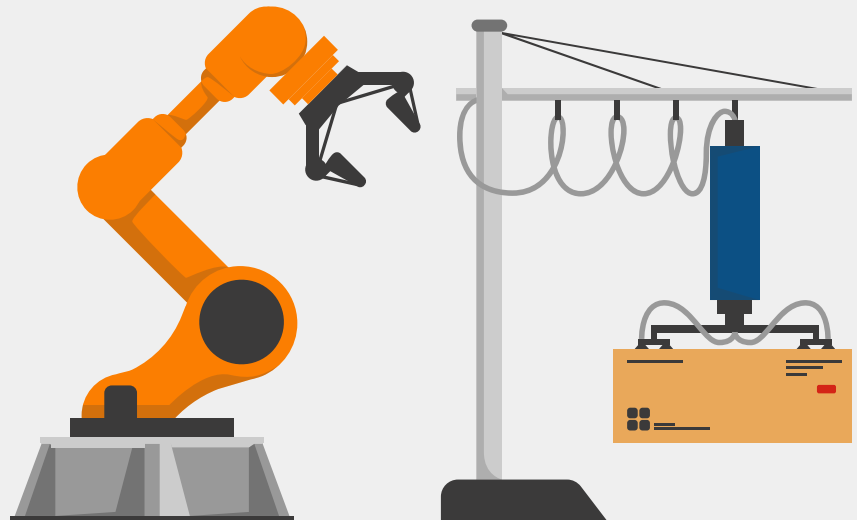


Influence of the robot's geometric behavior on task execution

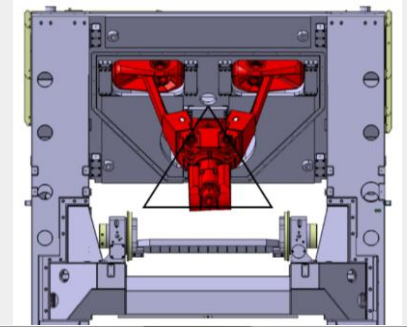
Hélène CHANAL
helene.chanal@sigma-clermont.fr



Who am I ?



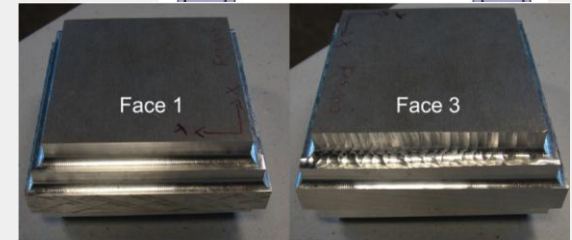
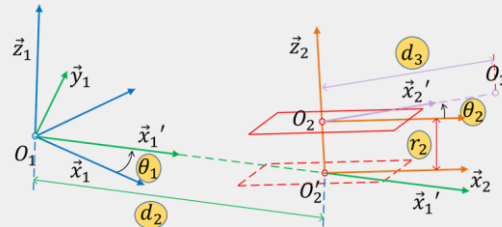
- Professor at SIGMA Clermont / Institut Pascal
- My research activities :
 - Controlling the behavior of machine tools:
 - Improving the precision of manufactured parts
 - Controlling the behavior of robots:
 - Improving task performance



Additive manufacturing



Mechanical modeling



Machining

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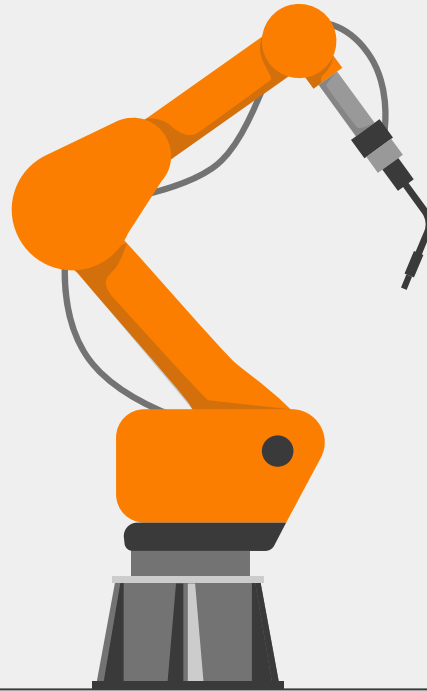
Introduction

Context and problematic

03

Kinematic modeling

Definition and methodologies



02

Programming principles

Setting an industrial robot in motion

04

Identification

Definition and methodologies



01

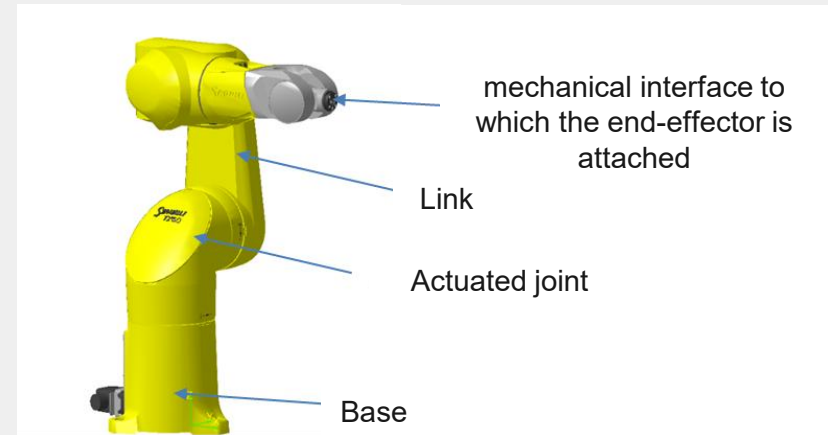
Introduction

Context and problematic

Introduction

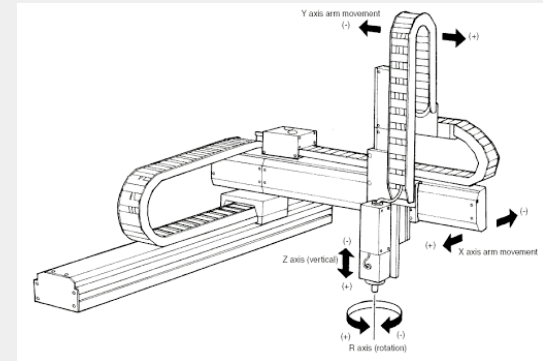
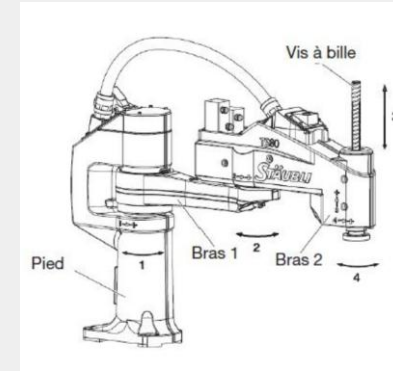
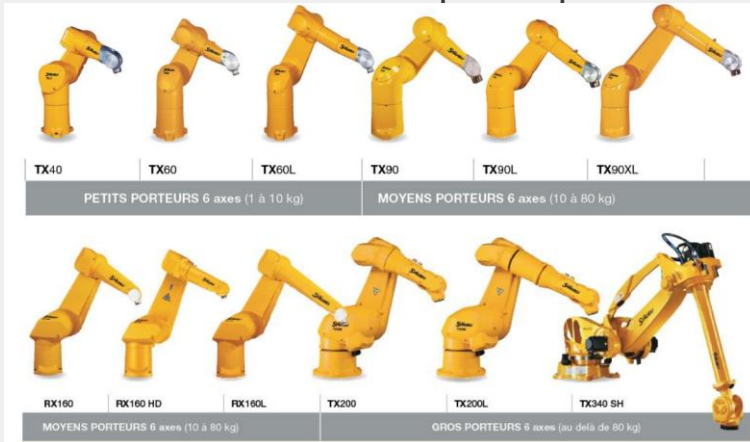
- Definition from ISO 8373
 - An industrial robot is a manipulator:
 - Adaptable to different applications
 - Movements can be programmed
 - An industrial robot:
 - Actuators
 - Mechanical architecture
 - Controller system
 - Communication interface

[ISO 8373] Robotics - Vocabulary



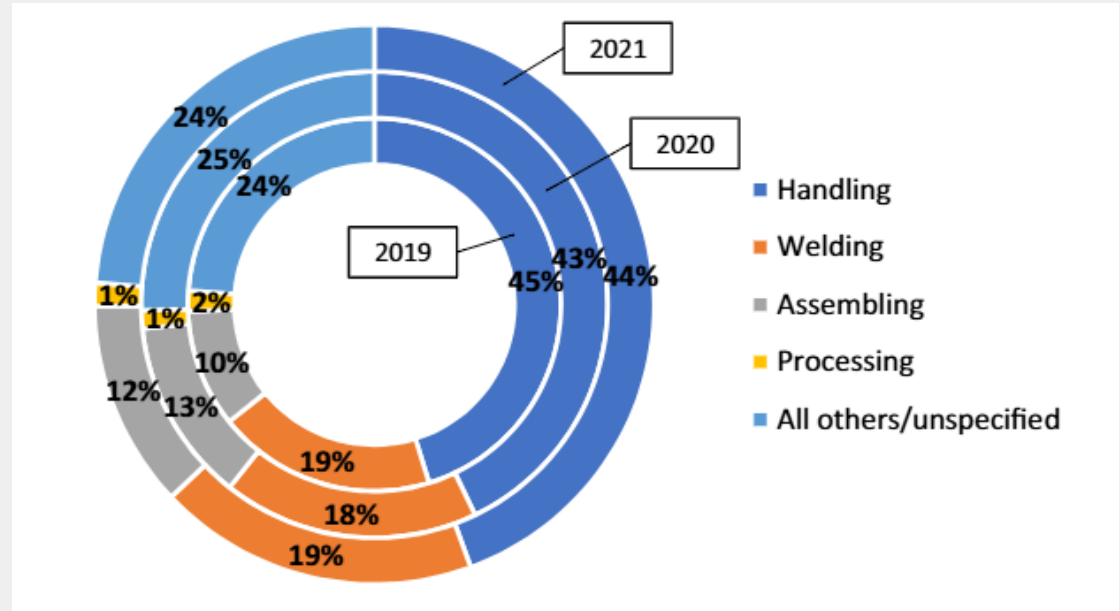
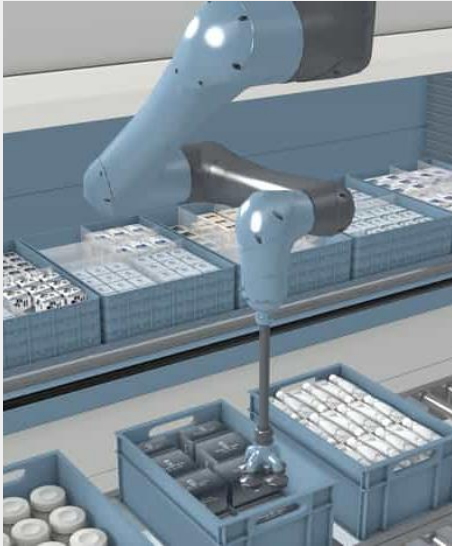
Introduction

- Different kinematics of industrial robots
 - SCARA robot
 - Parallel robot
 - Cartesian robot
 - Anthropomorphic robot



Introduction

- Different applications



Ivanov, V., Andrusyshyn, V., Pavlenko, I., Pitel', J., & Bulej, V. (2024). New classification of industrial robotic gripping systems for sustainable production. *Scientific reports*, 14(1), 295.

