MICRO 372 - Advanced Mechanisms for Extreme Environments

Chapter 8

(Ultra-) High precision

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(Ultra-) High precision

- Calibration
- Flexure's tolerance effect
  - Manufacturing
  - Assembly
- Kinematic couplings

Calibration of robot or mechanisms

- **Kinematics:**

Calibration of the robot's kinematics involves adjusting parameters related to its **joint angles**, **link lengths**, and **coordinate systems**. This ensures that the robot moves accurately according to its intended trajectory.

- **Accuracy and repeatability**:

Robots often undergo calibration procedures to **improve their accuracy and repeatability**.

- **Sensor calibration**:

If the robot is equipped with sensors such as **cameras**, **force/torque sensors**, or **proximity sensors**, these sensors may need calibration to ensure accurate data acquisition and integration into the robot's control system.

- **Environmental factors**:

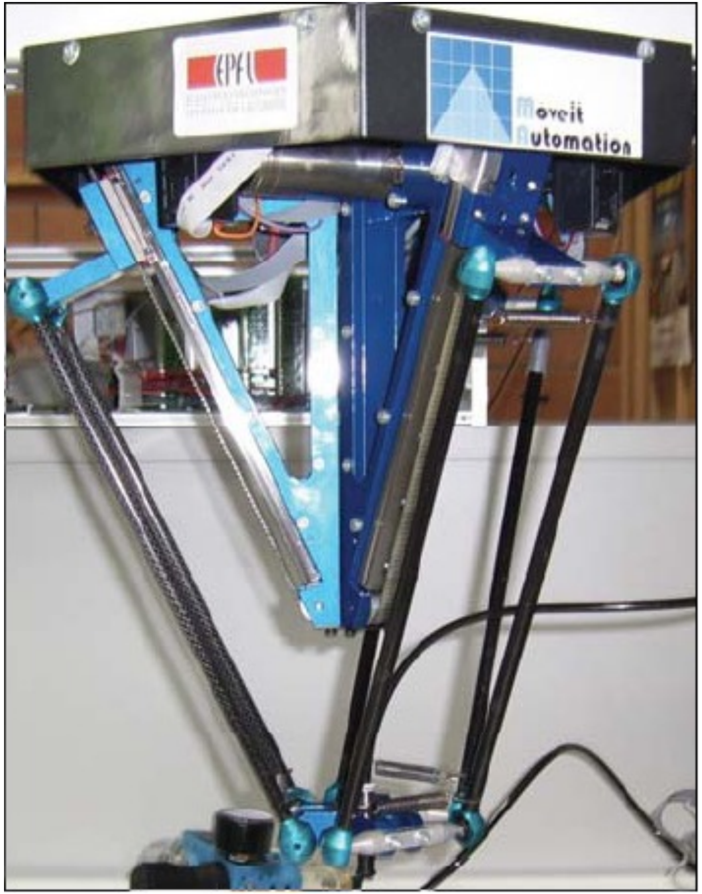
Calibration may also account for environmental factors such as **temperature variations**, **humidity levels**, and **gravitational effects**

- **Load and payload calibration**

calibration may involve adjusting parameters related to **varying loads** or payloads.

Calibration example: Kheops robot

- **Calibrate the robot** makes possible to bring the actual **output** (position of the tool) **as close as possible to the desired theoretical position**.
- The purpose to calibrate a robot is to **correct its positioning errors due to differences between theoretical values and actual values**.
- These errors can be due to an **inaccuracy of the geometric model**, like imprecision of the lengths of the robot arms.
- **Other types of error** that can be calibrated**: sensor drift, nonlinearity, hysteresis, noise, interference.**
- Or to an influence of the **robot's environment**: **temperature, humidity, pressure.**

