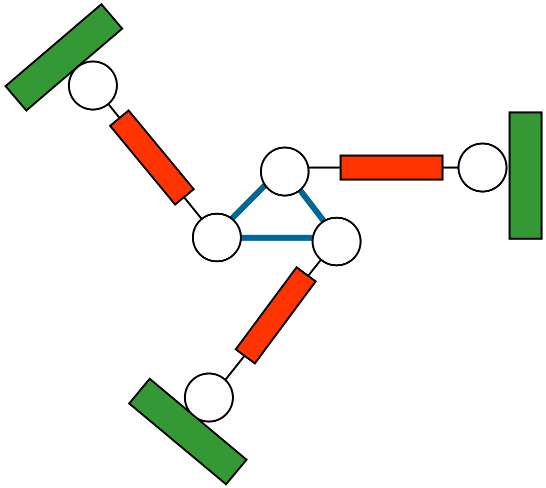
Fully Parallel or Non-Independent Chains

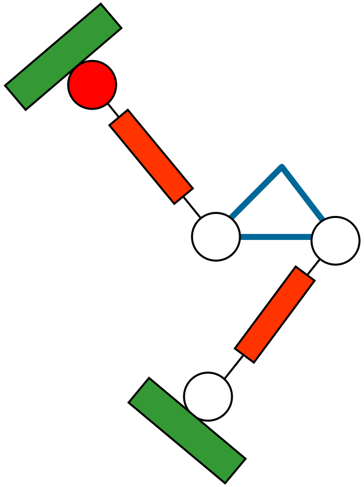


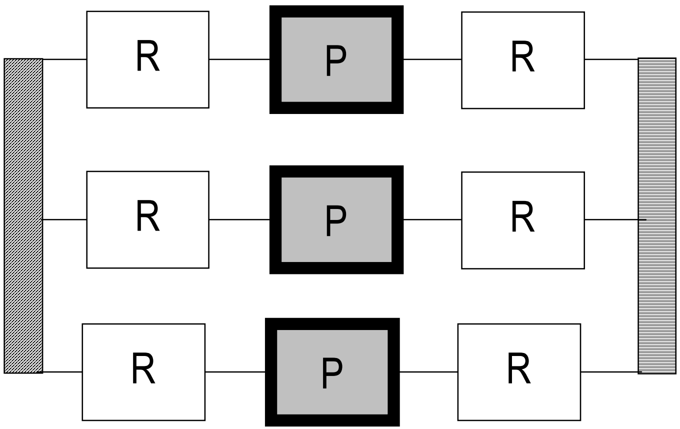


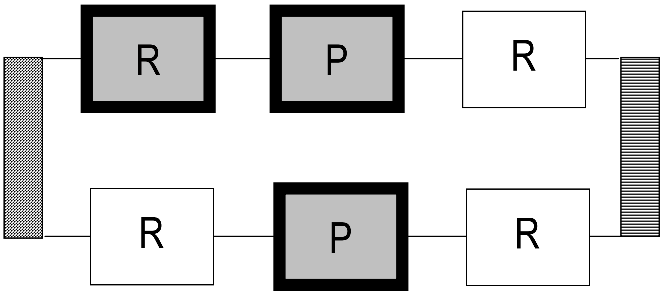


Fully Parallel or Non-Simple Chains



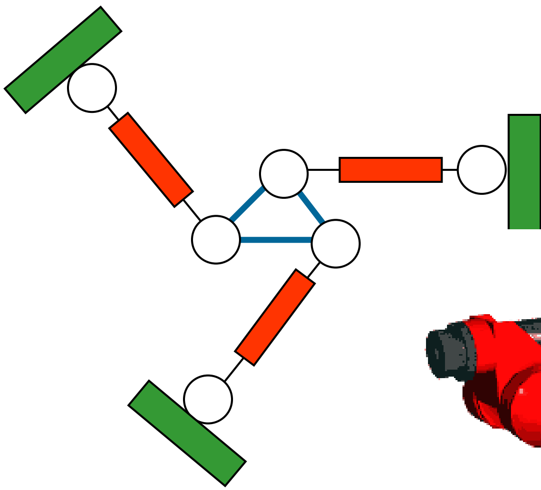


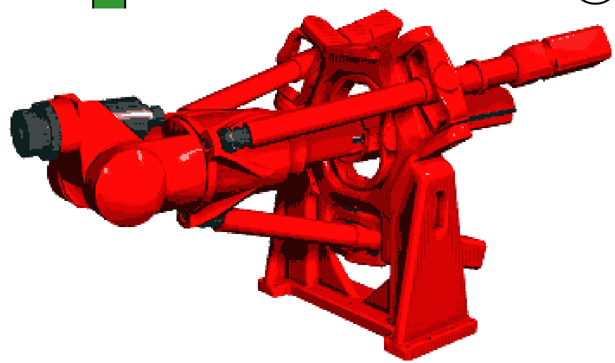


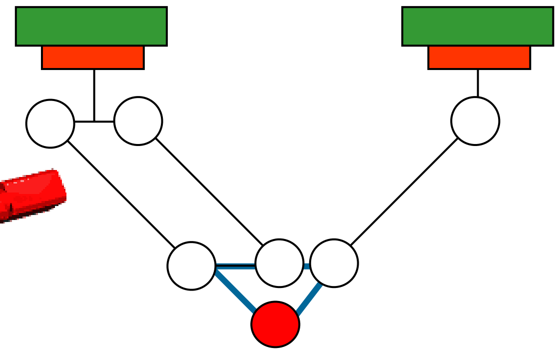


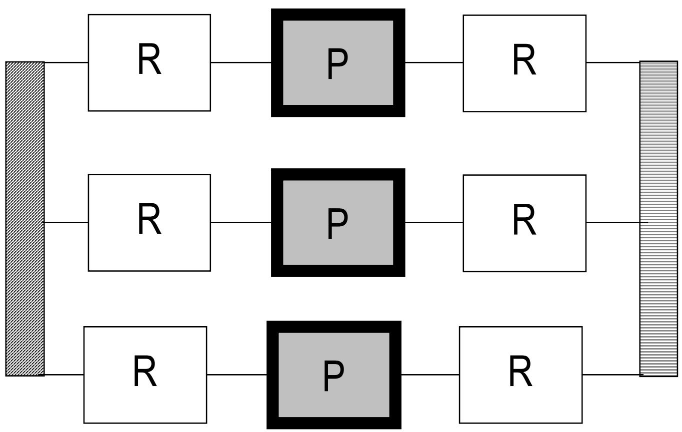
- The PKM Landscape -

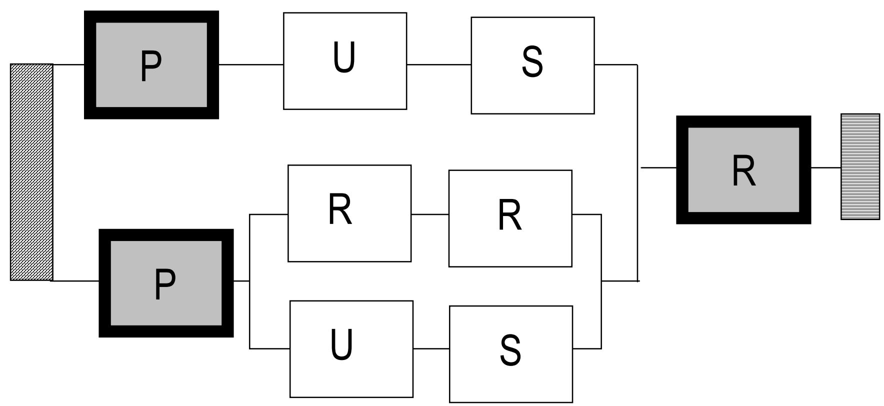
Parallel or Hybrid P-S