Introduction

- Different applications

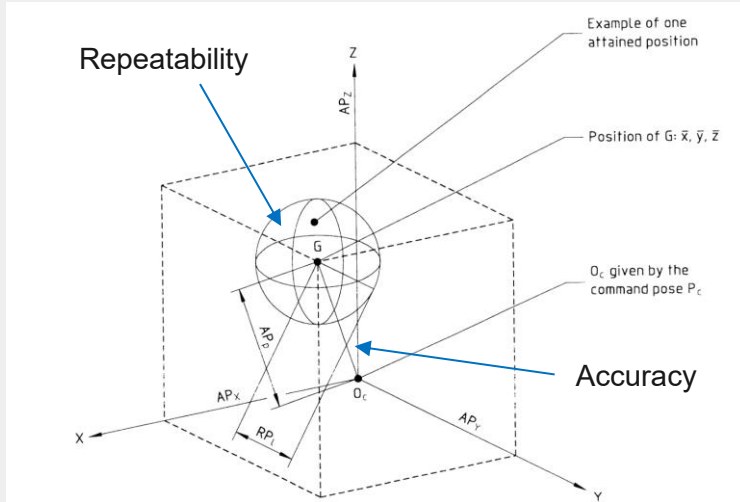
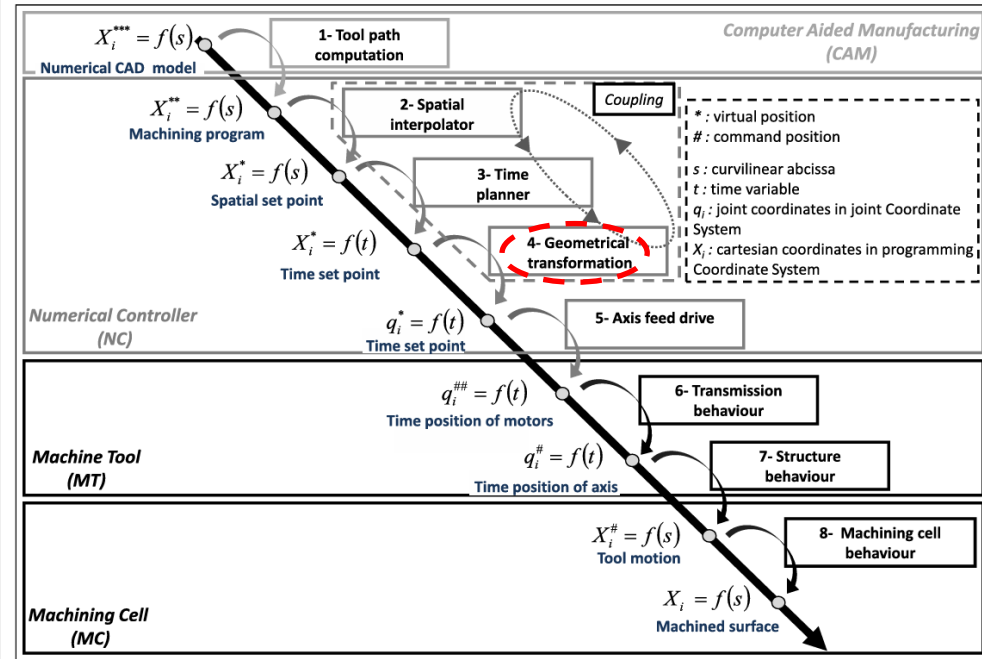
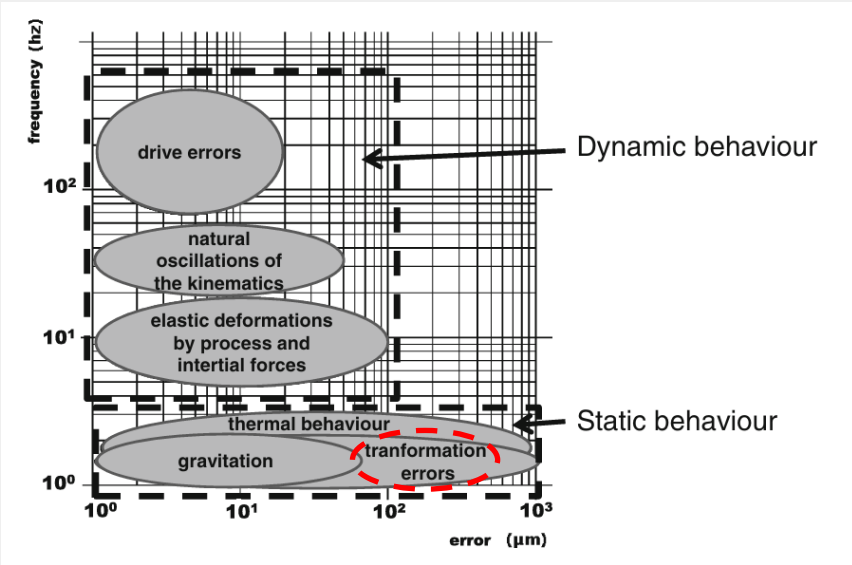


Table B.1 - Guide for selection of performance criteria for typical applications

Criteria to be used	Reference in ISO 9283	Applications									
		Spot welding		Handling/ loading/ unloading		1) Application where pose-to-pose control is normally used		2) Application where continuous path control is normally used			
		1)	1)	Assembly	Inspection	Machining/ deburring/ polishing/ cutting 2)	Spray-painting	Arc-welding	Adhesive/sealing		
				1)	2)	1)	2)	2)	2)	2)	
Pose accuracy	7.2.1	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾			X ³⁾	
Pose repeatability	7.2.2	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾			X ⁴⁾	
Multi-directional pose accuracy variation	7.2.3		X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾				
Distance accuracy/repeatability	7.3	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾				
Position stabilization time	7.4	X	X	X	X	X	X				
Position overshoot	7.5	X	X	X	X	X	X			X	
Drift of pose accuracy	7.6	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾			X ³⁾	
Drift of pose repeatability	7.6	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾			X ⁴⁾	
Exchangeability	7.7										
Path accuracy	8.2				X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾
Path repeatability	8.3				X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾	X ⁴⁾
Path accuracy on reorientation	8.4										
Cornering deviations	8.5				X	X	X				X
Path velocity accuracy	8.6.2						X ³⁾	X ³⁾	X ³⁾	X ³⁾	X ³⁾
Path velocity repeatability	8.6.3						X	X	X	X	X
Path velocity fluctuation	8.6.4						X	X	X	X	X
Minimum posing time	9	X	X	X							
Static compliance	10	X	X	X	X		X				
Weaving deviations	11.1									X	

Introduction

- Different behavior



Toolpath computation chain

Pateloup, S., Chanal, H., & Duc, E. (2013). Process parameter definition with respect to the behaviour of complex kinematic machine tools. The International Journal of Advanced Manufacturing Technology, 69(5), 1233-1248. of PKM. In Chemnitz Parallel Kinematic Seminar (pp. 313-333).

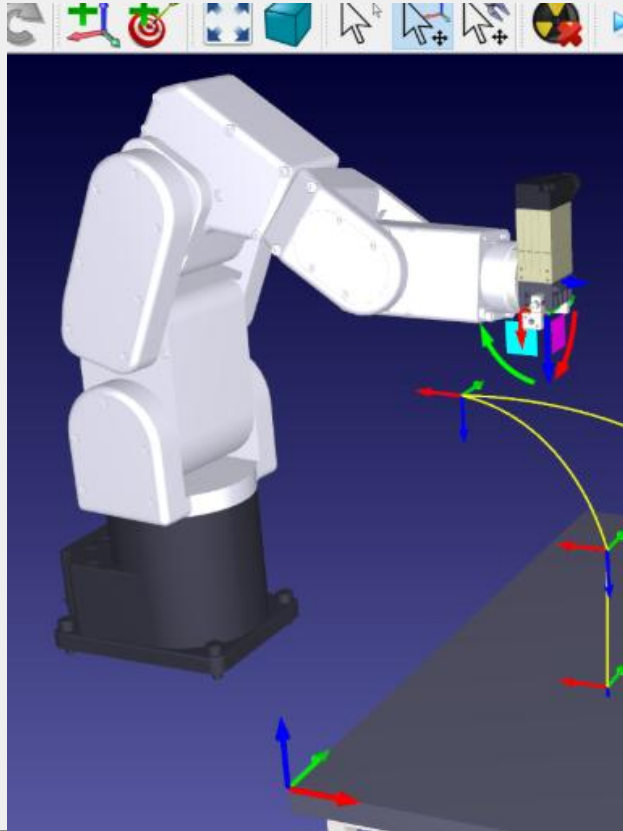
Pritschow, G., Eppler, C., & Garber, T. (2002, May). Influence of the dynamic stiffness on the accuracy of PKM. In Chemnitz Parallel Kinematic Seminar (pp. 313-333).

Introduction

- Problematics:
 - How is the robot geometric pose controlled?
 - How can the robot pose accuracy be improved?

End-effector pose:
Position + Orientation \rightarrow 6dof





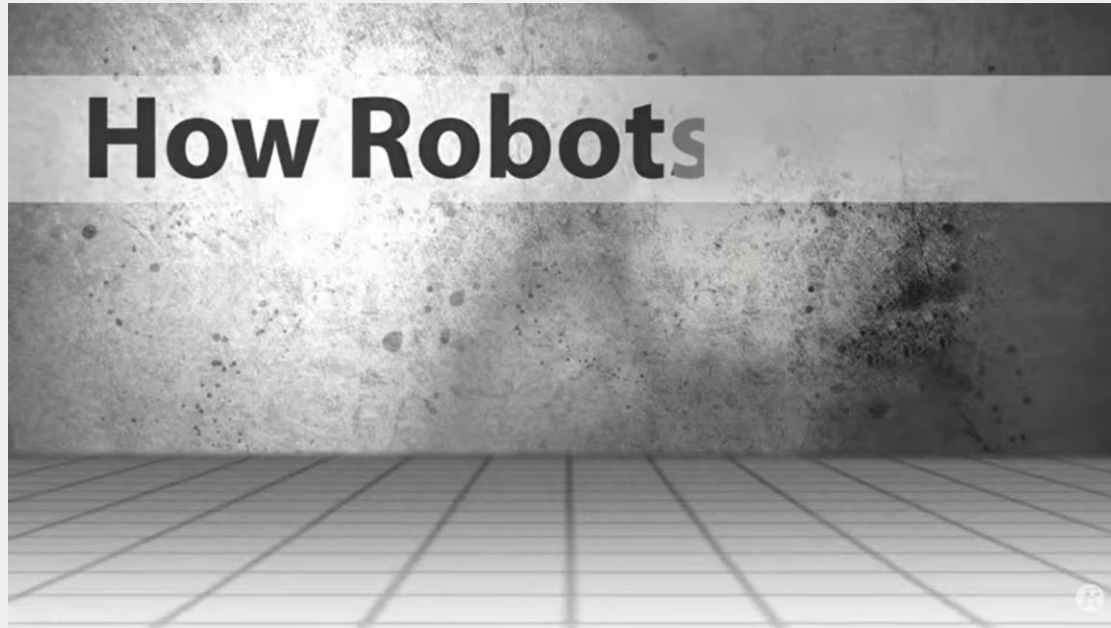
02

Programming principles

Setting an industrial robot in motion

Programming principles

- To realize a task:

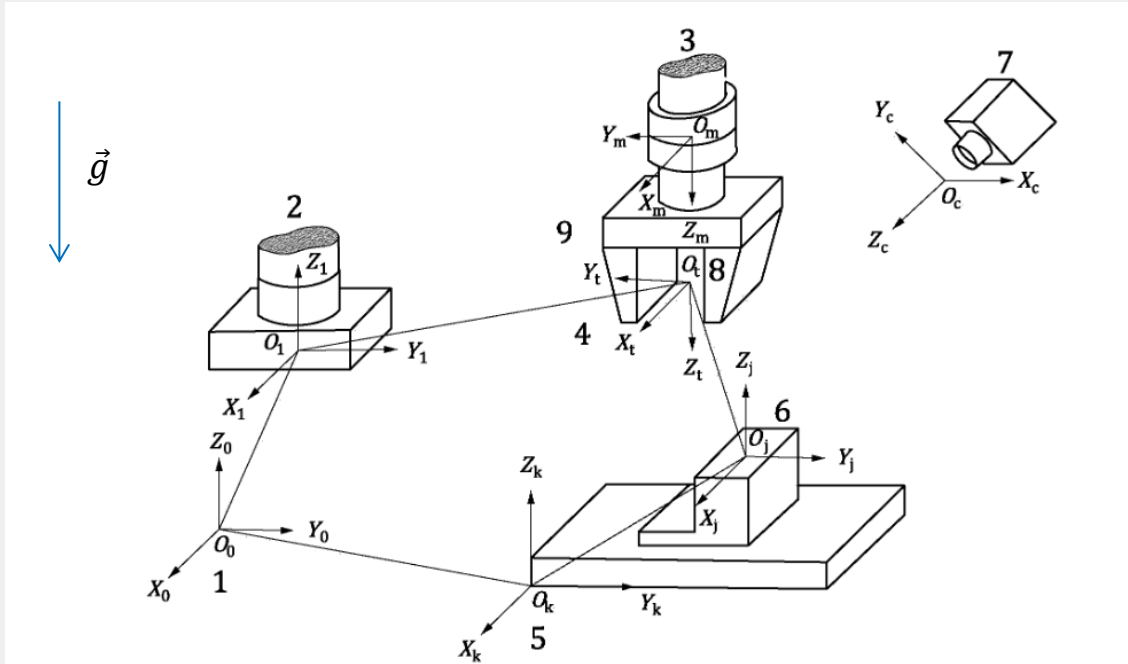


Programming principles

- Definition of coordinate systems:
 - ISO 9787: Robots and robotic devices - Coordinate systems and motion nomenclatures
 - Performing a task: moving an effector relative to an object:
 - Movement is achieved using motorized joints
 - All joint positions: robot configuration
 - Unique definition of coordinate systems for programming a robot
- Definitions of 7 coordinate systems:
 - Goal: control robot configurations to control effector positions in the task reference frame

Programming principles

- Definition of coordinate systems:



Key

- 1 world coordinate system
- 2 base coordinate system
- 3 mechanical interface coordinate system
- 4 tool coordinate system
- 5 task coordinate system
- 6 object coordinate system
- 7 camera coordinate system
- 8 TCP
- 9 gripper

[ISO9787.pdf](#)

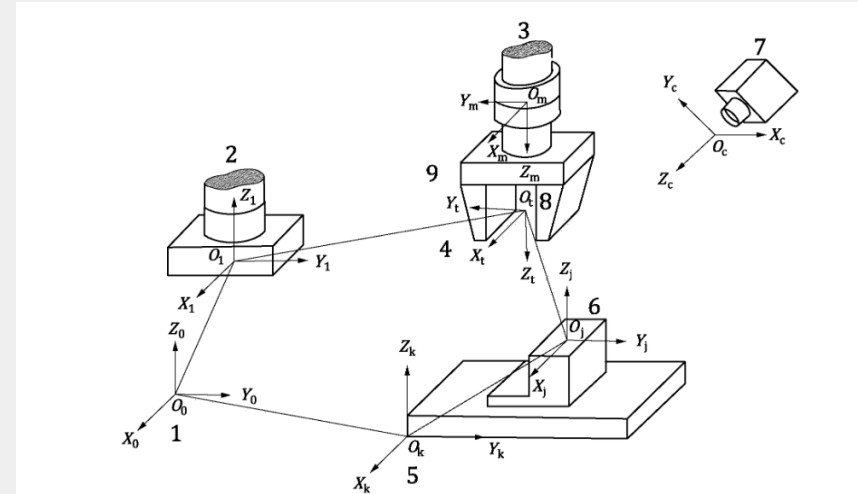
Programming principles

- Closed loop:

$$\overrightarrow{O_j O_t} = \overrightarrow{O_j O_k} + \overrightarrow{O_k O_o} + \overrightarrow{O_o O_1} + \overrightarrow{O_1 O_m} + \overrightarrow{O_m O_t}$$

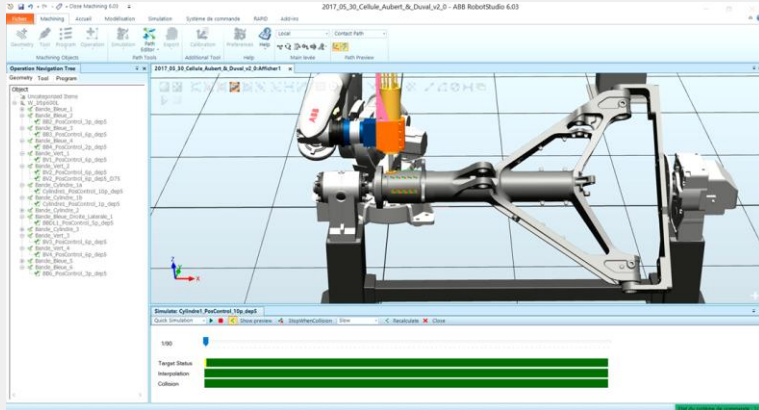
robot

$$\begin{pmatrix} \vec{x}_t & \vec{y}_t & \vec{z}_t \end{pmatrix} \begin{pmatrix} \vec{x}_j & \vec{y}_j & \vec{z}_j \end{pmatrix} = {}^j R_k {}^k R_o {}^o R_1 {}^1 R_m {}^m R_t \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

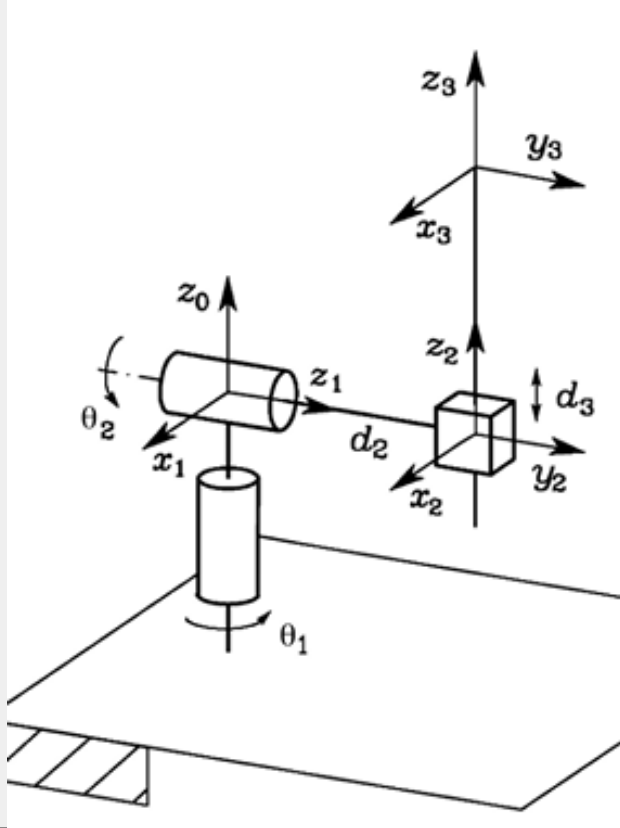


Programming principles

- Off-line programming:
 - Use of a digital environment :
 - CAD model of the robot
 - Programming the robot in the digital environment



- program in the Cartesian coordinate system
- Accurate model of the robot's geometric behavior in the NC



03

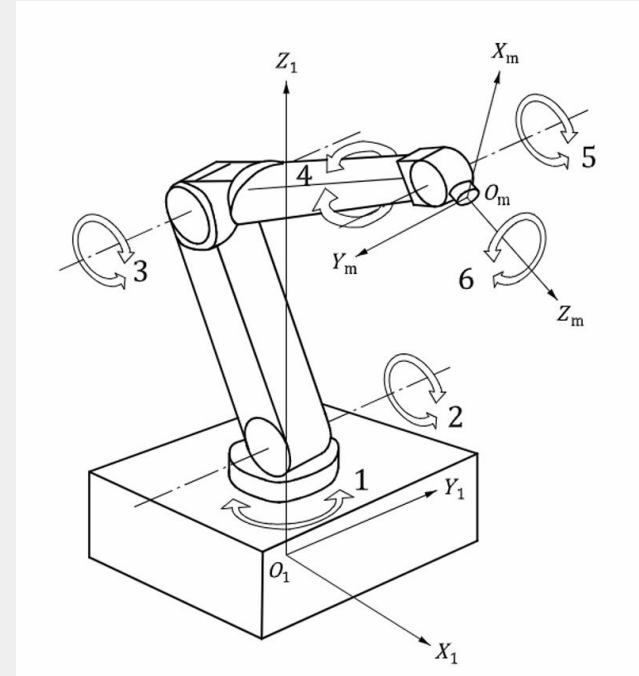
Kinematic modeling

Definition and methodologies

Kinematic modeling

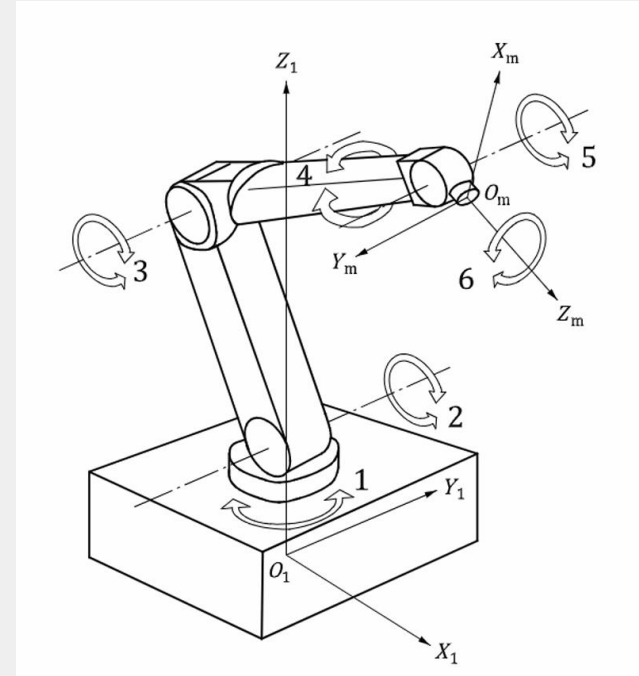
- Definition:
 - Manipulator: series of links connected by joints
 - Each link and joint : rigid
 - Kinematic modeling:
 - a mathematical representation of a robot's motion that focuses on the geometric relationships between elements

Paul, R. P. (1981). Robot manipulators: mathematics, programming, and control: the computer control of robot manipulators. Richard Paul.