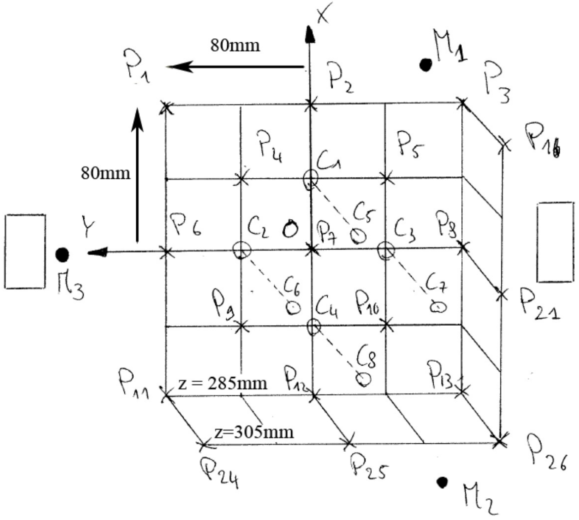


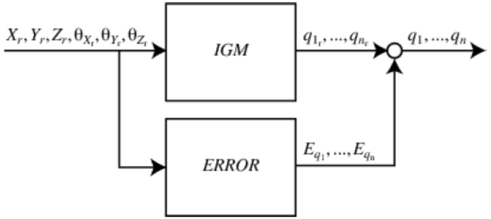
Calibration example: Kheops robot

Calibration procedure:

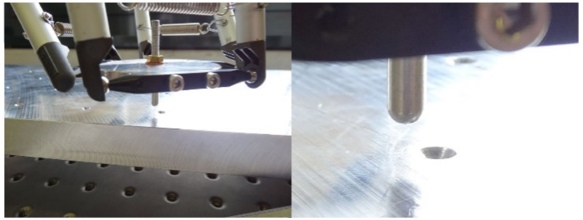
- **Calculate the IGM**
- **Manual positioning** the robot **on precise points** (motors off)
- **Measurement of the motor coordinates** at these points
- Determination of a **polynomial fit of measured errors**
- **Addition to the IGM**
- **Validation of the correction** by comparing the motor theoretical values and measured values **on control points** (motors still off)

Calibration points (P1-P26) and control points (C1-C8)