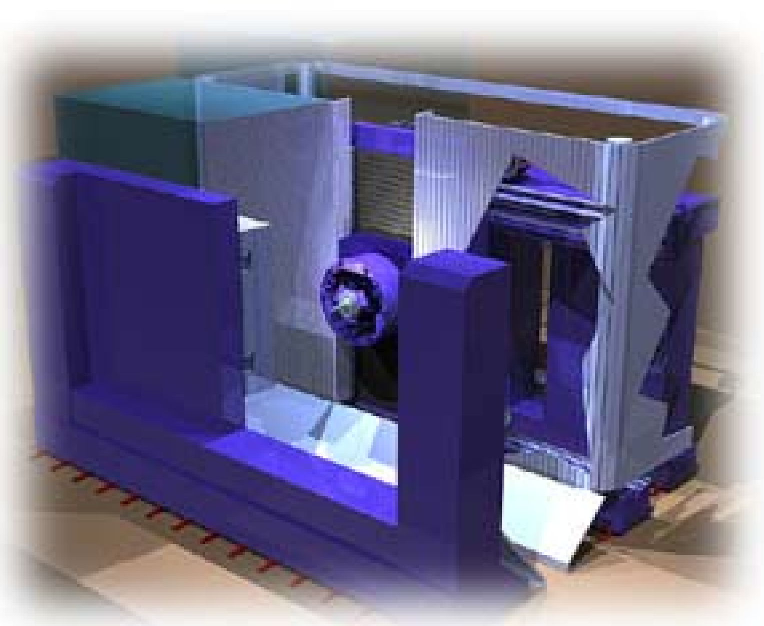


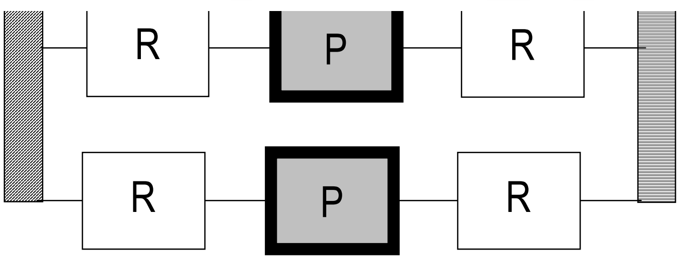


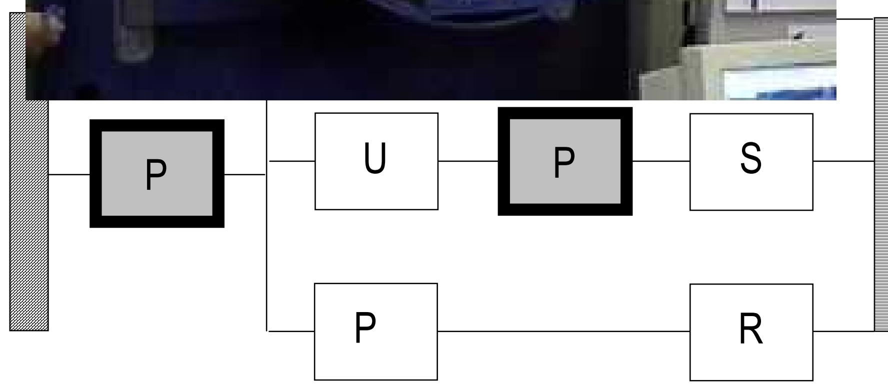




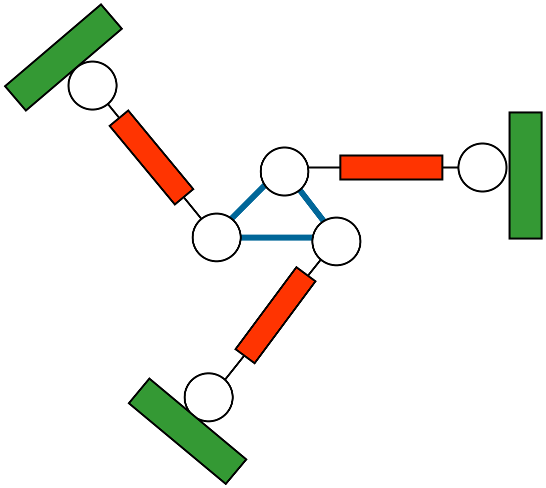
Parallel or Hybrid S-P

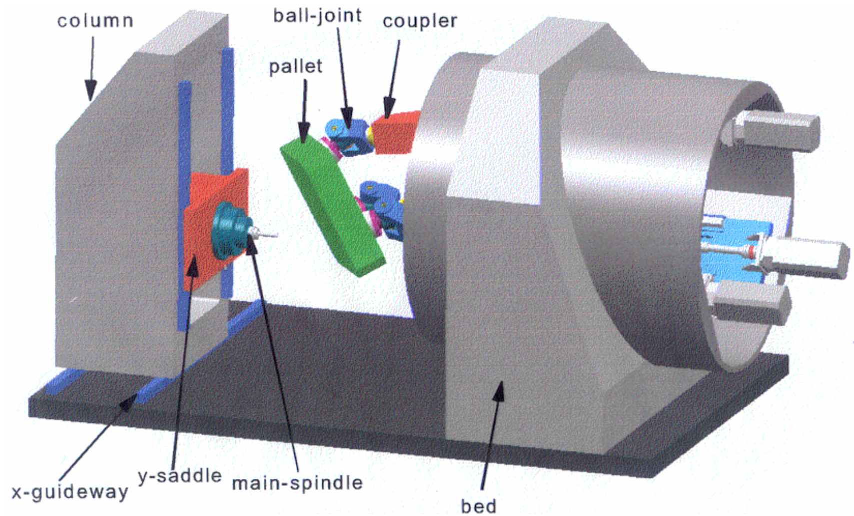


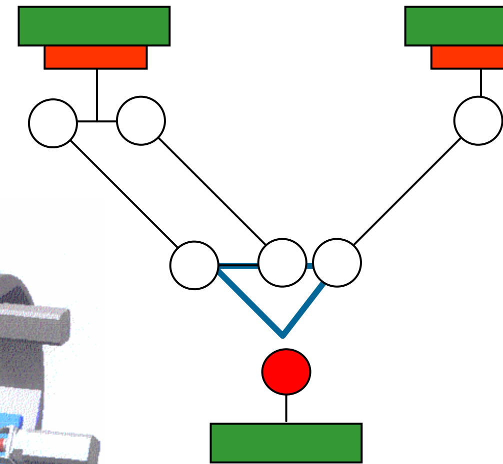


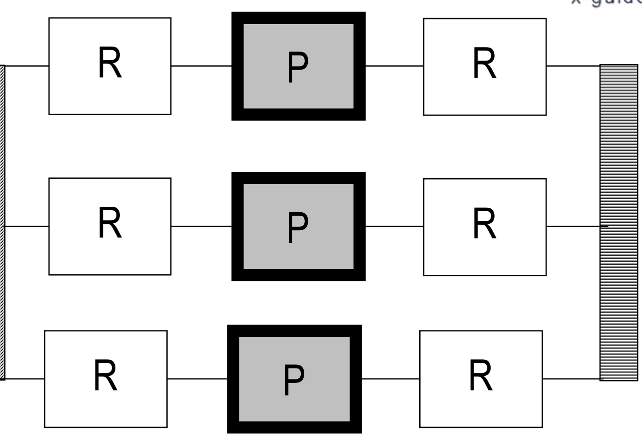


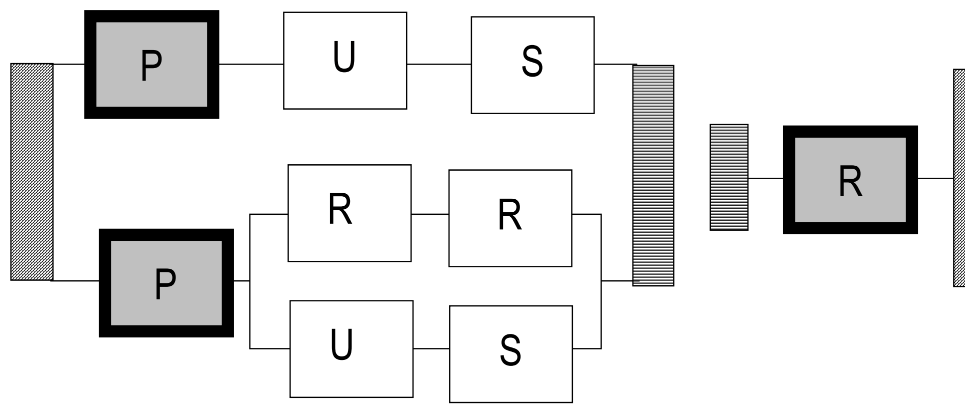
Parallel or Hybrid LH-RH



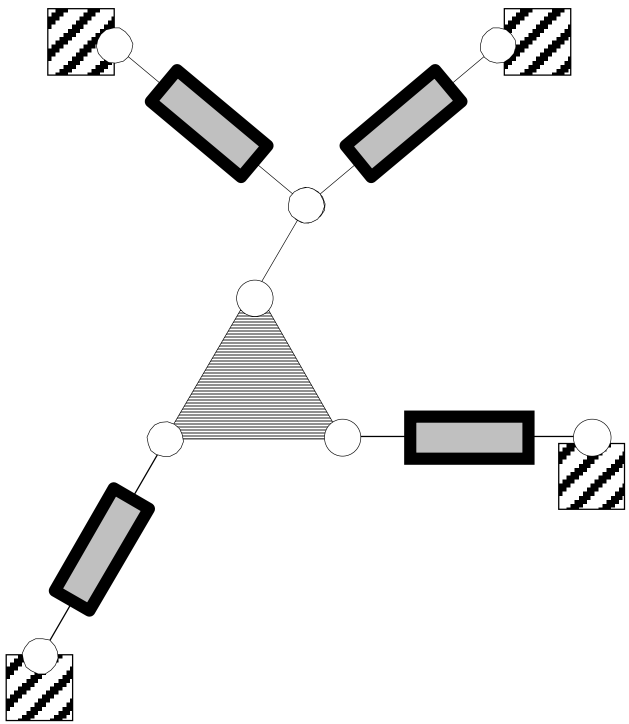


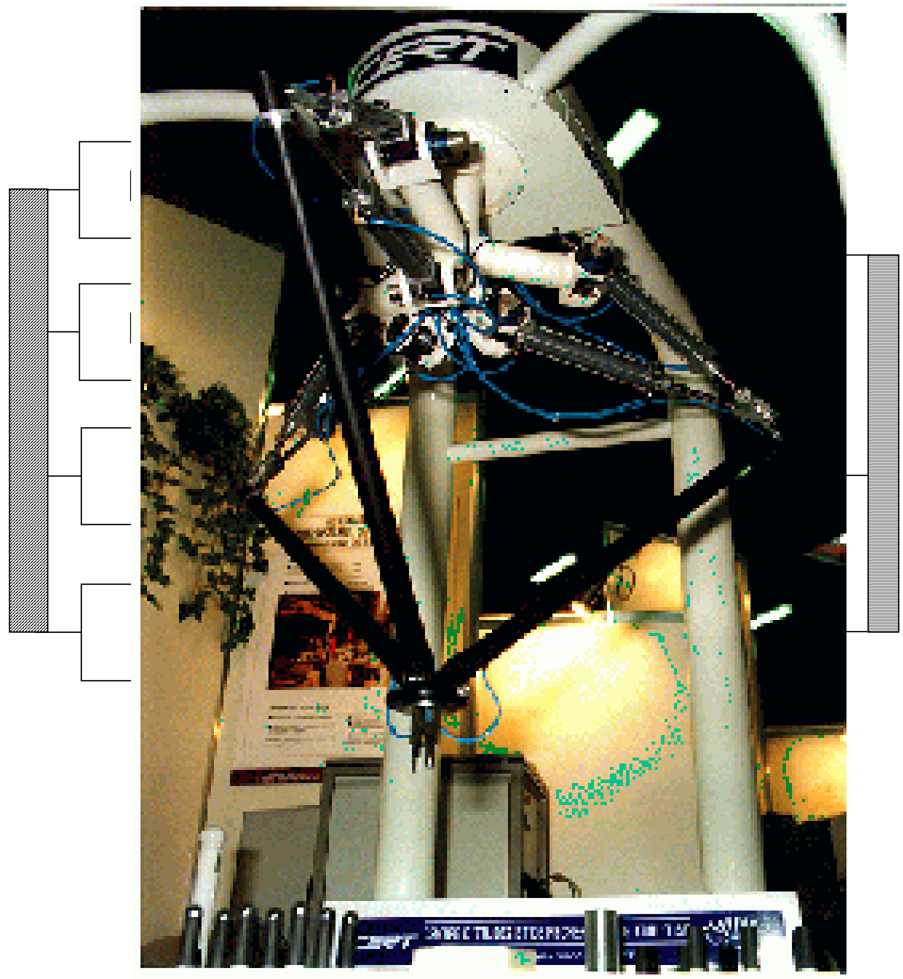




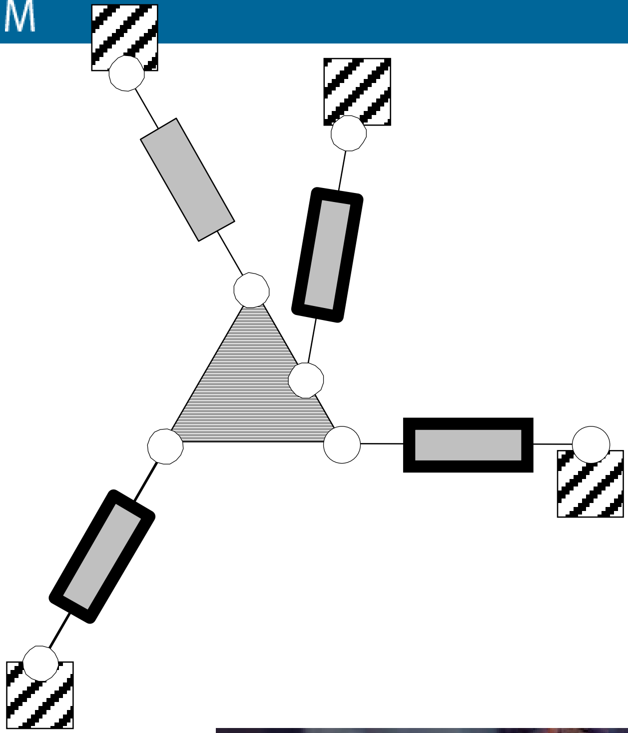