Kinematic modeling

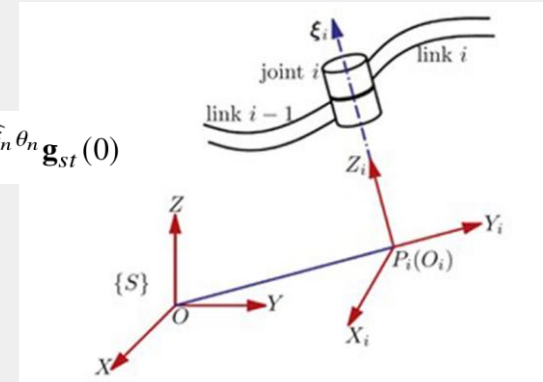
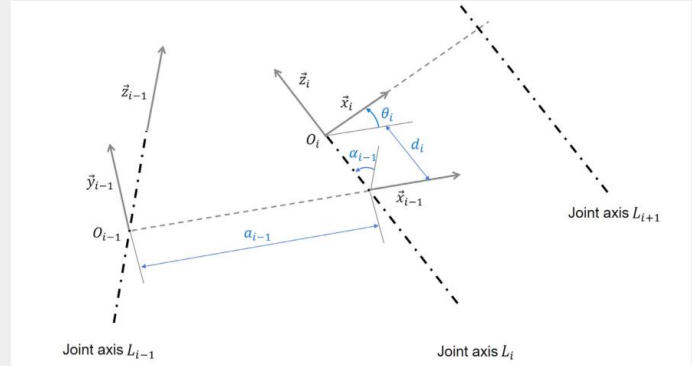
- Definition:
 - Inverse Kinematic Model (IKM):
 - Establishing the value of the joint coordinates corresponding to the end-effector configuration
 - $\mathbf{Q} = IKM(\mathbf{X})$
 - Direct Kinematic Model (DKM):
 - Determining the pose of the end-effector from a set of joint coordinates
 - $\mathbf{X} = DKM(\mathbf{Q})$



Merlet, J. P. (2006). *Parallel robots*. Dordrecht: Springer Netherlands.

Kinematic modeling

- Two main approaches:
 - Model based on geometric parameters identification:
 - Denavit-Hartenberg (DH) formalism
 - Simple and generic
 - Model based on the description of the kinematic movement of each joint:
 - Product of exponentials (POE)
 - Need a reference model



$$\mathbf{g}_d = \mathbf{e}^{\hat{\xi}_1 \theta_1} \dots \mathbf{e}^{\hat{\xi}_n \theta_n} \mathbf{g}_{st}(0)$$

Chanal, H., Guyon, J. B., Koessler, A., Dechambre, Q., Boudon, B., Blaysat, B., & Bouton, N. (2021). Geometrical defect identification of a SCARA robot from a vector modeling of kinematic joints invariants. *Mechanism and Machine Theory*, 162, 104339.

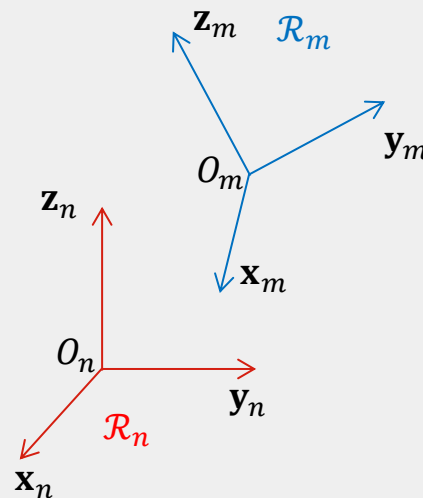
Kinematic modeling

- Homogeneous transformation matrix:
 - Model a linear transformation between two frames

$${}^n\mathbf{T}_m = \begin{bmatrix} \boxed{{}^n\mathbf{Rot}_m} & \begin{bmatrix} a \\ b \\ c \end{bmatrix} \\ 0 & 1 \end{bmatrix}$$

Rotation of frame \mathcal{R}_m expressed in frame \mathcal{R}_n

$\overrightarrow{O_n O_m}$ expressed in frame \mathcal{R}_n



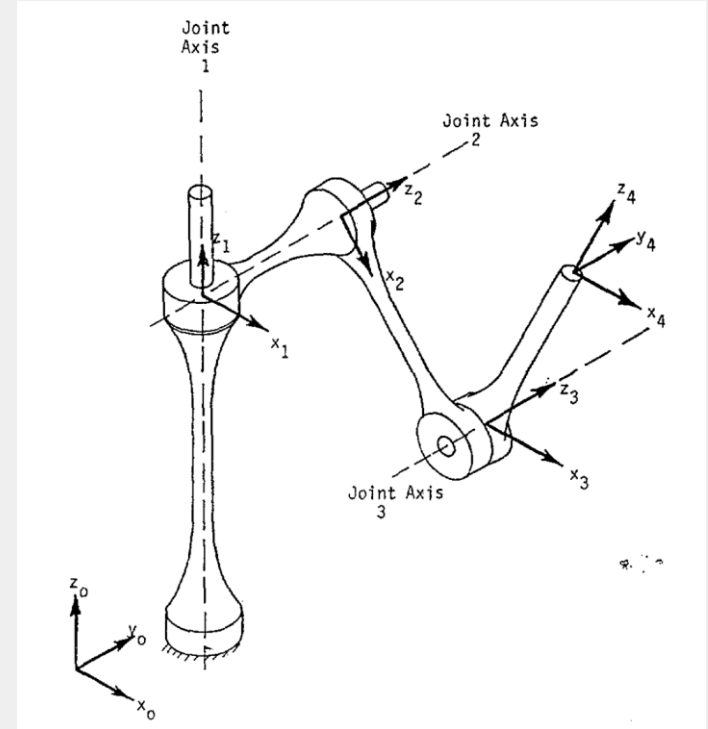
- Problematic: definition of each frame attached to robot joint – definition of parameters to describe the pose of each frame

Paul, R. P. (1981). Robot manipulators: mathematics, programming, and control: the computer control of robot manipulators. Richard Paul.

Kinematic modeling

- Geometric Parameters:
 - Use to describe the pose of two consecutive frames
 - Modeling joint: revolut or prismatic (1 dof)
 - Prismatic joint:
 - 2 param.: orientation of joint axis
 - 1 param.: mobility
 - Revolut joint:
 - 2 param.: orientation of joint axis
 - 2 param.: position of joint axis
 - 1 param. : mobility

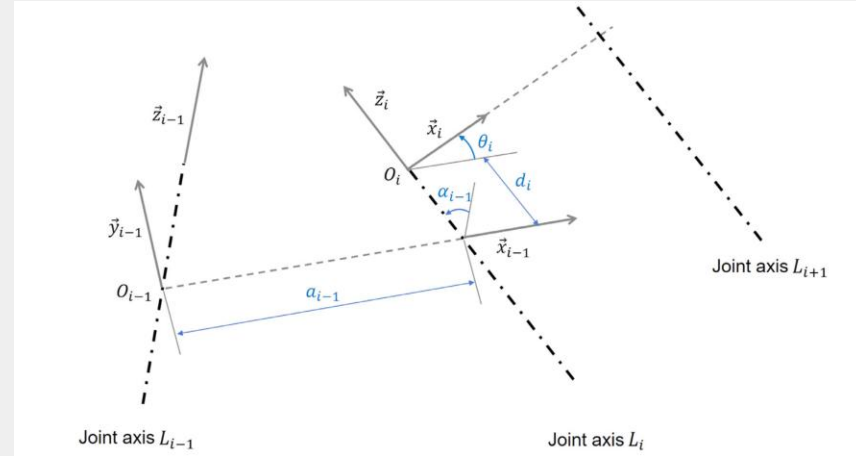
$$C = 4R + 2P + 6$$



Everett, L., Driels, M., & Mooring, B. (1987, March). Kinematic modelling for robot calibration. In Proceedings 1987 IEEE International Conference on Robotics and Automation (Vol. 4, pp. 183-189). IEEE.

Kinematic modeling

- Model based on geometric parameters identification:
 - Denavit-Hartenberg (DH) formalism:
 - Frame \mathcal{R}_i : attached to each link i :
 1. \vec{z}_i : axis of joint L_i ,
 2. \vec{x}_i : common normal between \vec{z}_i and \vec{z}_{i+1} ,
 3. origin O_i : intersection of \vec{x}_i and \vec{z}_i ,
 4. \vec{y}_i : right-hand rule
 5. d_i : distance between \vec{x}_{i-1} and \vec{x}_i along \vec{z}_i ,
 6. θ_i : angle between \vec{x}_{i-1} and \vec{x}_i ,
 7. a_i : distance between \vec{z}_i and \vec{z}_{i+1} along \vec{x}_i ,
 8. α_i : angle between \vec{z}_i and \vec{z}_{i+1} .



4 parameters: d_i , θ_i , a_i , α_i

Denavit, J., & Hartenberg, R. S. (1955). A kinematic notation for lower-pair mechanisms based on matrices.

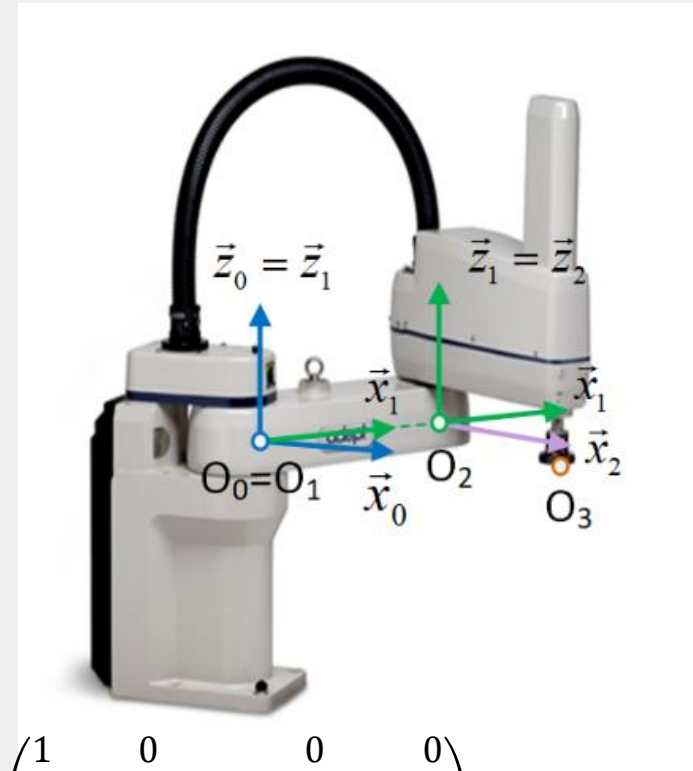
Rmq: geometric and mobility parameters

Kinematic modeling

- Example: 2 first joints of SCARA

	d_i	θ_i	a_i	α_i
$\mathcal{R}_0 \rightarrow \mathcal{R}_1$	-	-	0	0
$\mathcal{R}_1 \rightarrow \mathcal{R}_2$	d_1	q_1	a_1	0
$\mathcal{R}_2 \rightarrow \mathcal{R}_e$	0	q_2	a_2	0

$${}^i\mathbf{T}_{i+1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(\theta_i) & -\sin(\theta_i) & 0 & 0 \\ \sin(\theta_i) & \cos(\theta_i) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha_i) & -\sin(\alpha_i) & 0 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