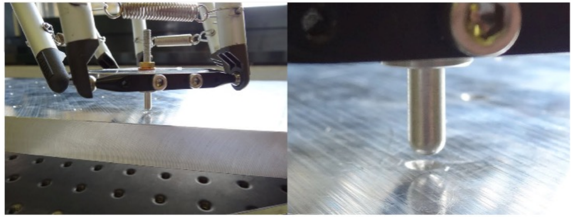




before calibration



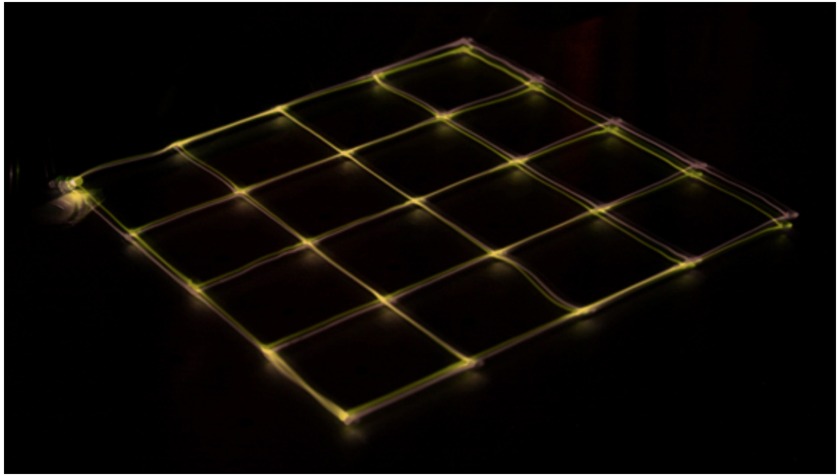
after calibration

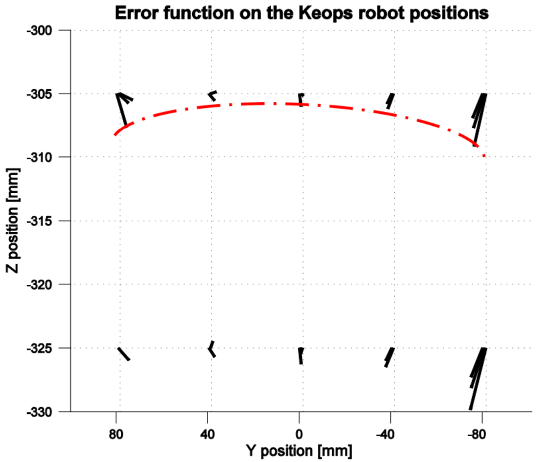


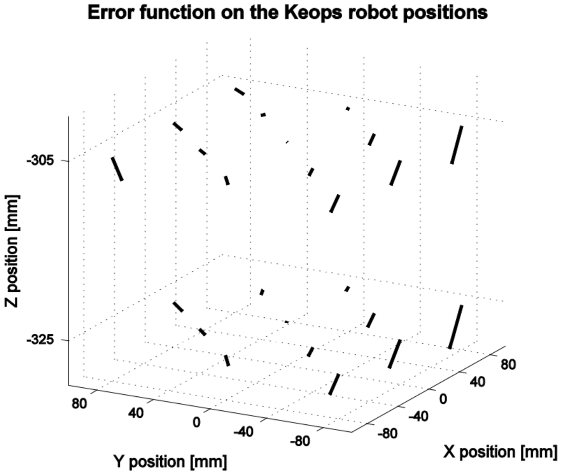
Calibration example: Kheops robot

Results:

- Prior to calibration, **the workspace of the robot is distorted**, mainly due to bad length identification of the robot arms.
- **Twisting, tilting and scaling effects** are removed from the workspace of the robot
- Resulting **absolute accuracy** over the workspace < 20 um