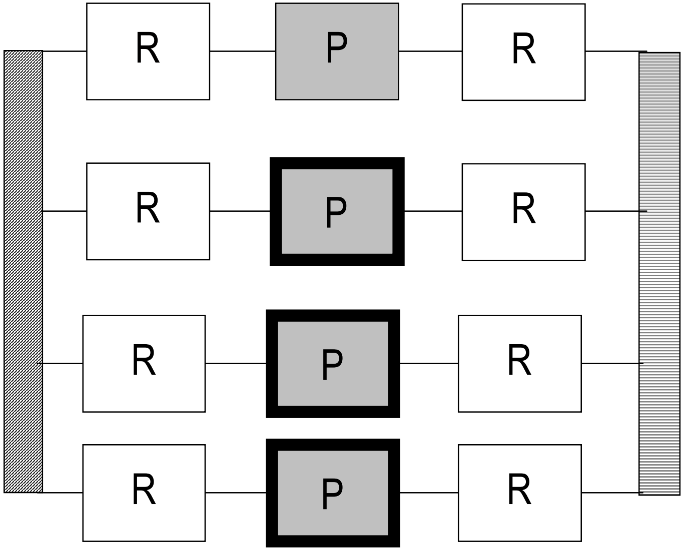
Kinematic Redundancy

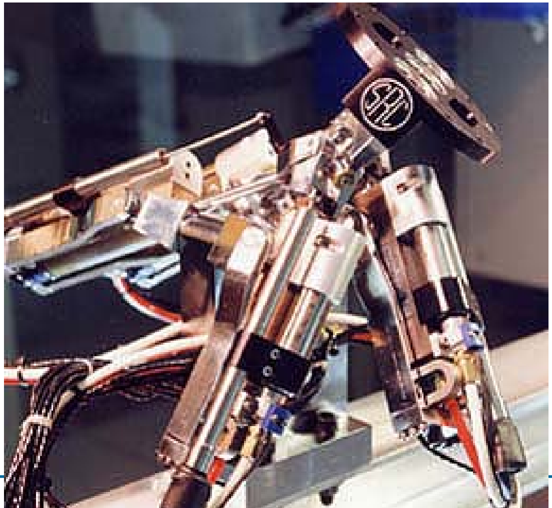


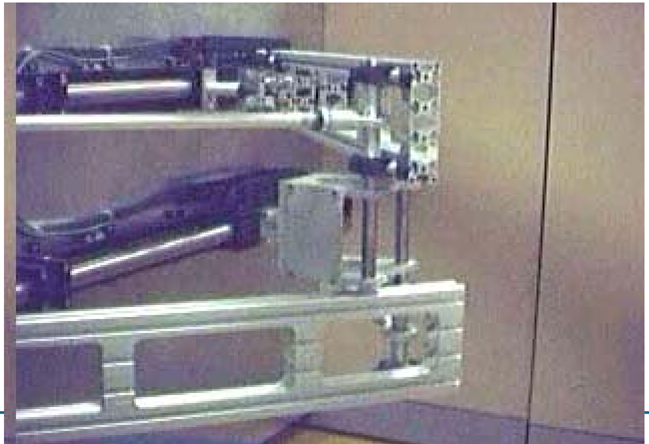


Actuation Redundancy

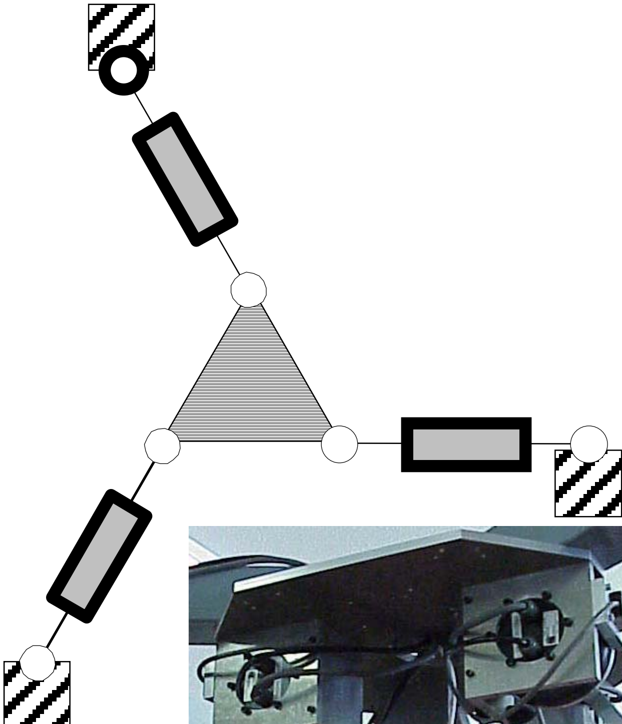


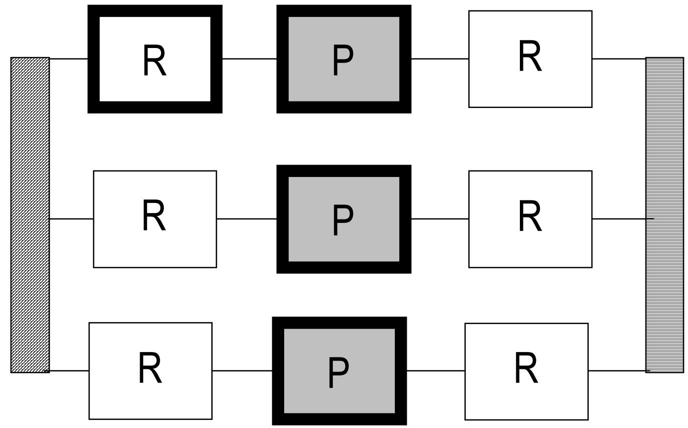


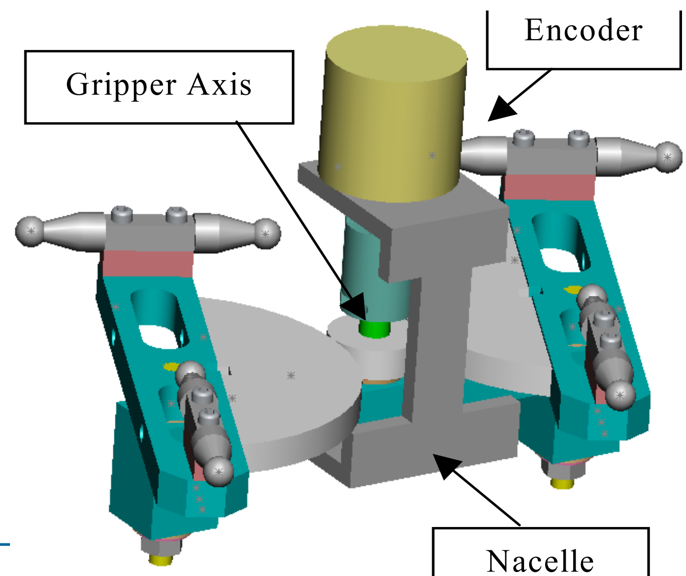




Measurement Redundancy

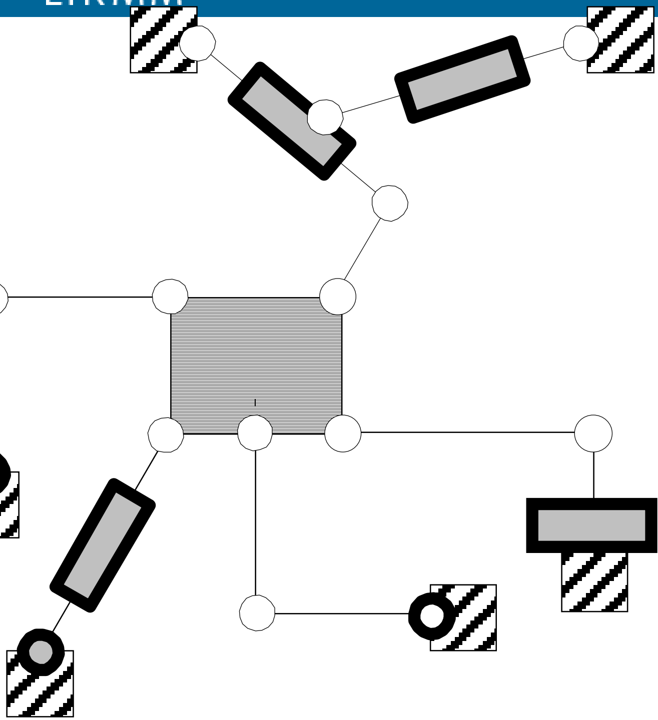


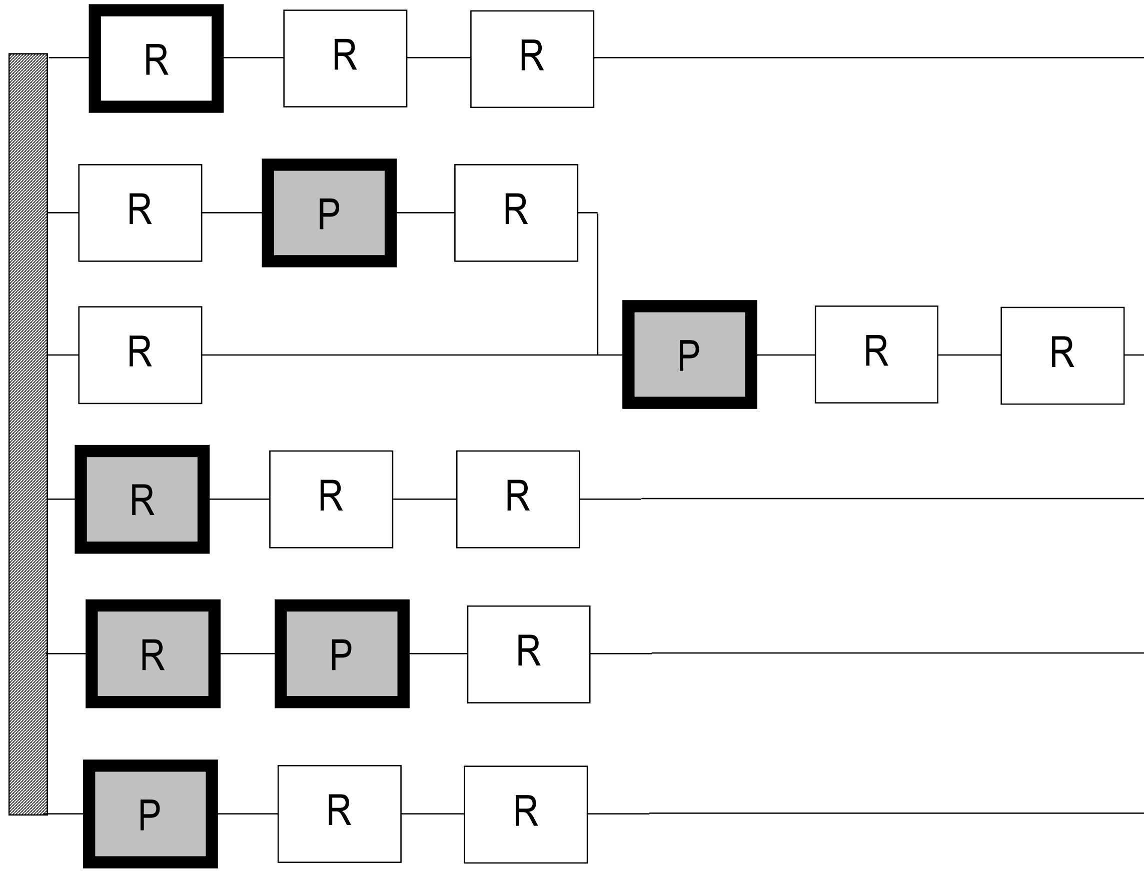


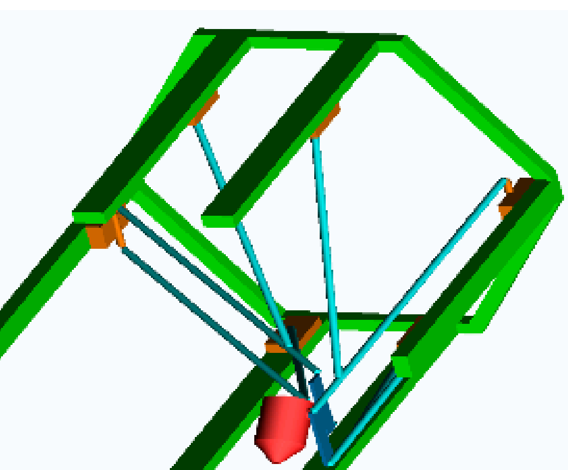


- The PKM Landscape -

No Limit!