Kinematic modeling

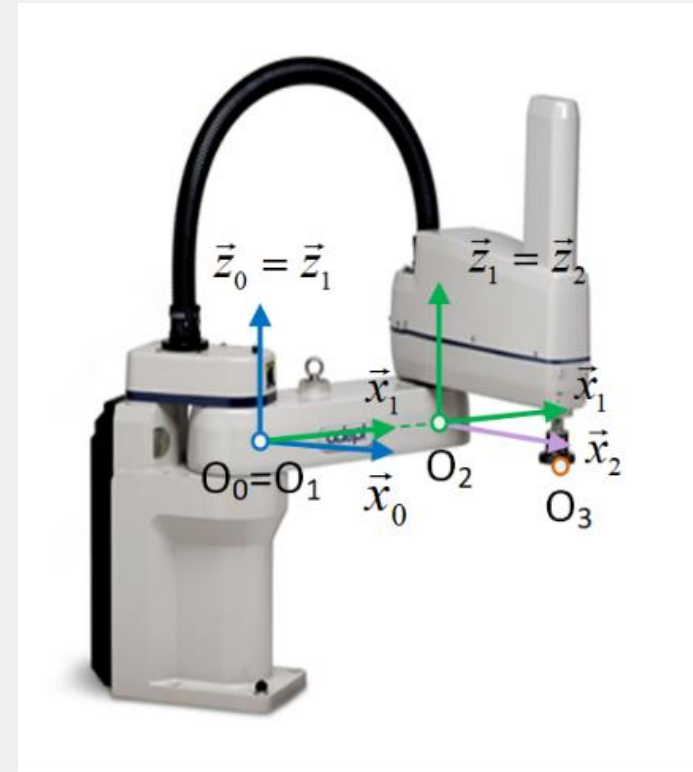
- Example: 2 first joints of SCARA:
 - Nominal direct kinematic model:

$${}^0\mathbf{T}_{N_3} = {}^0\mathbf{T}_{N_1} {}^1\mathbf{T}_{N_2} {}^2\mathbf{T}_{N_3}$$

$$= \begin{bmatrix} \cos(q_1 + q_2) & -\sin(q_1 + q_2) & 0 & a_2 \cos(q_1 + q_2) + a_1 \cos(q_1) \\ \sin(q_1 + q_2) & \cos(q_1 + q_2) & 0 & a_2 \sin(q_1 + q_2) + a_1 \sin(q_1) \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{X} = \begin{pmatrix} a_2 \cos(q_1 + q_2) + a_1 \cos(q_1) \\ a_2 \sin(q_1 + q_2) + a_1 \sin(q_1) \\ d_1 \end{pmatrix}$$

- Other formalisms exist: same DKM



Gogu, G. (2007). Structural synthesis of fully-isotropic parallel robots with Schönflies motions via theory of linear transformations and evolutionary morphology. *European Journal of Mechanics-A/Solids*, 26(2), 242-269.

Kinematic modeling

- Model based on the description of the kinematic movement of each joint:

- Product of exponentials (POE):

- Definition of a zero configuration:

1. $g_{st}(0)$: 4x4 matrix
2. A first expression of the pose of the end-effector frame expressed in the base frame

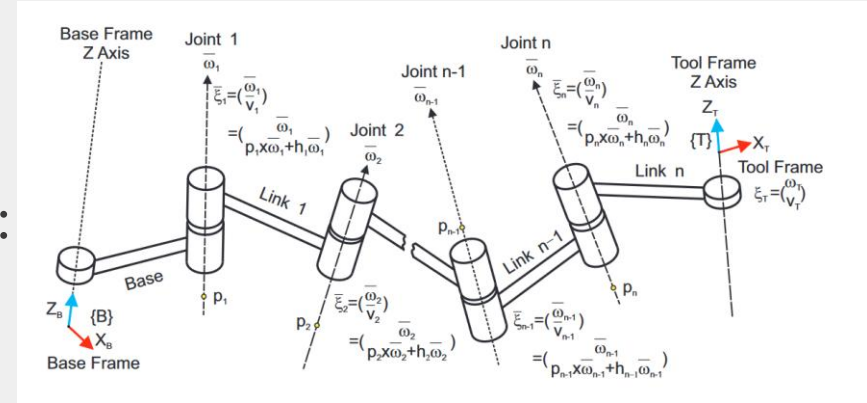
- DKM:

1. $g_d = e^{\hat{\xi}_1 \theta_1} \dots e^{\hat{\xi}_n \theta_n} g_{st}(0)$
2. $e^{\hat{\xi}_i \theta_i} = \begin{bmatrix} e^{\hat{\omega}_i \theta_i} & \mathbf{t}_i \\ 0 & 1 \end{bmatrix} \Rightarrow e^{\hat{\omega}_i \theta_i} = \mathbf{I} + \hat{\omega}_i \sin(\theta_i) + \hat{\omega}_i^2 (1 - \cos(\theta_i))$
and $\mathbf{t}_i = (\mathbf{I} - e^{\hat{\omega}_i \theta_i})(\omega_i \times \mathbf{v}_i) + \omega_i \omega_i^T \mathbf{v}_i \theta_i$

ω_i : joint axis

$$\mathbf{v}_i = \mathbf{p}_i \times \omega_i$$

$$3. \hat{\omega}_i = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}$$



Brockett, R. W. (2005, November). Robotic manipulators and the product of exponentials formula. In *Mathematical Theory of Networks and Systems: Proceedings of the MTNS-83 International Symposium Beer Sheva, Israel, June 20–24, 1983* (pp. 120-129). Berlin, Heidelberg: Springer Berlin Heidelberg.

Kinematic modeling

- Example: 2 first joints of SCARA:
 - Zero position:

$$\mathbf{g}_{st}(0) = \begin{bmatrix} 1 & 0 & 0 & a_2 + a_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- DKM:

$$\mathbf{g}_d = e^{\hat{\xi}_1 q_1} e^{\hat{\xi}_2 q_2} \mathbf{g}_{st}(0)$$

$$\boldsymbol{\omega}_1 = \boldsymbol{\omega}_2 = \mathbf{z}_0$$

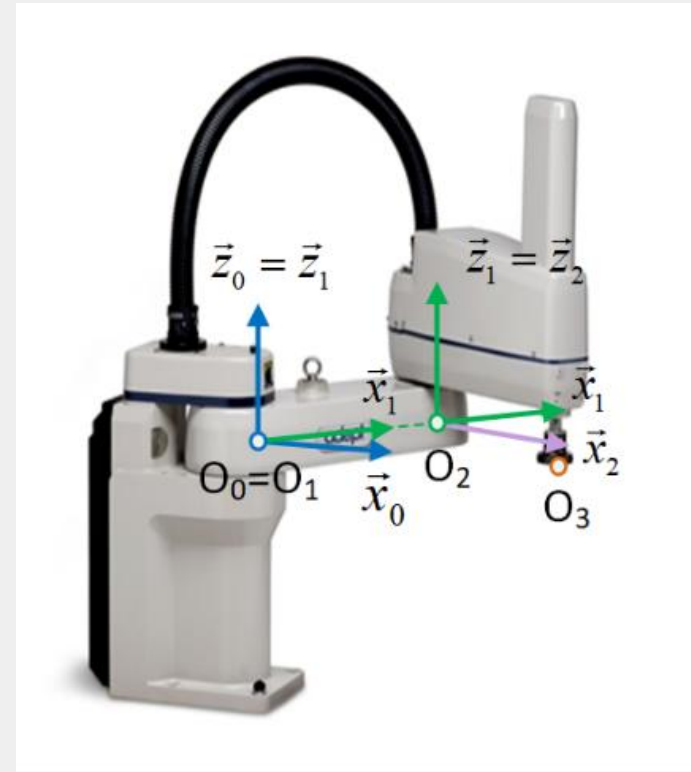
$$\mathbf{p}_1 = \mathbf{0}$$

$$\mathbf{p}_2 = a_1 \mathbf{x}_0$$

$$\hat{\boldsymbol{\omega}}_i = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{v}_1 = \mathbf{0}$$

$$\mathbf{v}_2 = -a_1 \mathbf{y}_0$$



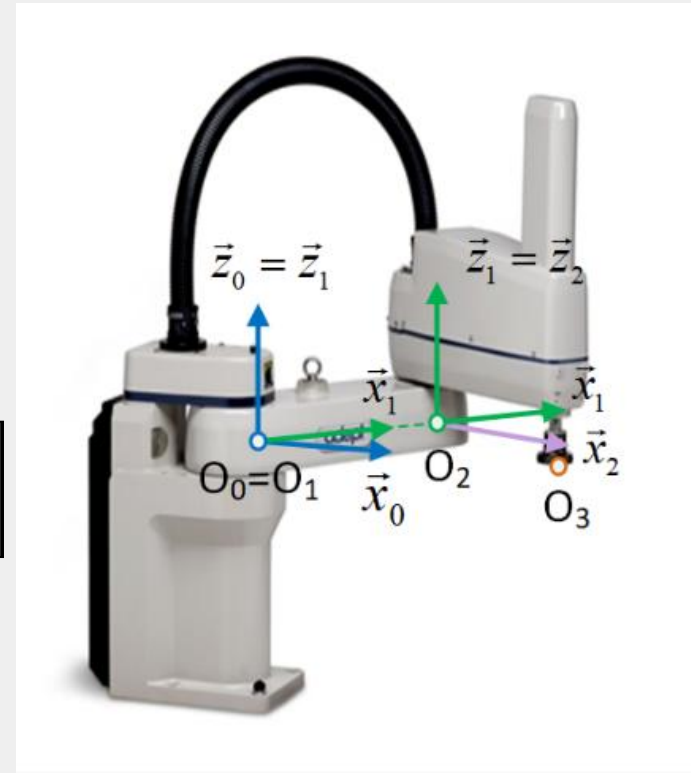
Kinematic modeling

- Example: 2 first joints of SCARA:
 - DKM:

$$e^{\hat{\omega}_i q_i} = \mathbf{I} + \hat{\omega}_i \sin(q_i) + \hat{\omega}_i^2 (1 - \cos(q_i)) = \begin{bmatrix} \cos(q_i) & -\sin(q_i) & 0 \\ \sin(q_i) & \cos(q_i) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