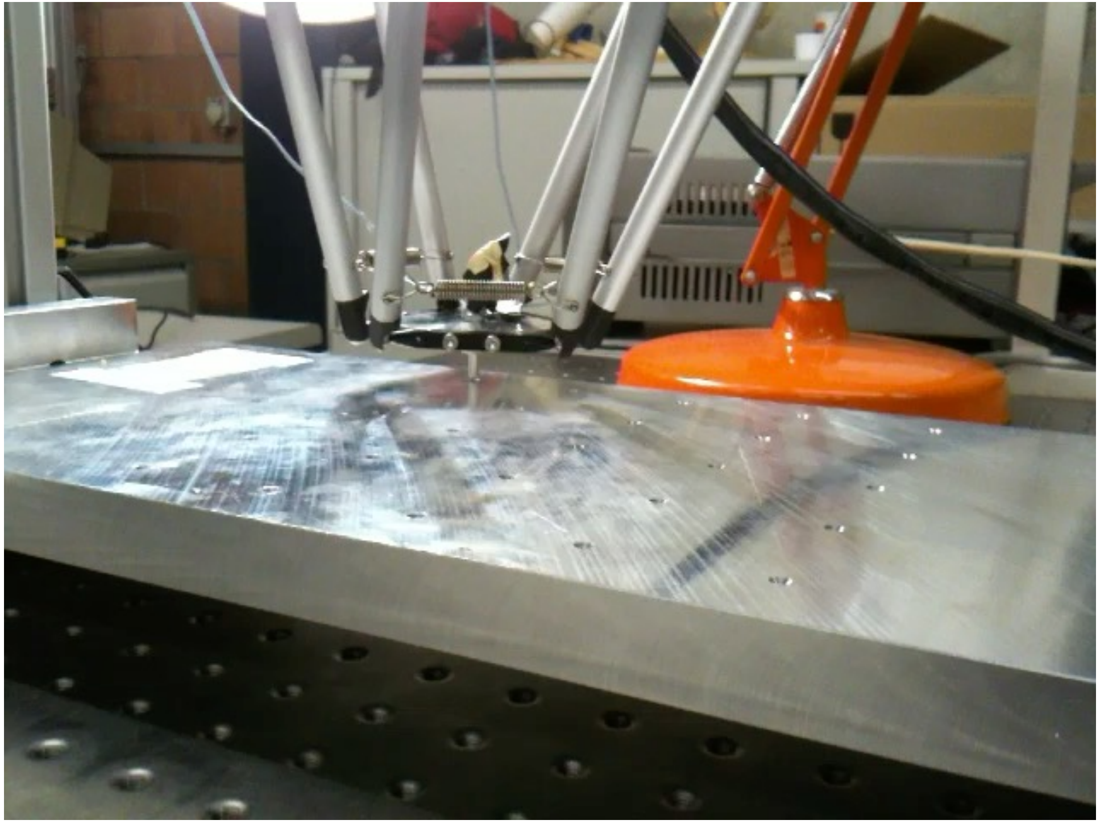






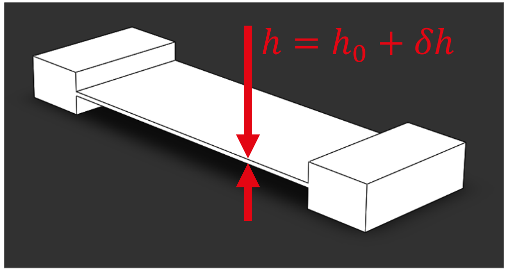
Calibration example: Kheops robot

Kheops robot's tool stays at 0.2 mm of the surface



Flexure's manufacturing tolerance calculation

δh depends mainly on the manufacturing technology



SPRINGS			STIFFNESS K: N/m $K = \frac{F}{x}$ Ka: Nm/rad	ADMISSIBLE STROKE x: m α: rad
BENDING	PURE		$K = \frac{E \cdot b \cdot h^3}{12 \cdot l}$	$\alpha = \frac{2 \cdot \sigma \cdot l}{E \cdot h}$
	SIMPLE		$K = \frac{E \cdot b \cdot h^3}{4 \cdot l^3}$	$x = \frac{2 \cdot \sigma \cdot l^2}{3 \cdot E \cdot h}$

STIFFNESS

$$\frac{\delta h}{h_0} \ll 1$$

$$K = K_0 \cdot \left(\frac{h_0 + \delta h}{h_0}\right)^3 = K_0 \cdot \left(1 + 3\frac{\delta h}{h_0} + 3\frac{\delta h^2}{h_0^2} + \frac{\delta h^3}{h_0^3}\right) \cong K_0 \cdot \left(1 + 3\frac{\delta h}{h_0}\right)$$