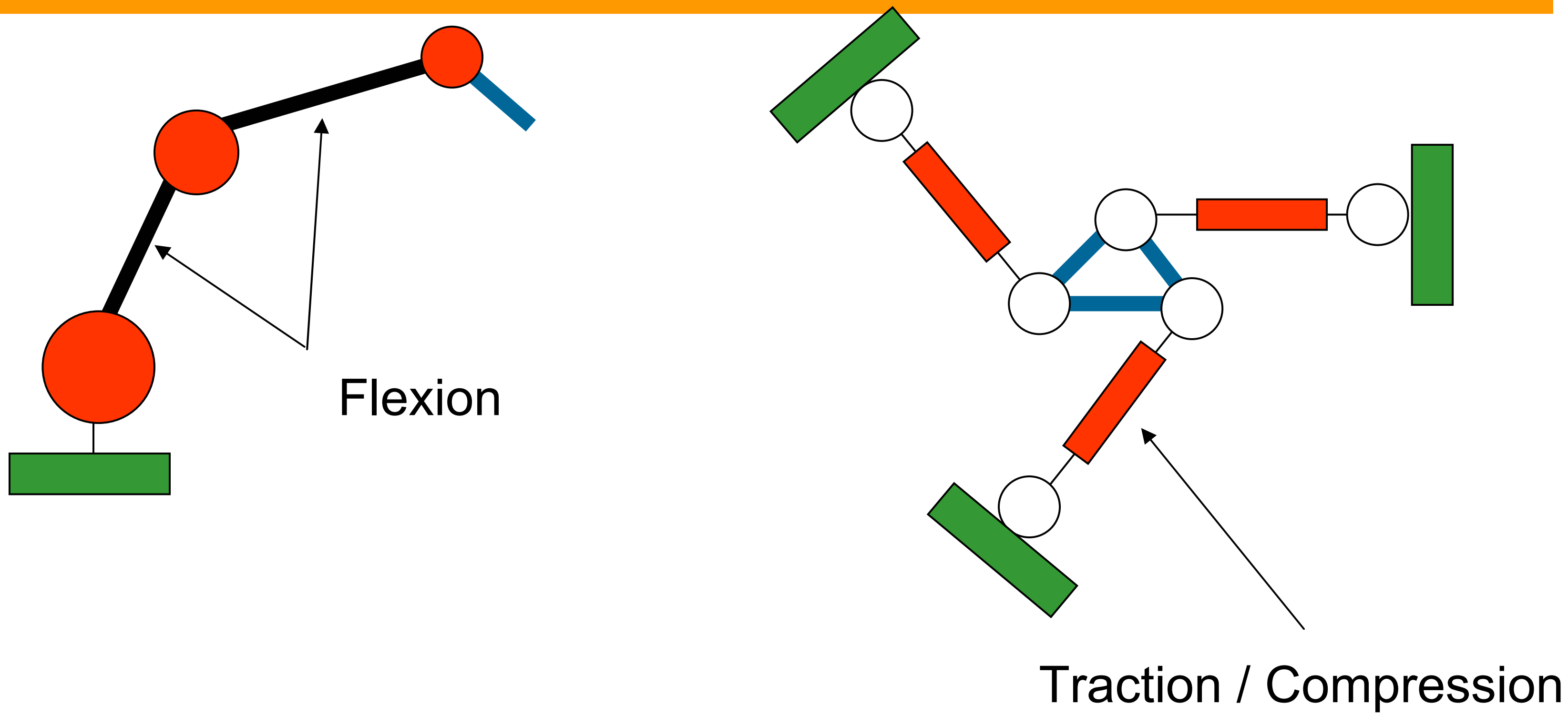






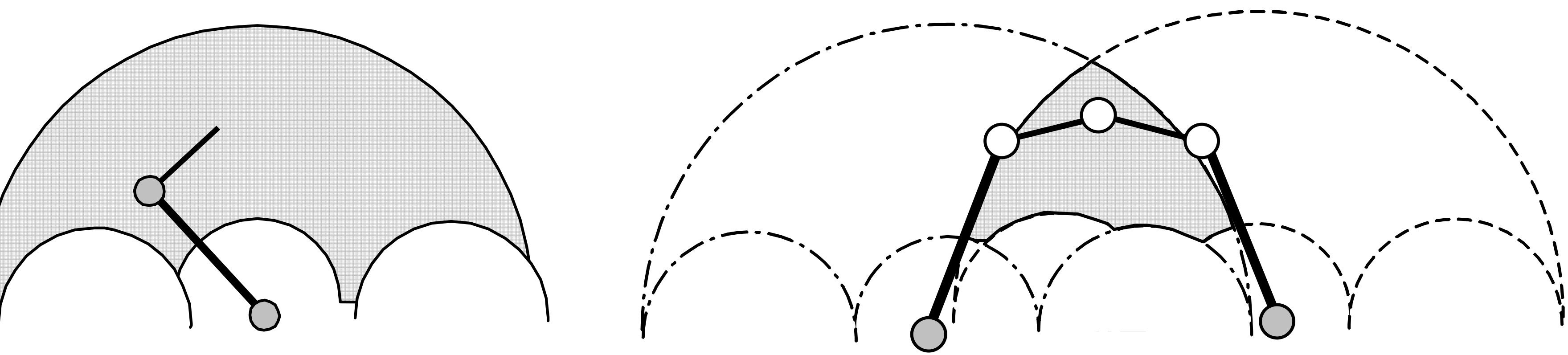
Common (Claimed) Advantages

- Stiffness, Accuracy, Speed, Acceleration (up to 40 g!)
- Good Weight/Load Ratio
- Lots of Common Parts
- Very good dynamic capabilities and ability to force control

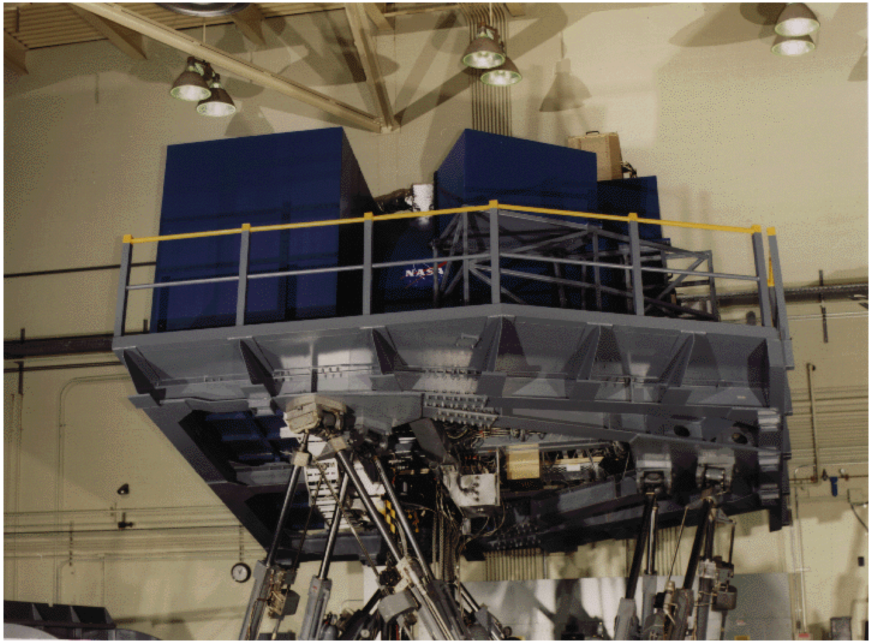


(Most) Commun Drawbacks

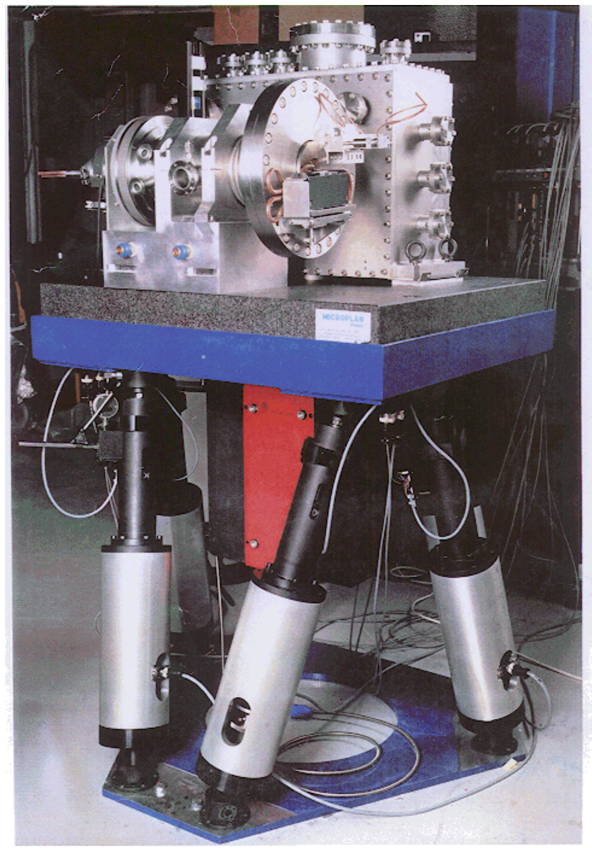
- Lots of Passive Joints
- Modeling / Singularities
- Not always supported by conventional NC
- Non classical calibration
- Too « advanced » for some markets
- Bad Foot-Print/Workspace Ratio



Application domains: simulators

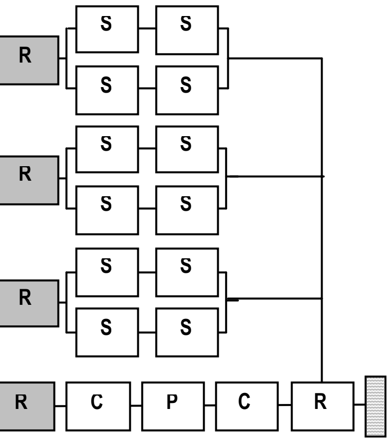


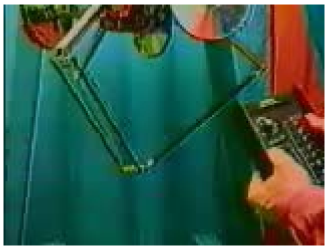
Application domains: positioning systems