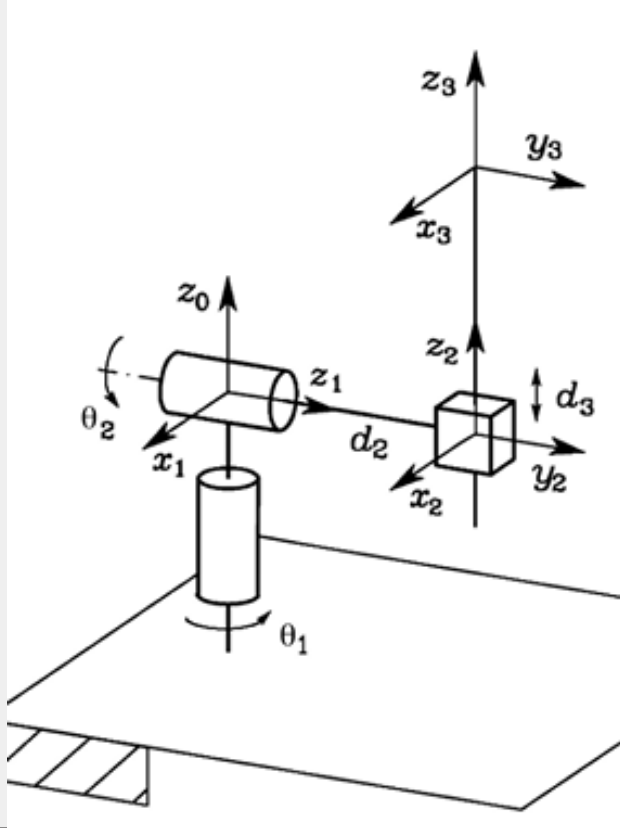
$$t_1 = (\mathbf{I} - e^{\hat{\omega}_1 q_1})(\omega_1 \times v_1) + \omega_1 \omega_1^T v_1 q_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad t_2 = \begin{bmatrix} -a_1(\cos(q_2) - 1) \\ -a_1 \sin(q_2) \\ 0 \end{bmatrix}$$

$$g_d = \begin{bmatrix} \cos(q_1 + q_2) & -\sin(q_1 + q_2) & 0 & a_2 \cos(q_1 + q_2) + a_1 \cos(q_1) \\ \sin(q_1 + q_2) & \cos(q_1 + q_2) & 0 & a_2 \sin(q_1 + q_2) + a_1 \sin(q_1) \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



Kinematic modeling

- Different formalisms and approaches:
 - Mathematical methodology to compute nominal DKM and IKM
- To improve industrial robot geometric accuracy:
 - Identification process:
 - Real geometric behavior vs Model geometric behavior
 - Decrease inverse transformation errors
 - Problematic:
 1. Impact of the robot's kinematic model on the identification process ?
 2. Impact on the final accuracy ?



04

Identification

Definition and methodologies

Identification

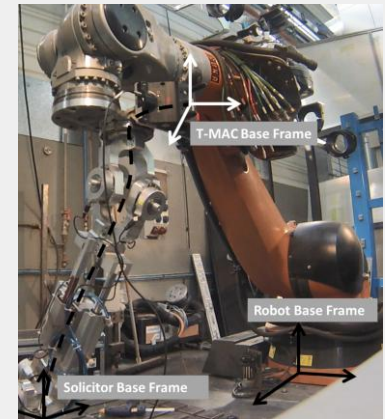
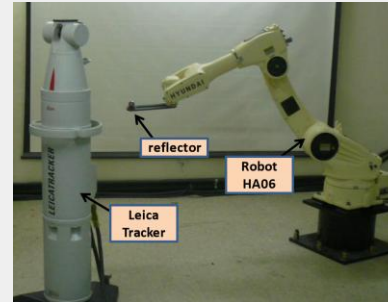
- Classical process in 4 steps:
 - Step 1: Definition of a mathematical model that describes the robot geometry and motion.
 - Step 2: Measurement of the position of the robot. Classically, this is the robot end-effector position and/or orientation which are measured and define in the world or robot coordinate system.
 - Step 3: Identification of the geometric and kinematic parameters of the robot according to a numerical optimization process.
 - Step 4: Implementation of the identified kinematic model of the robot in the numerical controller.

consistency

Y. Bai, H. Zhuang, et Z. S. Roth, « Experiment study of PUMA robot calibration using a laser tracking system », in SMCia 2003 - Proceedings of the 2003 IEEE International Workshop on Soft Computing in Industrial Applications, 2003, p. 139-144. doi: 10.1109/SMCIA.2003.1231359.

Identification

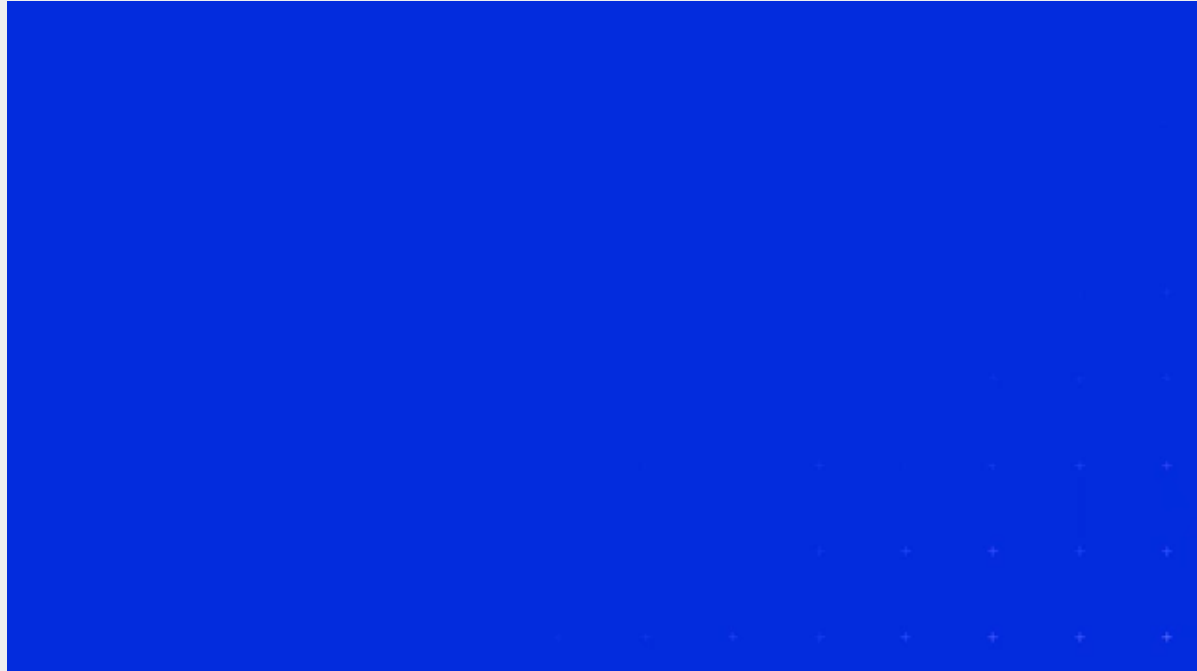
- Measurement means:
 - Cameras
 - Inexpensive
 - Pb of occlusion and size of the measured area
 - Low metrological performance
 - System generating mechanical constraints
 - Good estimation of the robot pose
 - Constrained by the accuracy of the system
 - Possible robot configuration limited
 - Laser Tracker
 - High accuracy
 - Expensive



H.-N. Nguyen, J. Zhou, et H.-J. Kang, A New Full Pose Measurement Method for Robot Calibration, Sensors, vol. 13, no 7, p. 9132-9147, (2013)

Identification

- Measurement means:
 - Laser Tracker



Identification

- Principle of identification process with a Laser Tracker:
 - Robot frame regarding LT frame:
 - Measurement of same points or same parts
 - ${}^{LT}\mathbf{T}_0$
 - Measurement of different point M_i :
 - Coordinates in the LT frame: \mathbf{X}_{LTi}
 - Articular coordinates: \mathbf{Q}_{LTi}
 - Cost function:
 - $f_{cost}(\xi) = \min_{\xi} (\sum_{i=1}^n (DKM(\mathbf{Q}_{LTi}, \xi) - \mathbf{X}_{LTi})^2)$
 - $f_{cost}(\xi) = \min_{\xi} (\sum_{i=1}^n (IKM(\mathbf{X}_{LTi}, \xi) - \mathbf{Q}_{LTi})^2)$

or



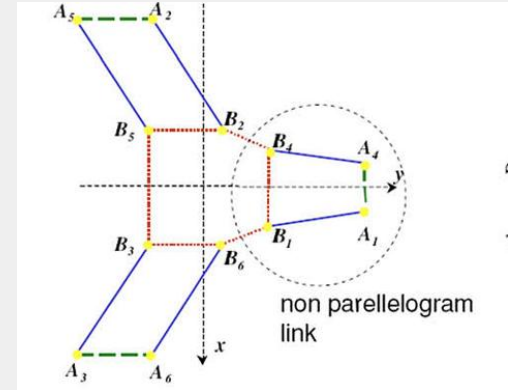
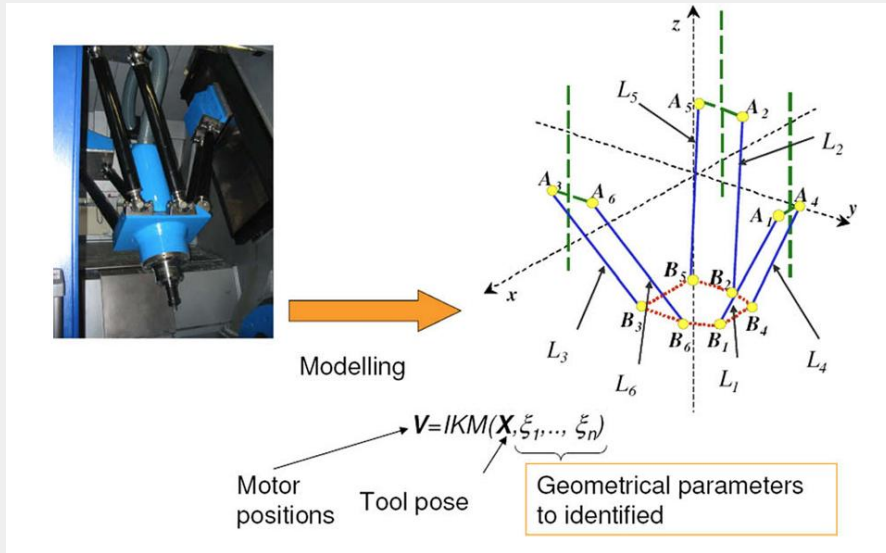
Identification

- Principle of identification process with a Laser Tracker:
 - Use of a numerical optimization with an end-effector position measurement:
 - Sufficient measurement points regarding parameters numbers
 - All parameters should have an influence on the end-effector measurement poses
 - Angles and lengths: different orders, different sensibilities
 - Validation of the problem conditioning



Identification

- Definition of the kinematic model:
 - Sensitivity analysis



$$L_i^2 = \overrightarrow{A_i B_i}^2, \text{ 6 legs} \Rightarrow \mathbf{V} = IKM(\mathbf{X}, \xi)$$

$$\Rightarrow d\mathbf{V} = \frac{\partial IKM(\mathbf{X}, \xi)}{\partial \mathbf{X}} d\mathbf{X} + \frac{\partial IKM(\mathbf{X}, \xi)}{\partial \xi} d\xi$$