$$\Delta K \cong 3\frac{\delta h}{h_0}$$

STRESS

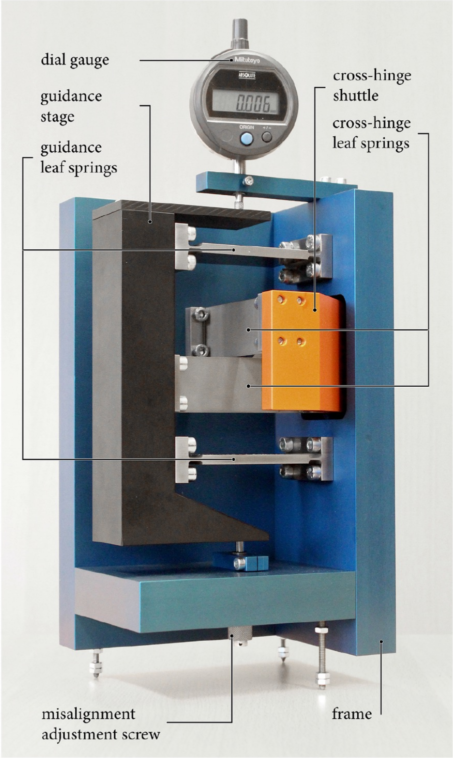
$$\sigma \sim h$$

$$\Delta \sigma \cong \frac{\delta h}{h_0}$$

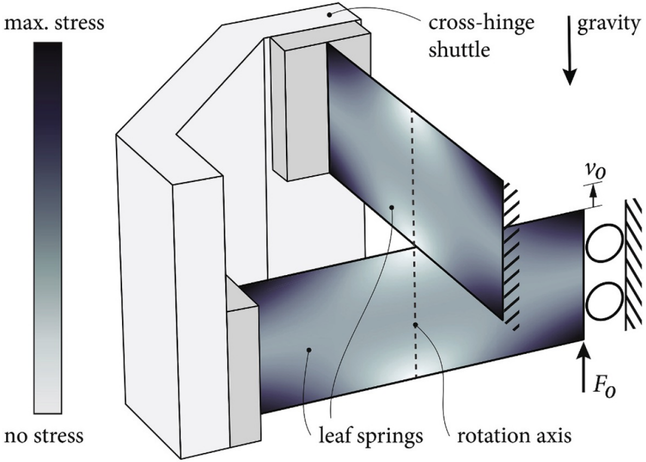
Flexure's assembly tolerance calculation

- The effect of assembly tolerances is assessed
- Analytical and FEM values are compared with measurements

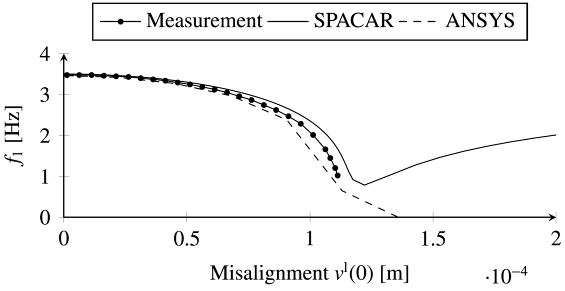
Experimental setup



Stress within the pivot blades



First eigenfrequency of the pivot

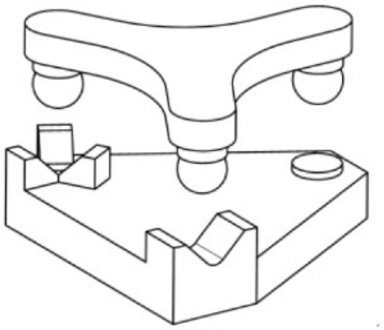


Overconstrained cross-hinge design consisting of two leaf springs. Gray scales in the leaf springs represent the von Mises stress distribution caused by misalignment v0 due to a force F0.

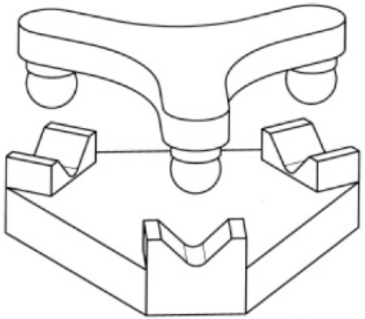
M. Nijenhuis, J.P. Meijaard, D.M. Brouwer, «Misalignments in an overconstrained flexure mechanism: A cross-hinge stiffness investigation», Precision Engineering 62, pp.181–195, 2020

Kinematic coupling: Kelvin and Maxwell Clamps

- Kinematic couplings are **exact constraint design couplings** because they use six known contact points to locate one component with respect to another.
- They have long been known to provide an **economical and dependable method** for attaining high repeatability in fixtures.
- **Kinematic couplings are deterministic** because they only make contact at a number of points equal to the number of degrees of freedom that are to be restrained.