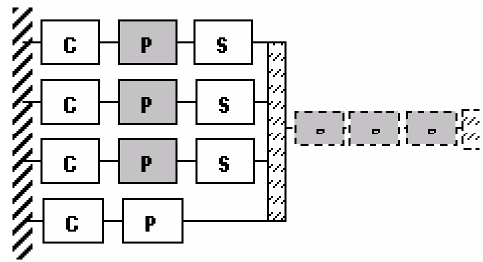


Application domains: handling

Delta

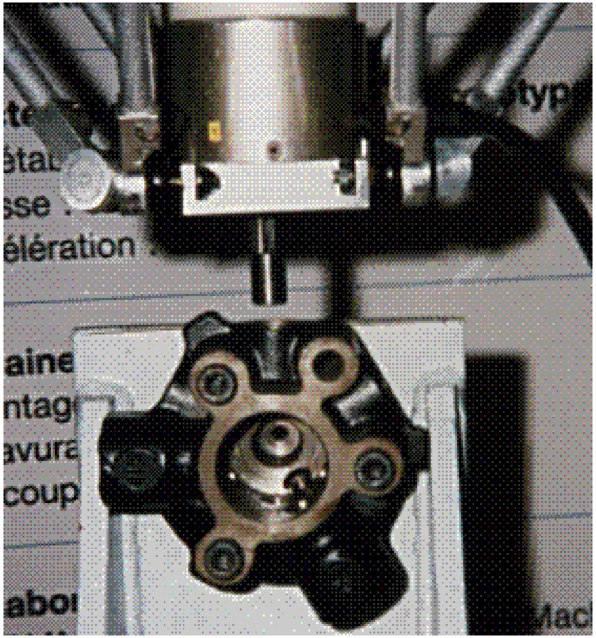






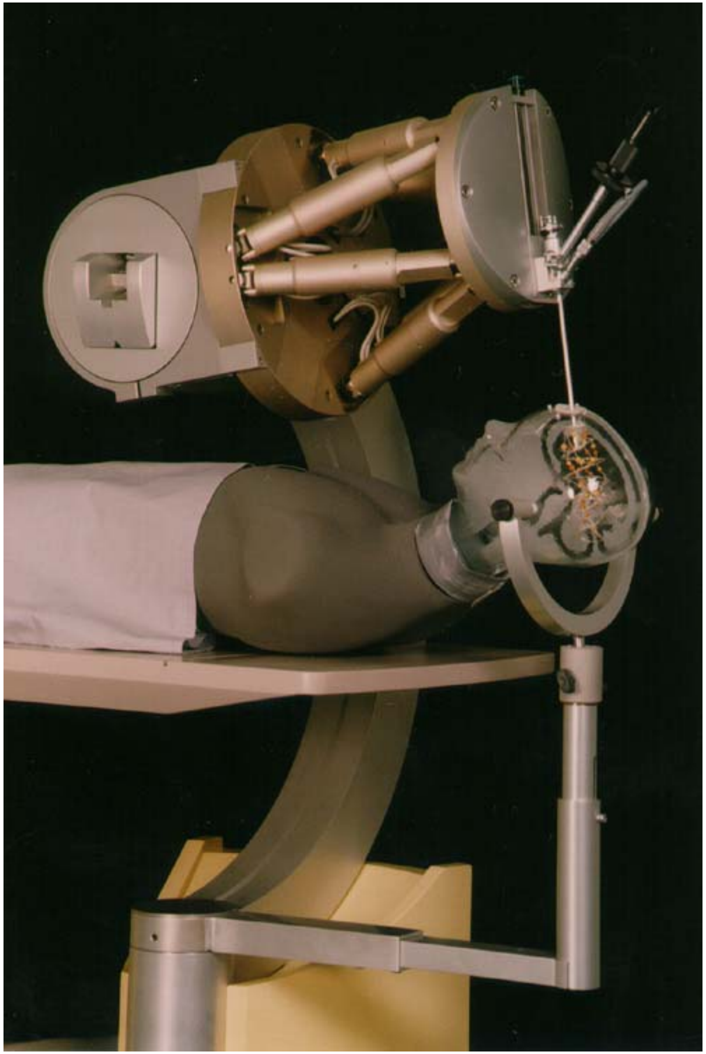
Tricept

Application domains: handling

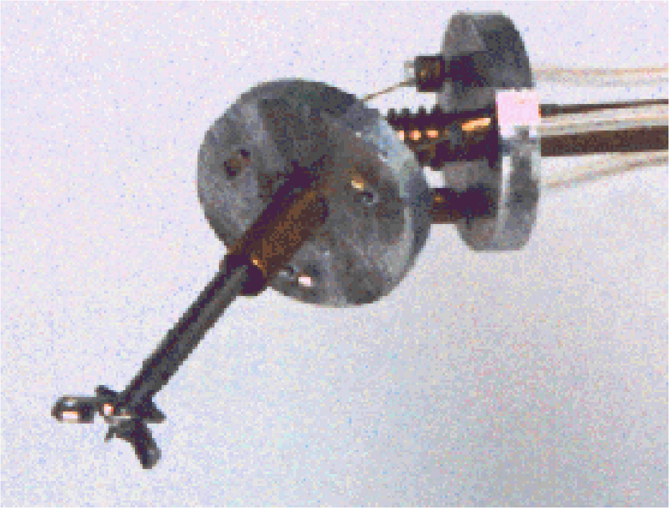


Application domains: machine-tool

Application domains: surgery

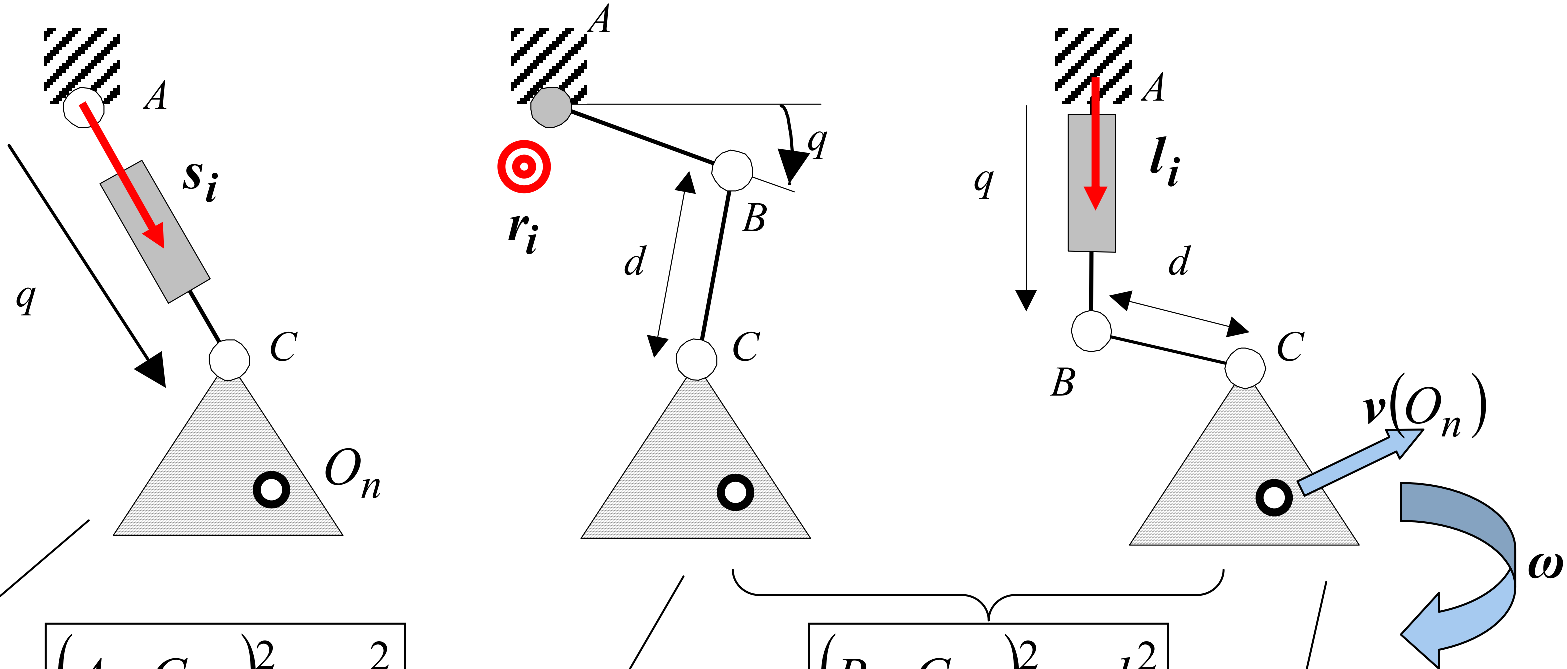


Application domains: surgery



Application domains: haptic devices

IKM (from *x* to *q*)



$$(A_{i,b}C_{i,b})^2 = q_i^2$$

$$= \mathbf{s_i} \cdot \mathbf{v}(O_n) + (\mathbf{s_i} \times C_iO_n) \cdot \boldsymbol{\omega}$$

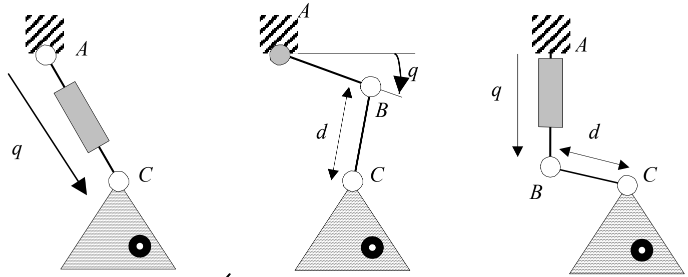
$$(B_{i,b}C_{i,b})^2 = d_i^2$$

$$\dot{q}_i (B_iA_i \times \mathbf{r_i}) \cdot B_iC_i = B_iC_i \cdot \mathbf{v}(O_n) + (B_iC_i \times C_iO_n) \cdot \boldsymbol{\omega}$$

$$\dot{q}_i (\mathbf{l_i} \cdot B_iA_i) \cdot B_iC_i = B_iC_i \cdot \mathbf{v}(O_n) + (B_iC_i \times C_iO_n) \cdot$$

Singularities (1)

$$\dot{\boldsymbol{q}} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \vdots \\ \dot{q}_k \end{bmatrix}$$



$$\dot{\boldsymbol{x}} = \begin{bmatrix} \boldsymbol{v}(O_n) \\ \boldsymbol{\omega} \end{bmatrix}$$

$$\boldsymbol{J_q} \cdot \dot{\boldsymbol{q}} = \boldsymbol{J_x} \cdot \dot{\boldsymbol{x}}$$

$$J_x = \begin{bmatrix} \boldsymbol{b}_1^t & (\boldsymbol{b}_1 \times C_1 O_n)^t \\ \boldsymbol{b}_2^t & (\boldsymbol{b}_2 \times C_2 O_n)^t \\ \vdots & \\ \boldsymbol{b}_k^t & (\boldsymbol{b}_k \times C_k O_n)^t \end{bmatrix}$$

$$\boldsymbol{J_q} = \boldsymbol{Ident_k}$$

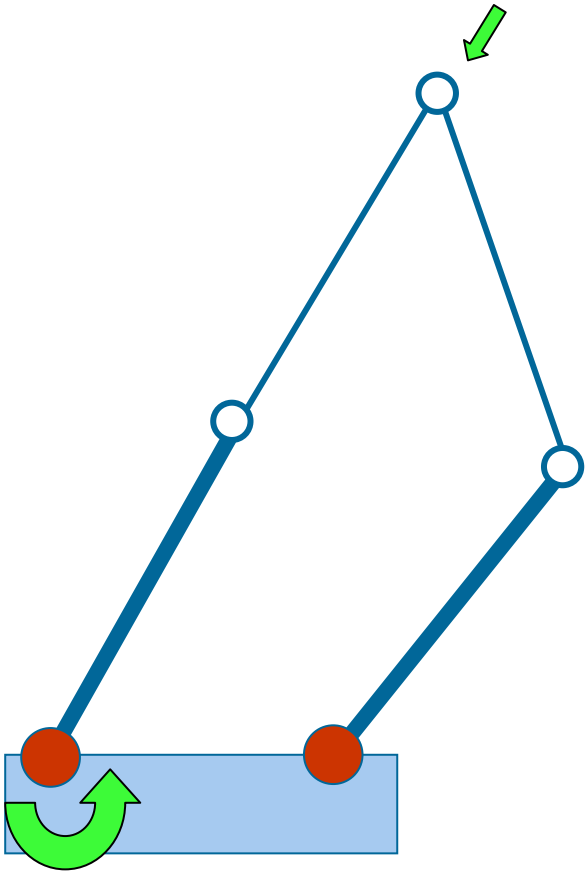
$$J_q = \begin{bmatrix} (B_1 A_1 \times \boldsymbol{r_1}) \cdot \boldsymbol{b_1} & 0 & 0 & 0 \\ 0 & (B_2 A_2 \times \boldsymbol{r_2}) \cdot \boldsymbol{b_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & (B_k A_k \times \boldsymbol{r_k}) \cdot \boldsymbol{b_k} \end{bmatrix}$$

$$\boldsymbol{J_q} = \begin{bmatrix} \boldsymbol{l_1}.\boldsymbol{b_1} & 0 & 0 & 0 \\ 0 & \boldsymbol{l_2}.\boldsymbol{b_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \boldsymbol{l_k}.\boldsymbol{b_k} \end{bmatrix}$$

Singularities (2)

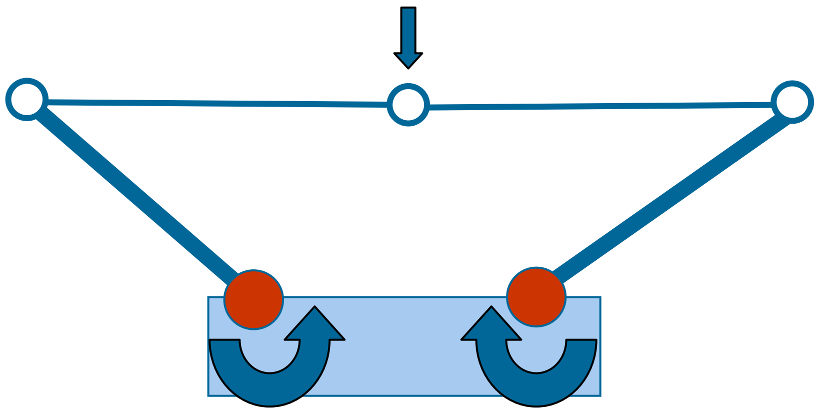
Under-mobility (serial):