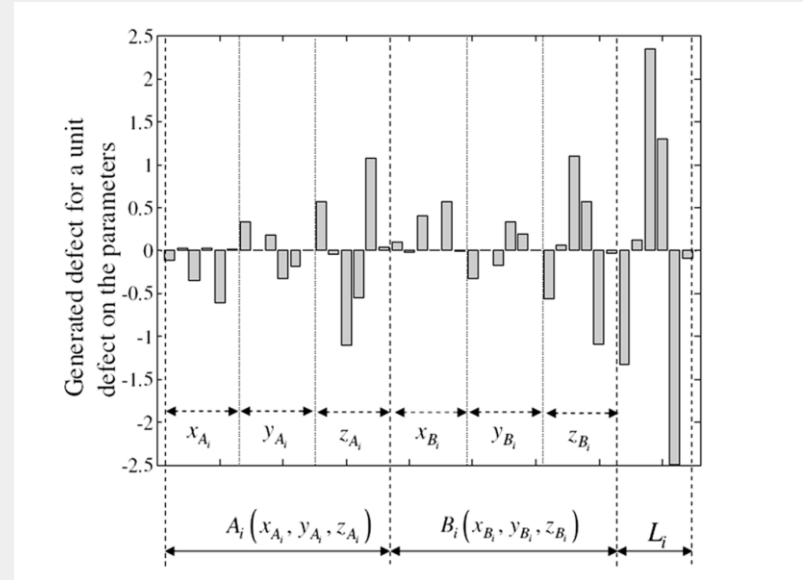
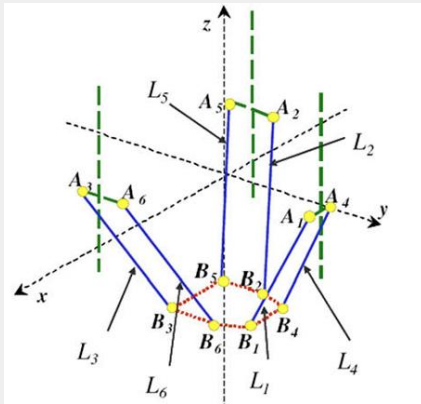
$$\mathbf{X}: \text{measurement} \Rightarrow d\mathbf{V} = \mathbf{0}$$

$$\Rightarrow d\mathbf{X} = - \left(\frac{\partial IKM(\mathbf{X}, \xi)}{\partial \mathbf{X}} \right)^{-1} \frac{\partial IKM(\mathbf{X}, \xi)}{\partial \xi} d\xi = \mathbf{S} d\xi$$

Sensitivity matrix

Identification

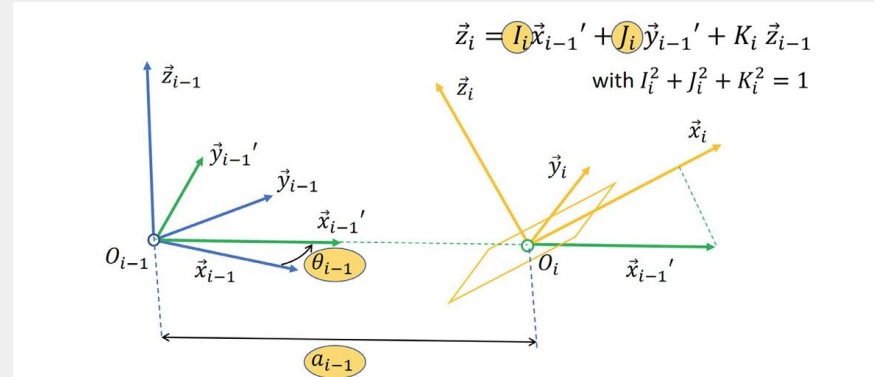
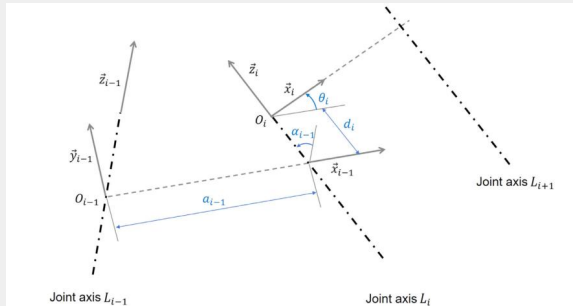
- Definition of the kinematic model:
 - Sensitivity analysis



Chanal, H., Duc, E., Hascoët, J. Y., & Ray, P. (2009). Reduction of a parallel kinematics machine tool inverse kinematics model with regard to machining behaviour. *Mechanism and Machine Theory*, 44(7), 1371-1385.

Identification

- Definition of the kinematic model:
 - Nature of parameters:
 - Angles or lengths \rightarrow Influence on the numerical optimization
 - Small variation from the nominal values
 - DH formalism:
 - Motion and geometric parameters are mixed together:
 1. Other formalism can be more relevant identification process



Identification

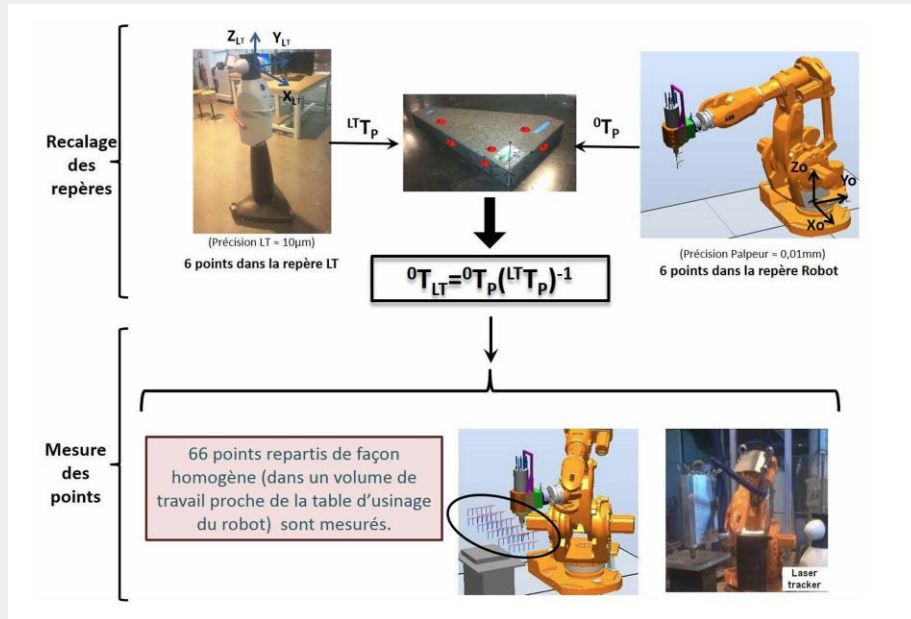
- Definition of the measurement points:
 - Optimum calibration configurations:
 - $\Delta \mathbf{Y} = \mathbf{W} \Delta \xi \Rightarrow \mathbf{W}$: observation matrix
 - Maximize the observability= Minimize the condition number of matrix \mathbf{W}
 - Number of poses > number of parameters
 - $rank(\mathbf{W}) = \text{parameter number}$
 - $cond(\mathbf{W}) = \frac{\sigma_{max}}{\sigma_{min}}$, with σ_{max} and σ_{min} : largest and smallest singular values

in case of industrial robot: task workspace can be smaller than robot workspace

Renaud, P., Andreff, N., Gogu, G., & Dhome, M. (2003, October). Optimal pose selection for vision-based kinematic calibration of parallel mechanisms. In Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003)(Cat. No. 03CH37453) (Vol. 3, pp. 2223-2228). IEEE.

Identification

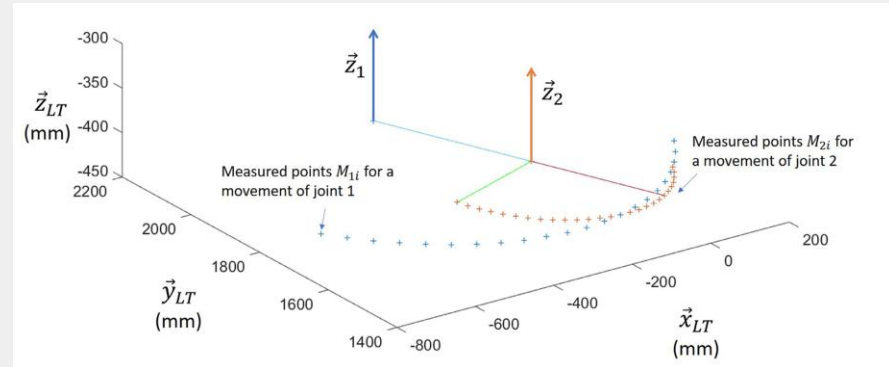
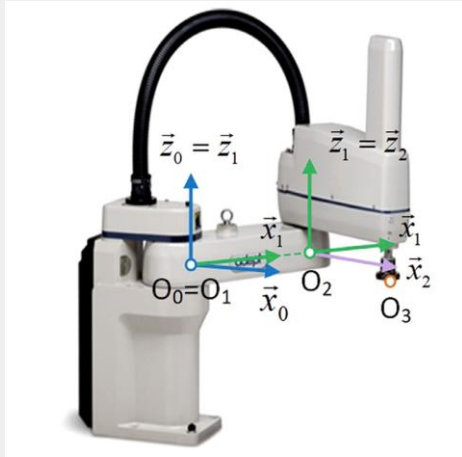
- Definition of the measurement points:
 - Use points in the robot workspace



Gutiérrez, J., Chanal, H., Durieux, S., & Duc, E. (2017, July). Adaptation of the geometric model of a 6 dof serial robot to the task space. In *Computational Kinematics: Proceedings of the 7th International Workshop on Computational Kinematics* that was held at Futuroscope-Poitiers, France, in May 2017 (pp. 569-576). Cham: Springer International Publishing.

Identification

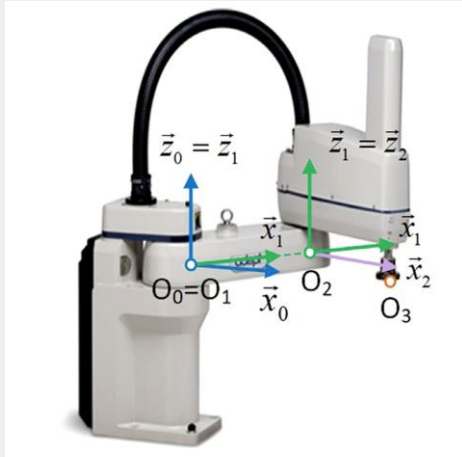
- Example : SCARA



Chanal, H., Guyon, J. B., Koessler, A., Dechambre, Q., Boudon, B., Blaysat, B., & Bouton, N. (2021). Geometrical defect identification of a SCARA robot from a vector modeling of kinematic joints invariants. *Mechanism and Machine Theory*, 162, 104339.