Kelvin clamp



Maxwell clamp

Kinematic coupling: Hertzian contact

- Heinrich Hertz is a mathematician famous for his work in the frequency domain
- He also created the first analytical solution for determining the stress between two bodies in point contact
- Exact constraint design often creates contact at single points

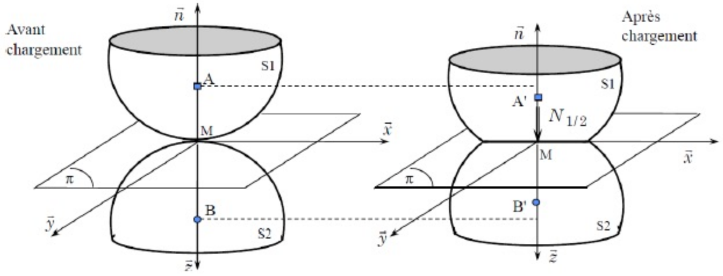


FIGURE 3 – Modélisation des déformations

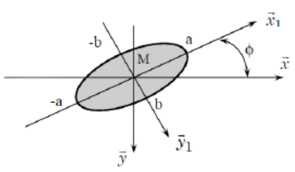


FIGURE 4 – Zone de contact

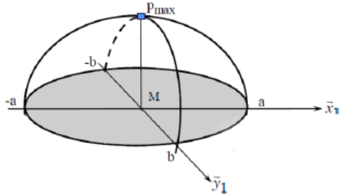
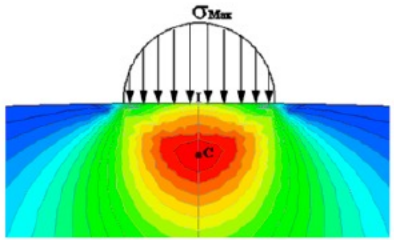
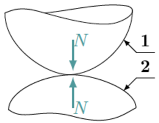
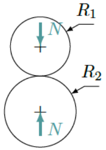
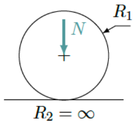
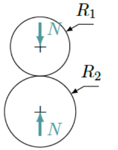
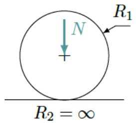
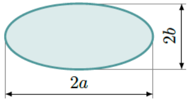
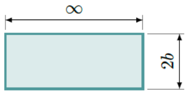
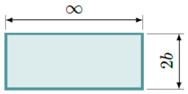


FIGURE 5 – Répartition de pression (ellipsoïde)

On détermine alors : $p_{moy} = \frac{N_{1\to 2}}{\pi a b}$ et $p_{max} = \frac{3}{2} p_{moy}$ $\Rightarrow$ $p_{max} = \frac{3}{2} \frac{N_{1\to 2}}{\pi a b}$



Kinematic coupling: Hertzian contact

		Contact ponctuel			Contact linéique	
		Solides quelconques	Sphère/sphère	Sphère/plan	Cylindre/cylindre	Cylindre/plan
Types de contacts						
Surface de contact	Forme	Ellipse (a, b) 	Cercle (a) 	Cercle (a) 	Rectangle (∞, b)  q charge par unité de longueur	Rectangle (∞, b)  q charge par unité de longueur
	Dimensions	$a = m\sqrt[3]{\frac{3\pi}{2}\frac{k_1+k_2}{C_1+C_1'+C_2+C_2'}N}$ $b = \frac{n}{m}a$	$a = \sqrt[3]{\frac{3\pi}{4}(k_1+k_2)\frac{R_1R_2}{R_1+R_2}N}$	$a = \sqrt[3]{\frac{3\pi}{4}(k_1+k_2)RN}$	$b = 2\sqrt{(k_1+k_2)\frac{R_1R_2}{R_1+R_2}q}$	$b = 2\sqrt{(k_1+k_2)qR}$
Rapprochement δ		$\delta = r\frac{3\pi}{4a}(k_1+k_2)N$	$\delta = \sqrt[3]{\frac{9\pi^2}{16}(k_1+k_2)^2\frac{R_1+R_2}{R_1R_2}N^2}$	$\delta = \sqrt[3]{\frac{9\pi^2}{16}\frac{(k_1+k_2)^2}{R}N^2}$	$\delta = 3{,}84 \cdot 10^{-5}\frac{N^{0,9}}{L^{0,8}}$ (acier)	
Pression max p_{max}		$p_{max} = \frac{3}{2}\frac{N}{\pi ab}$	$p_{max} = \frac{3}{2}\frac{N}{\pi a^2}$	$p_{max} = \frac{3}{2}\frac{N}{\pi a^2}$	$p_{max} = 0,59\sqrt{\frac{E_1E_2}{E_1+E_2}\frac{R_1+R_2}{R_1R_2}q}$ Si $\nu = 0,3$: $p_{max} = \frac{2N}{\pi Lb} = \frac{2q}{\pi b}$ $p_{max} = \frac{1}{\pi}\sqrt{\frac{1}{k_1+k_2}\frac{R_1+R_2}{R_1R_2}q}$	$p_{max} = 0,59\sqrt{\frac{E_1E_2}{E_1+E_2}\frac{1}{R}q}$ Si $\nu = 0,3$: $p_{max} = \frac{2N}{\pi Lb} = \frac{2q}{\pi b}$ $p_{max} = \frac{1}{\pi}\sqrt{\frac{1}{k_1+k_2}\frac{1}{R}q}$
Profondeur pour τ_{max} (pour $\nu = 0,3$)		Fonction de l'excentration de l'ellipse	$h = 0,5a$	$h = 0,5a$	$h = \frac{\pi}{4}b$	$h \approx 0,78b$