motor moves ➔ no tool motion

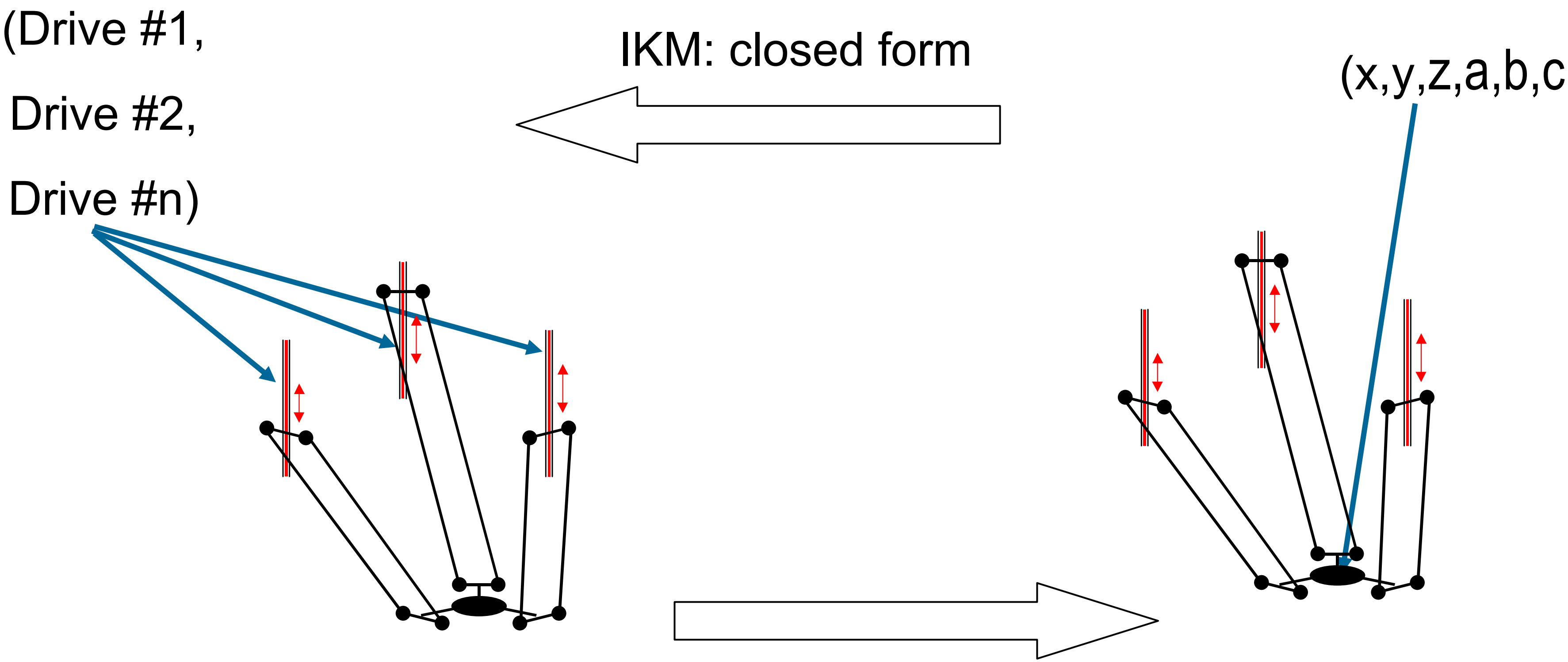


Over-mobility (parallel):

High motor torque ➔ no force at tool



FKM (from *q* to *x*) (1)



FKM :

- Few “nice” cases with closed form
- Often: numerical resolution (polynomial of 4^{th}, 8^{th} , 16^{th} , ... order)

FKM (from *q* to *x*) (2)

Two options for numerical solving:

- Solving the polynomial (☺ all solutions, ☹ computation cost)
- Looking for ONE solution (☺ fast, ☹ instability risk)

$$\hat{x}_0 \quad \rightarrow \quad q_0 = mgi(\hat{x}_0)$$

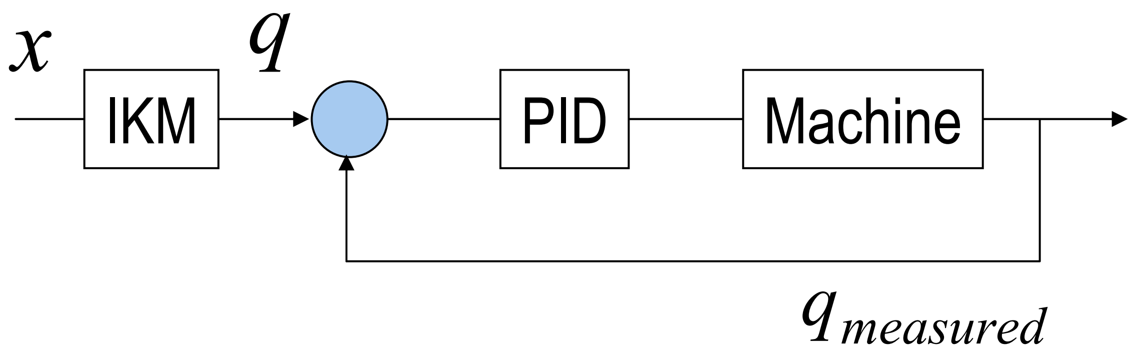
$$\hat{x}_0 \quad \rightarrow \quad (J_x, J_q)_0 \quad \rightarrow \quad J_0 = J_x^{-1} J_q$$

$$e_0 = q_{mesuré} - q_0 \quad \rightarrow \quad \hat{x}_1 = \hat{x}_0 + J_0 . e_0$$

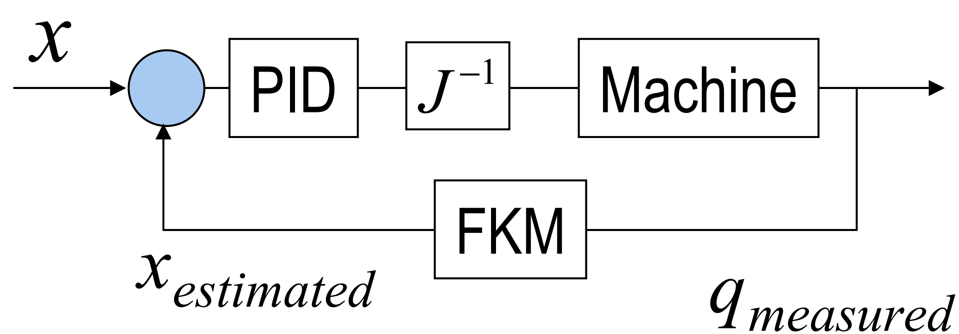
$$\ldots stop\ if\ \left\| e_k \right\| < accuracy \quad threshold$$

General remarks about control

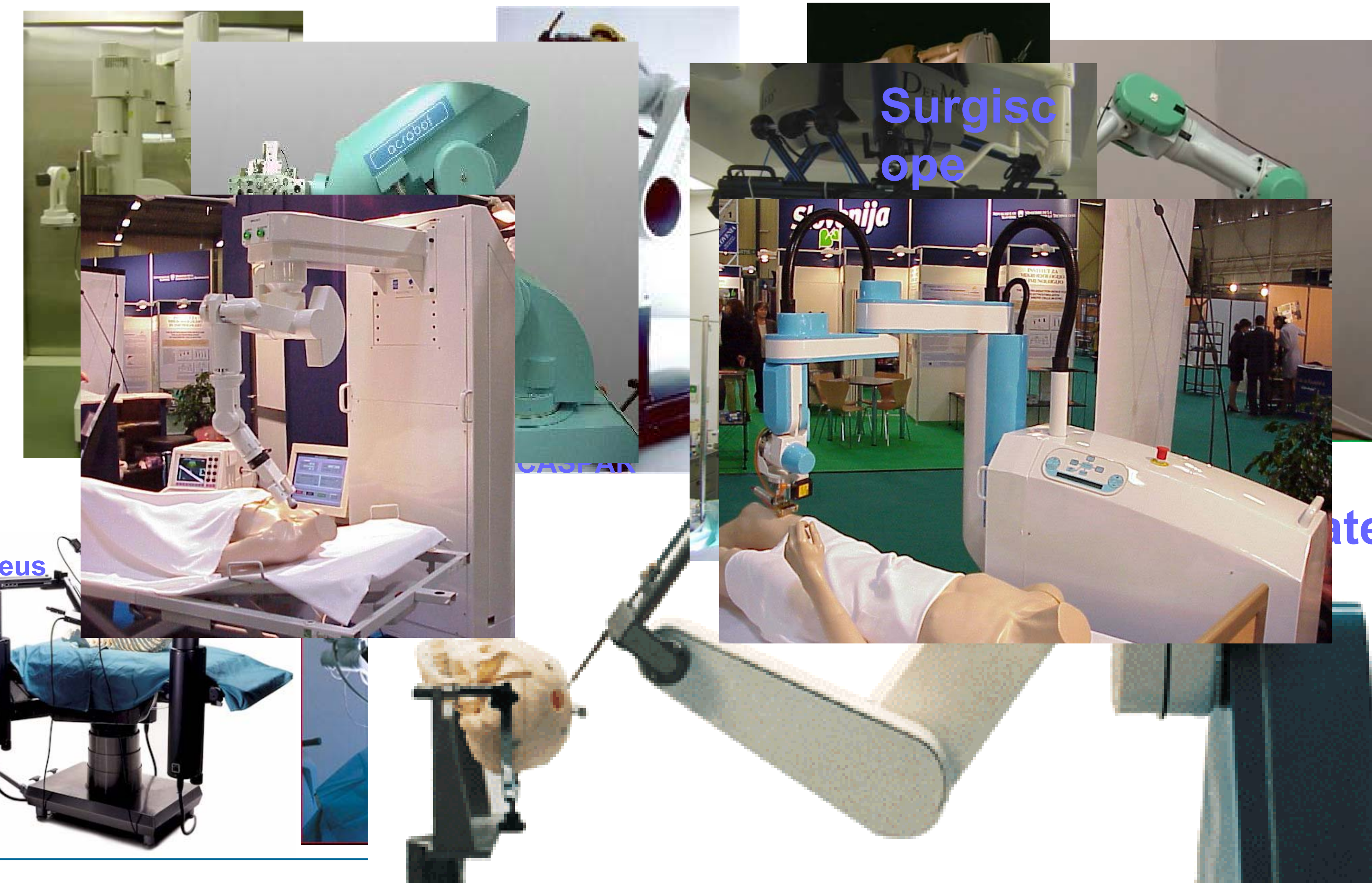
- In Joint Space with IKM



- In Cartesian Space with Jacobian



Not enough?



A need for multi-purpose systems

- An industry sector is mature when standards exist

- This help to reach:
  - Lower costs
  - Better reliability
  - Portability of applications and tools
  - Creation of a “universal” knowledge

Multi-purpose systems?

- How many dof?
- What velocity, acceleration?
- What force?
- What kinematics?
- Above questions hold for both master and slave arms

Multi-purpose slave arm: dof

- Nb of dof:
  - Brain➔5 dof (a point & one direction)
  - Orthopedic ➔ 5 dof (drilling) or 6 dof (cutting)
  - M.I.S. ➔5 dof extra-body + 3 dof (intra-body rotations)
    ➔6 dof extra-body (if Rz is accounted for) + 2 dof (intra-body)
  - Skin grafting ➔ 6 dof

A multi-purpose slave arm may be composed of:

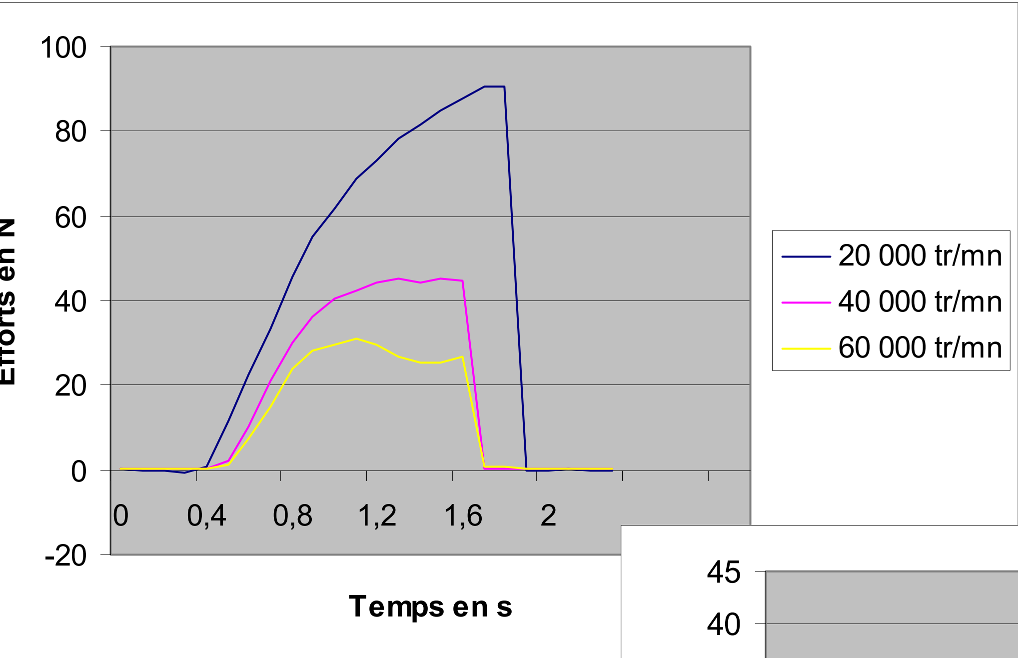
- A “universal” carrier with 5 or 6 dof
- A “specific” wrist with 1 to 3 dof

Multi-purpose slave arm: speed & force

- Speed, acceleration
  - Brain ➔ often works at rest
  - Skin grafting ➔a few mm/s
  - M.I.S. ➔ several 100mm/s (large rotations of tool x tool length)
  - Orthopedic ➔a few mm/s
  - Heart ➔ Acceleration probably > 1g (if “heart-beating surgery” is considered)

- Forces:
  - Brain ➔ ?
  - Skin grafting ➔40 N ~ 80 N
  - M.I.S. ➔ few N (+ disturbances due to the trocar)
  - Orthopedic ➔ up to 100 N (extremely dependent on cutting param.)