Identification

- Example : SCARA



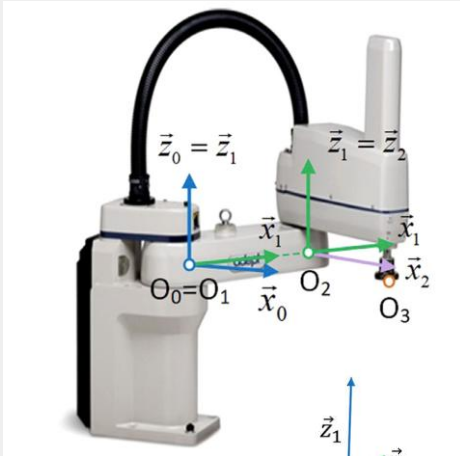
	d_i	θ_i	a_i	α_i
$\mathcal{R}_0 \rightarrow \mathcal{R}_1$	-	-	0	0
$\mathcal{R}_1 \rightarrow \mathcal{R}_2$	d_1	q_1	a_1	0
$\mathcal{R}_2 \rightarrow \mathcal{R}_e$	0	q_2	a_2	0

Geometric parameters	Identified values
${}^{\mathcal{R}_0}T_{\mathcal{R}_1}$	$\begin{bmatrix} -0.383553 & 0.923472 & 0.009258 & -295.393 \text{ mm} \\ -0.923519 & -0.383539 & -0.003396 & 2044.593 \text{ mm} \\ 0.000415 & -0.009853 & 0.999951 & -413.640 \text{ mm} \\ 0 & 0 & 0 & 1 \end{bmatrix}$
a_1	325.034 mm
a_2	274.199 mm
d_2	0.022 mm

First order model

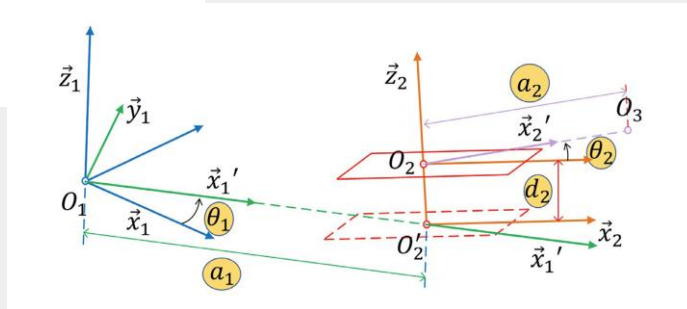
Identification

- Example : SCARA



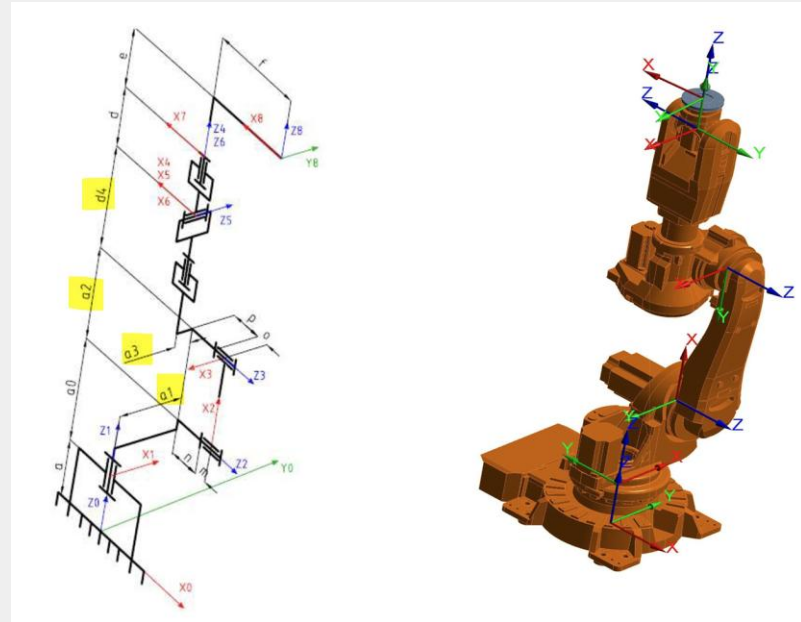
Errors between the position of the measured points and the different test DKM.

SCARA geometrical model	Max error (mm)	Mean error (mm)
Vector model	0.046	0.027
DH first-order model	0.122	0.098
DH first and second-order model	0.055	0.033



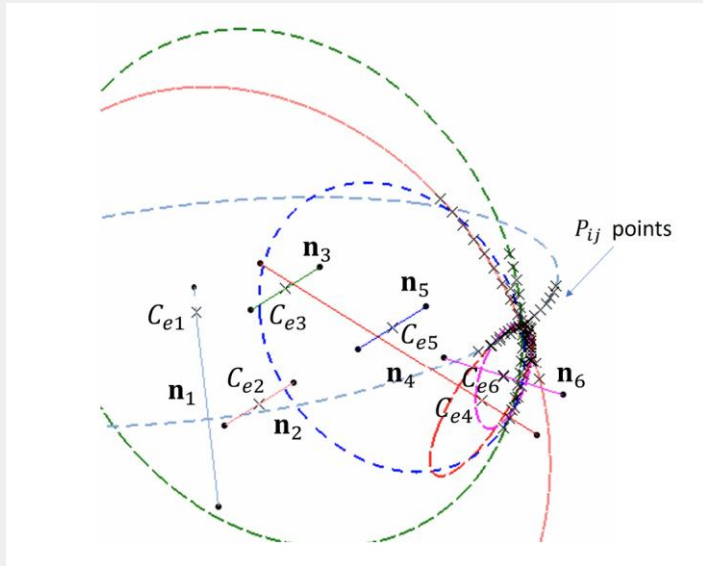
Identification

- Example : robot 6 axes ABB
 - DH formalism vs POE



Identification

- Example : robot 6 axes ABB
 - DH formalism



- Axis \mathbf{z}_i is along the axis of joint i , thus $\mathbf{z}_i = \mathbf{n}_i$.
- Axis \mathbf{x}_i is aligned with the common normal between \mathbf{z}_i and \mathbf{z}_{i+1} , thus $\mathbf{x}_i = \frac{(\mathbf{n}_i \times \mathbf{n}_{i+1})}{\|\mathbf{n}_i \times \mathbf{n}_{i+1}\|}$.
- The intersection between \mathbf{z}_i and \mathbf{x}_i defines origin O_i . The coordinate vector of O_i in the laser tracker coordinate system is noted \mathbf{o}_i . Thus $\mathbf{o}_i = \frac{\mathbf{c}_i - ((\mathbf{c}_{i+1} - \mathbf{c}_i) \cdot \mathbf{n}_i)(\mathbf{n}_i \cdot \mathbf{n}_{i+1})}{(\mathbf{n}_i \cdot \mathbf{n}_{i+1})^2 - 1}$.
- Axis \mathbf{y}_i is formed by the right hand rule to complete the coordinate system, thus $\mathbf{y}_i = \mathbf{n}_i \times \mathbf{x}_i$.
- d_i is the distance between \mathbf{x}_{i-1} and \mathbf{x}_i , thus $d_i = (\mathbf{o}_i - \mathbf{o}_{i-1}) \cdot \mathbf{n}_i$.
- θ_i is the angle between \mathbf{z}_i and \mathbf{z}_{i+1} , thus $\theta_i = \text{sign}(\mathbf{x}_{i-1} \cdot \mathbf{x}_i) \arccos(\mathbf{x}_{i-1} \cdot \mathbf{x}_i)$.
- a_i is the distance between \mathbf{z}_i and \mathbf{z}_{i+1} , thus $a_i = (\mathbf{c}_{i+1} - \mathbf{c}_i) \cdot \mathbf{x}_i$.
- α_i is the angle between \mathbf{z}_i and \mathbf{z}_{i+1} , thus $\alpha_i = -\text{sign}(\mathbf{n}_{i+1} \cdot \mathbf{y}_i) \arccos(\mathbf{n}_i \cdot \mathbf{n}_{i+1})$.

Table 1 identified DH parameters of the robot IRB6620.

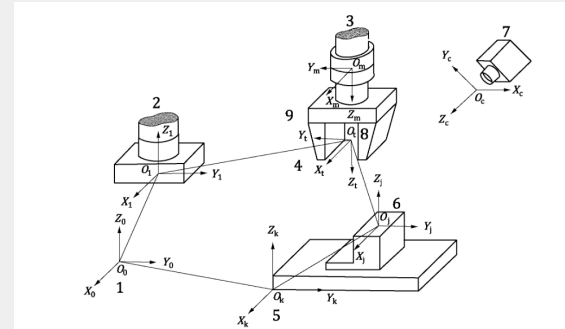
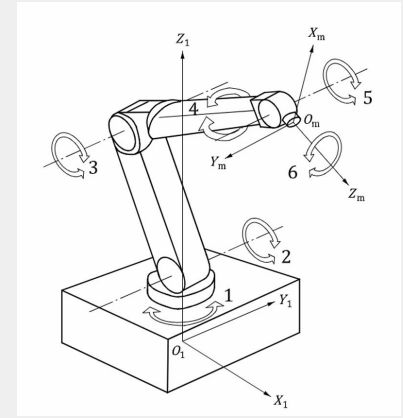
	a_{i-1} (mm)	α_{i-1} (rad)	d_i (mm)	θ_i (rad)
$\mathcal{R}_0 \rightarrow \mathcal{R}_1$	0	0.023	659.216	$q_1 - (1.203 + q_{10})$
$\mathcal{R}_1 \rightarrow \mathcal{R}_2$	318.941	1.570	3366557.236	$-q_2 + (-1.142 + q_{20})$
$\mathcal{R}_2 \rightarrow \mathcal{R}_3$	-693.737	0.0002	-3366557.399	$-q_3 + (2.218 + q_{30})$
$\mathcal{R}_3 \rightarrow \mathcal{R}_4$	200.254	1.571	885.145	$q_4 - (0.001 + q_{40})$
$\mathcal{R}_4 \rightarrow \mathcal{R}_5$	-0.022	1.571	0.174	$q_5 + (2.878 - q_{50})$
$\mathcal{R}_5 \rightarrow \mathcal{R}_6$	-0.007	1.571	0	$q_6 + q_{60}$



Conclusion

Conclusion

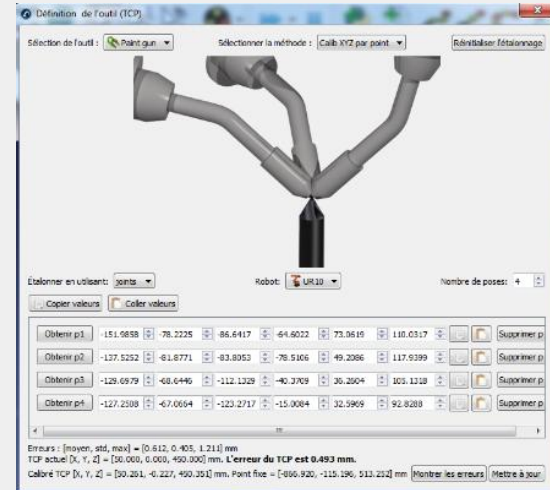
- Industrial robot accuracy
 - Control the pose of each frame of the robotic cell:
 - Kinematic model
 - Identification process
 - Identification process:
 - Measurement mean
 - Point measurement selections
 - Use a numerical optimization



The strategy to define nominal kinematic model can be different of the one for identified kinematic model

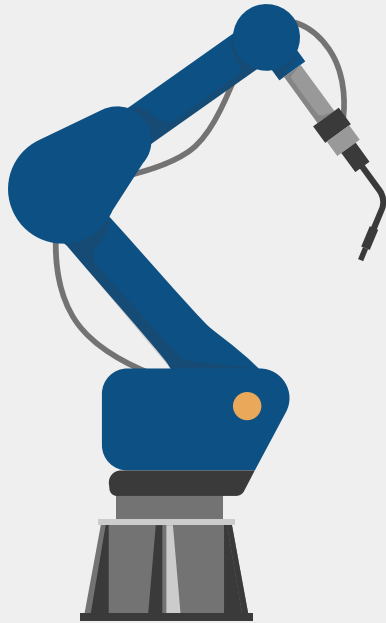
Conclusion

- A need to develop new tool for accuracy
 - Measurement means:
 - Accurate one are expensive compared to robot cost
 - A challenge to develop new one



Thanks!

Any questions?



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