* avec : $k_i = \frac{1-\nu_i^2}{\pi E_i}$

Kinematic coupling parameters

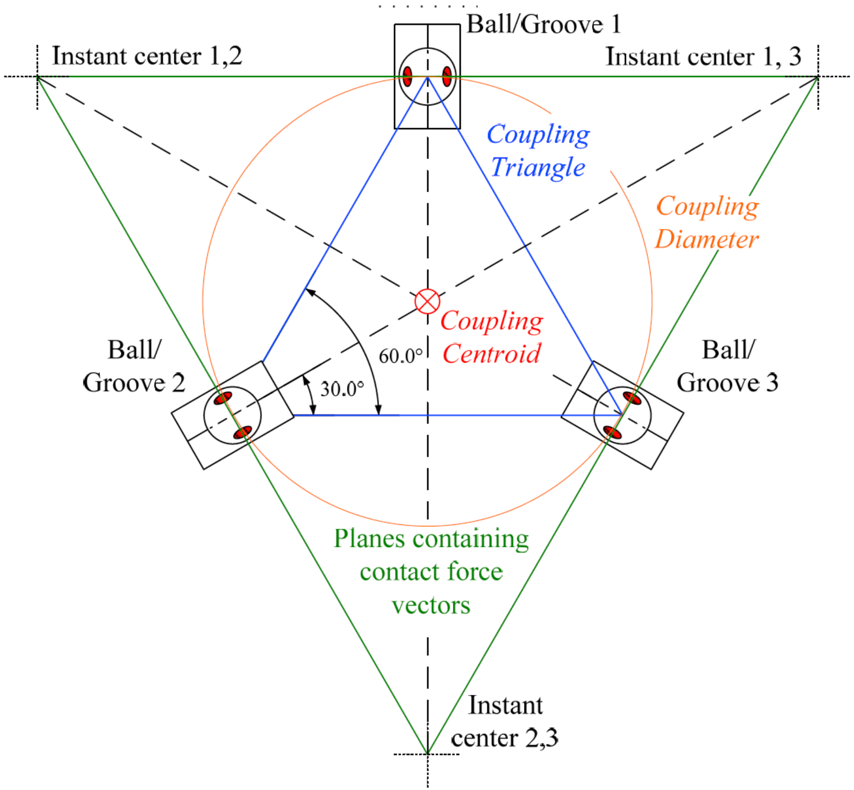


Figure 5 Geometric parameters for a three groove kinematic coupling.

Alexander Slocum, Kinematic couplings: A review of design principles and applications, International Journal of Machine Tools and Manufacture, Volume 50, Issue 4, pp 310-327, 2010.