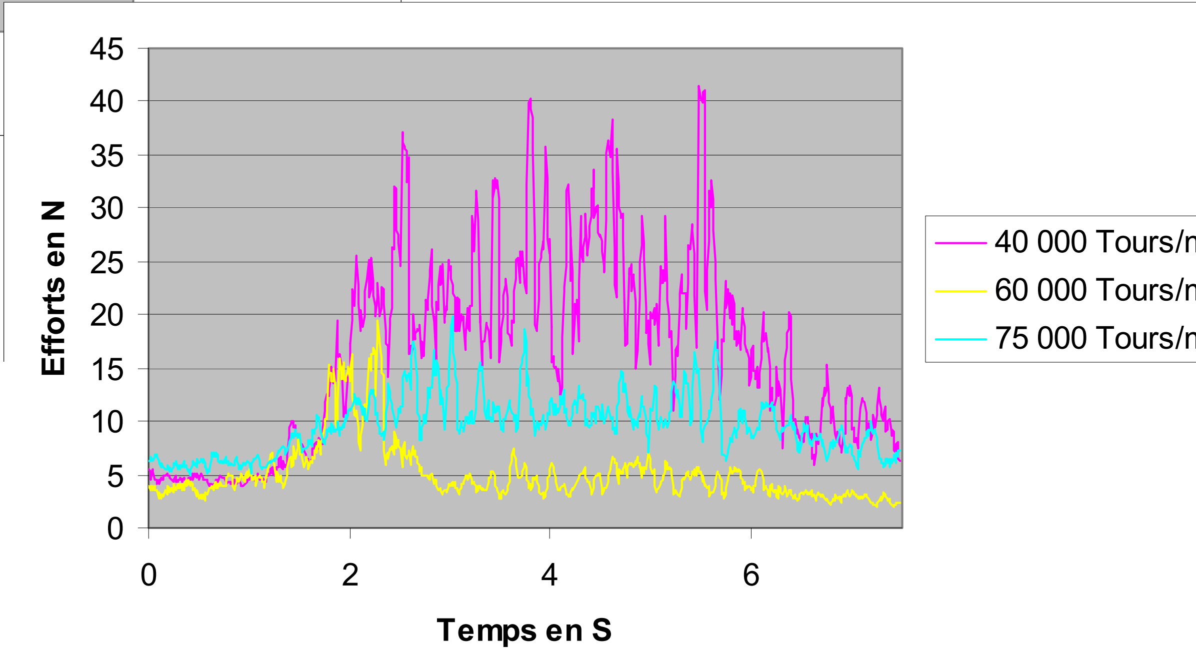
Remark: forces in machining bone



Drilling

Tool Diameter 2 mm

Speed 5.8 mm/s



Milling

Tool Diameter 12.5 mm

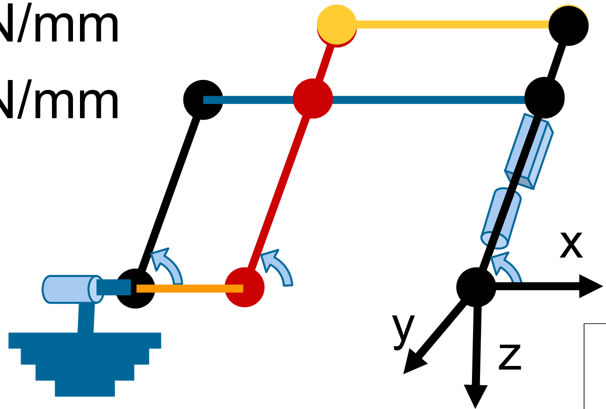
Depth of cut 2 mm

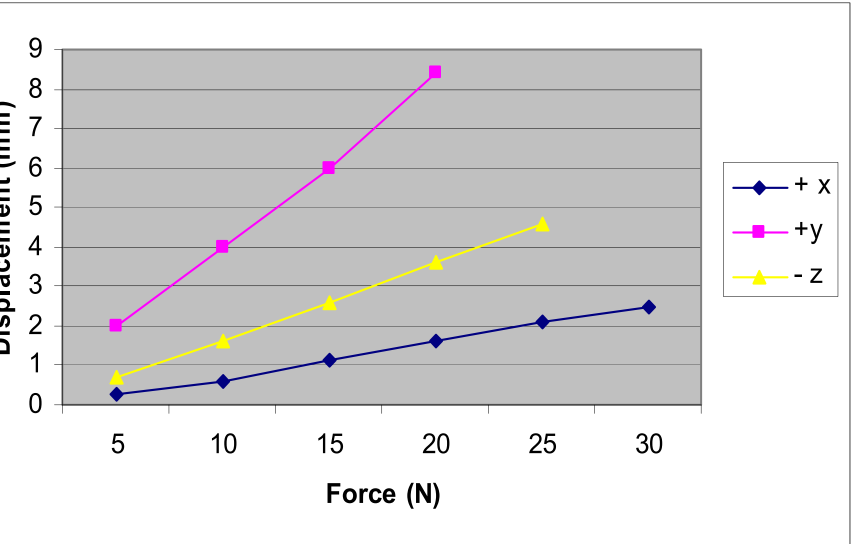
Speed 4.0 mm/s

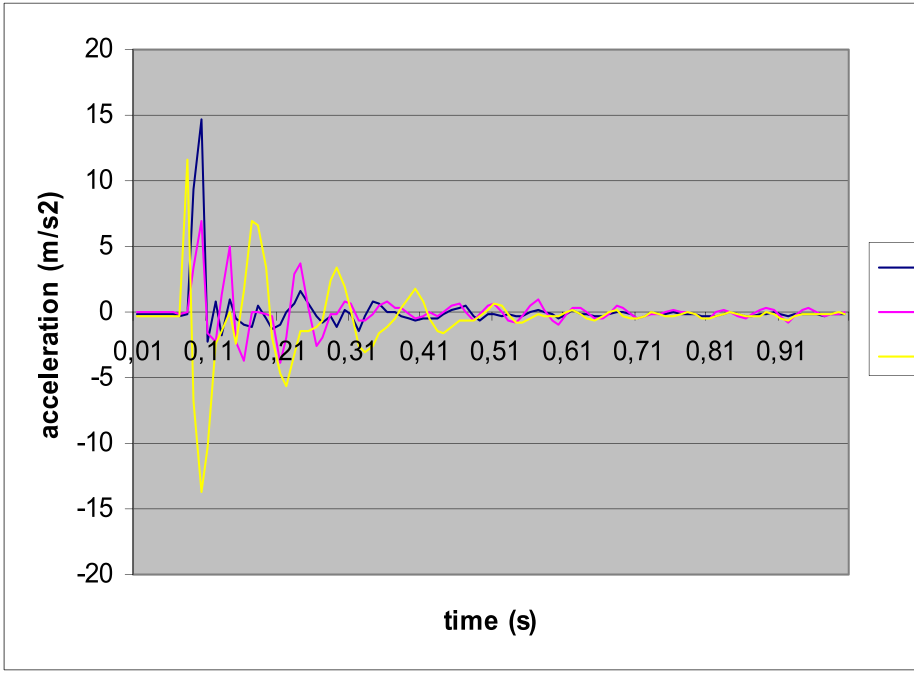
Remark: DaVinci arm is not made for bone machining

- kx = 12 N/mm
- ky = 2,4 N/mm
- kz = 5,4 N/mm

- Very low vibration frequency







Multi-purpose slave arm: force & speed

- A multi-purpose slave arm may be required to offer:
  - Good behavior at speed as low as few mm/s
  - The capability to move as fast as several 100mm/s
  - A sensitivity good enough to guarantee low forces
  - The capability to exert force up to 100N
  - Good acceleration ability (for “heart-beating surgery”)
  - Good stiffness

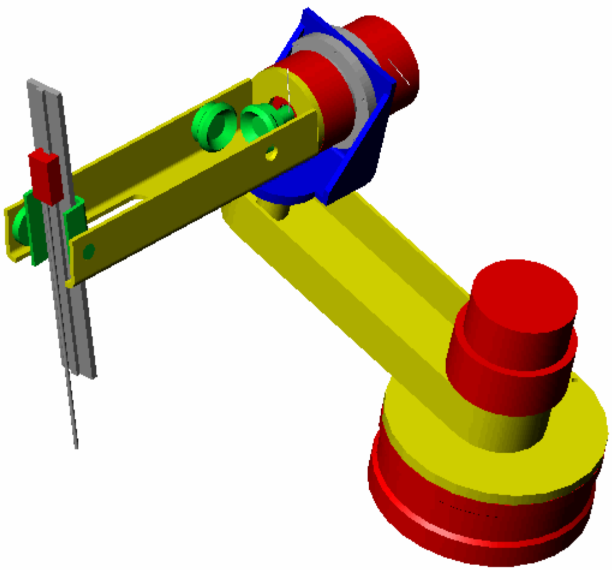
A multi-purpose slave arm could be based on Direct Drives

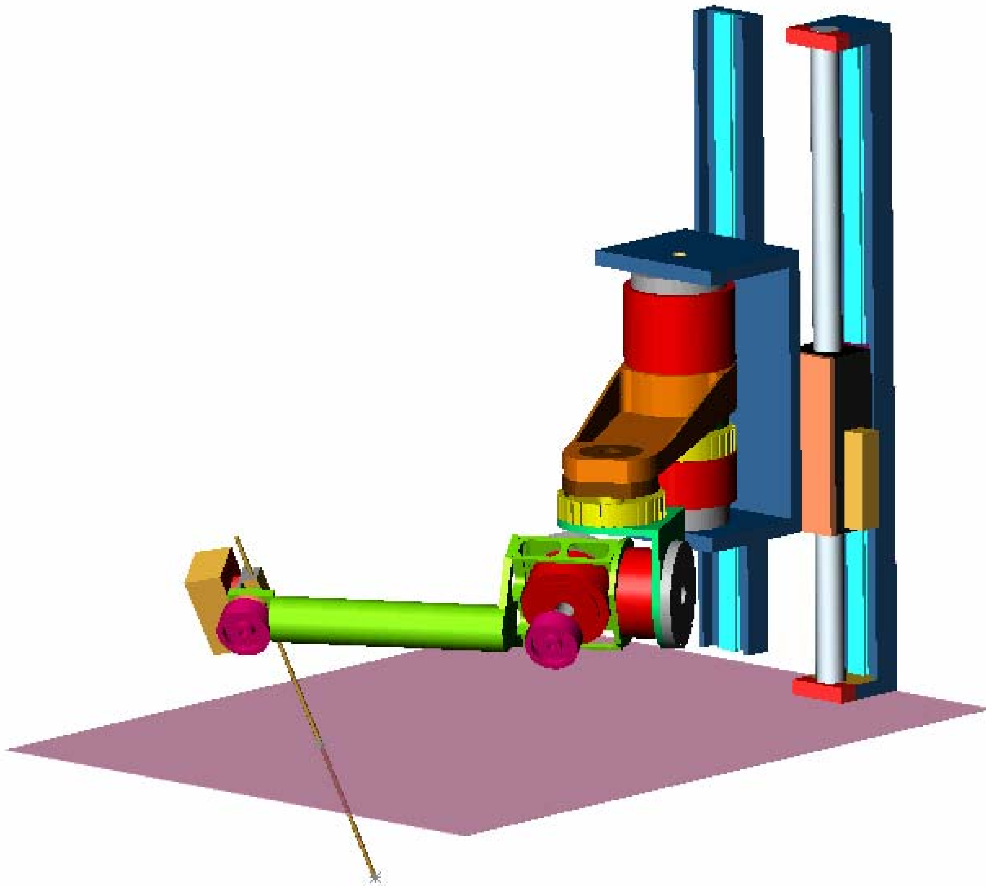
(safety issues?)

Multi-purpose slave arm: kinematics

- The carrier part of a multi-purpose slave arm may be based on Scara kinematics for the following reasons:
  - Convenient fit between robot workspace and human body volume
  - Models are straightforward, even with “fancy” wrists
  - Singularities are easily managed
  - Gravity effect may not be such a big problem
  - Scara fits well with DD technology

Multi-purpose slave arm: potential solutions





Selection of a master arm

- Dof: 6
- Range of motion
  - Translation ⬄ [10 cm]^3 ~ [20 cm]^3
  - Rotation ⬄ > (140 x 90 x 120) degrees
- Force-feedback capable
  - Several N for rough force sensing (orthopedic)
  - < N for M.I.S.
  - High dynamic, e.g. for heart surgery (“the touch of a finger on an atheromatous artery”)

- High dynamics and extreme sensitivity makes it difficult for serial arms ➔ incredible costs!
- No “pure” PKM exists with such a large range of motion

Selection of a master arm: the PKM way

- A multi-purpose master arm may be based on advanced PKM concepts:

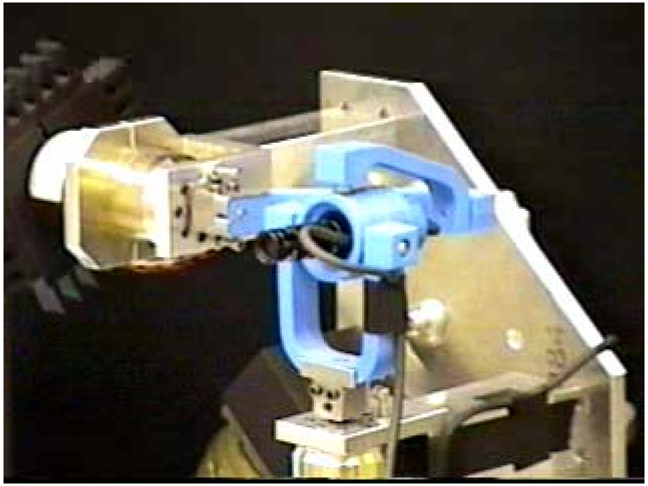
  – Hybrid design

  or

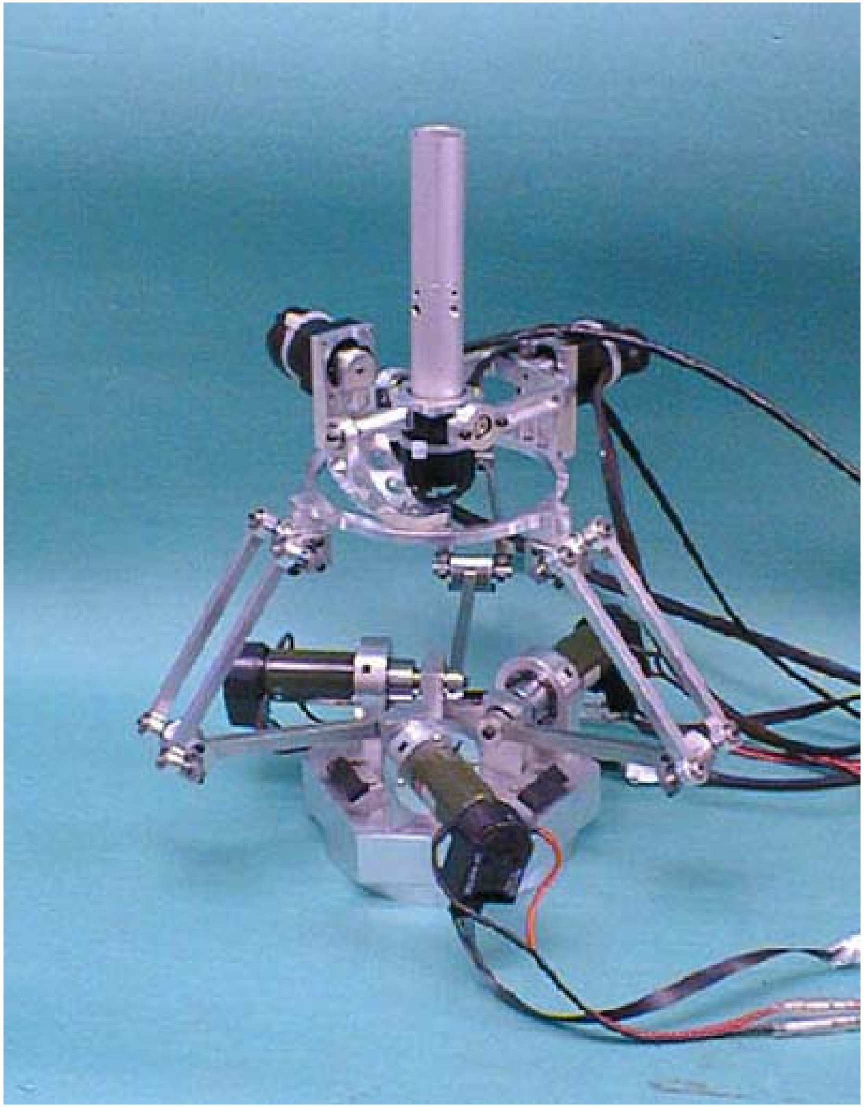
  – Redundancy

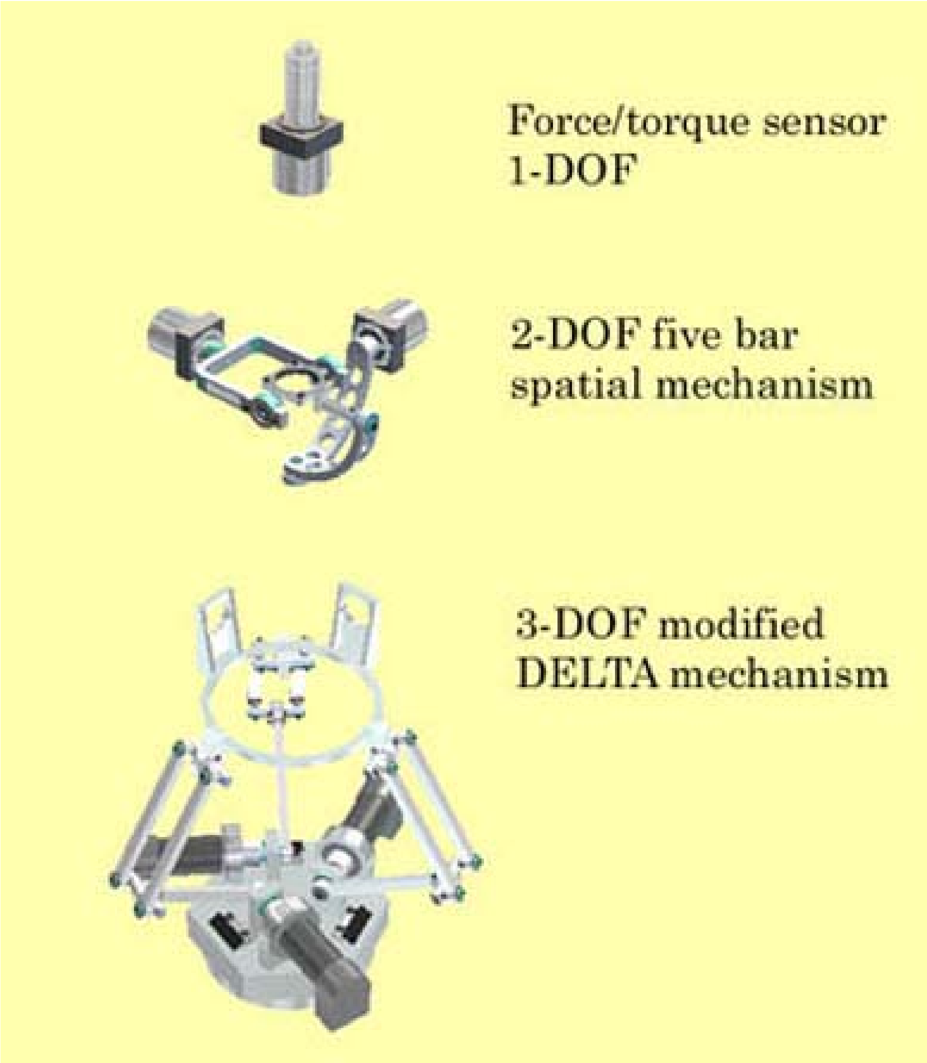
  or

  – Both

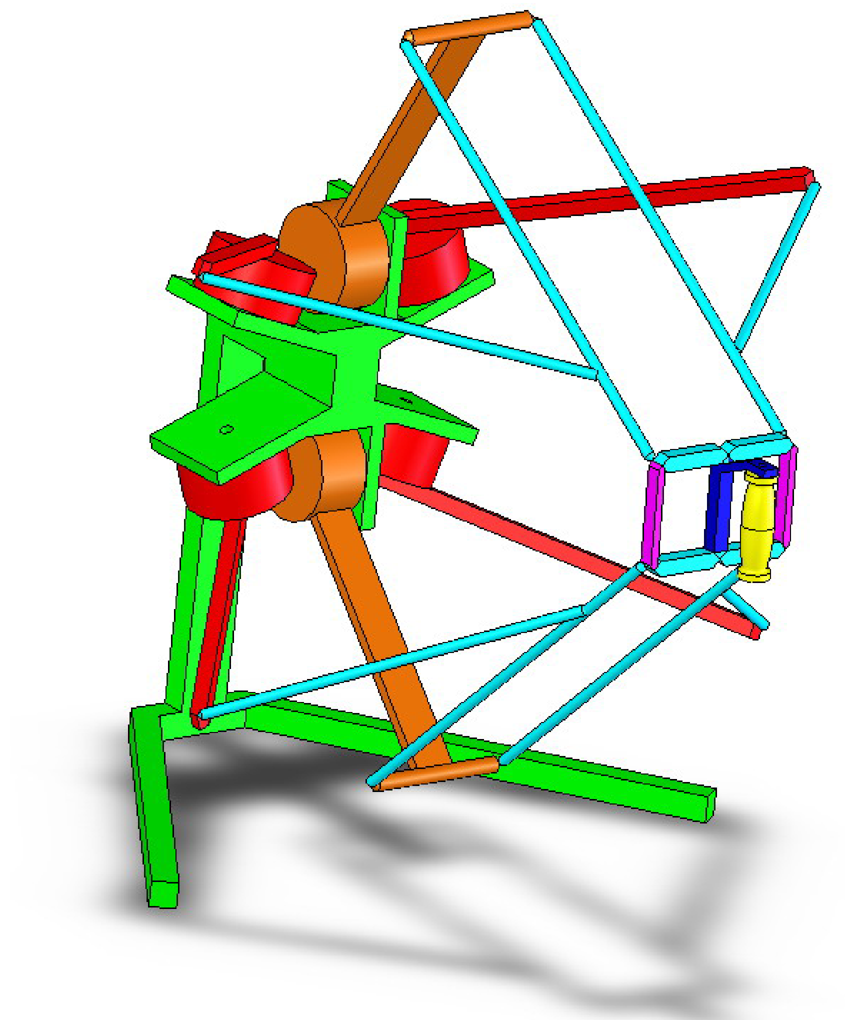


Multi-purpose master arm: potential solutions





Multi-purpose master arm: potential solutions



Multi-purpose systems: a general picture

Standardized
Scara-like
DD arms
Under force control

Remotely operated by

Hybrid PKM with
Large tilting capabilities

And Carrying
Specific Wrists