Kinematic coupling: Canoe ball

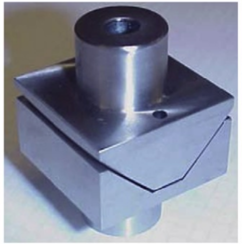
- Acts like a **ball 1 meter in diameter**
- Has **100 times the stiffness** and **load capacity** of a normal **1" ball**
- The **large shallow Hertzian zone** is very repeatable

a) Modular "Canoe ball" and vee

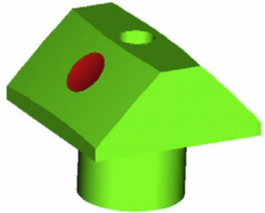
b) Solid model showing Hertz contact zone used in the kinematic coupling.

c) Preloading a kinematic coupling through the coupling elements to avoid deforming the rest of the structure.

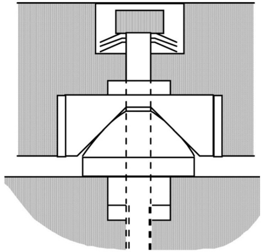
a)



b)



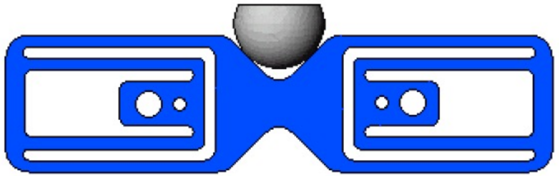
c)

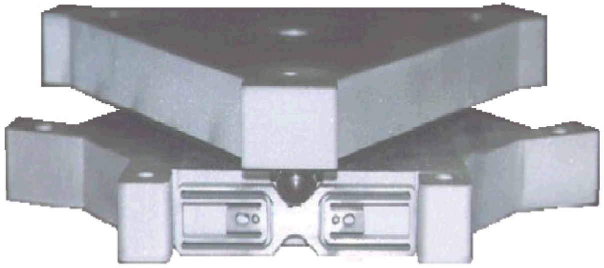


Alexander Slocum, Kinematic couplings: A review of design principles and applications, International Journal of Machine Tools and Manufacture, Volume 50, Issue 4, pp 310-327, 2010.

Flexural Kinematic coupling

- Combines the **repeatable location** of traditional kinematic couplings with the **stiffness characteristics** of many other coupling methods
- After the kinematic members (3 "balls" and 3 "grooves") are mated, **force is applied to bring the two components together.**
- Parts of the kinematic coupling (flexures attached to one of the major components) displace and allow the components to mate, thereby creating a **classical surface-to-surface, high load capacity joint.**
- When properly designed, this can be accomplished **without compromising the kinematic nature of the coupling.**



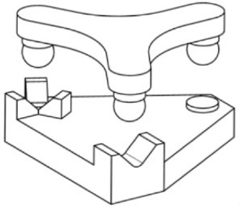


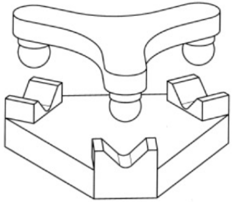
Kinematic coupling: repeatability calculation

Nonrepeatability (ρ) due to friction decreases linearly with decreasing coefficient of friction between the balls and grooves, following the general relation between the friction coefficient (μ), ball radius (R), the applied load (P) and the elastic modulus (E):

$$\rho = \mu \left(\frac{2}{3R} \right)^{\frac{1}{3}} \left(\frac{P}{E} \right)^{\frac{2}{3}}$$

Kelvin clamp





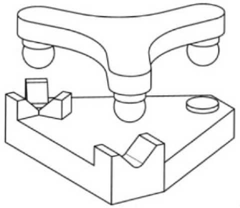
Maxwell clamp

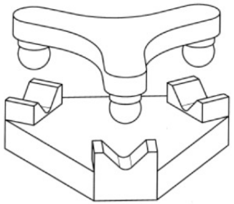
http://pergatory.mit.edu

Kinematic coupling: conclusions

- Offers **very high positioning accuracy**
- **Repeatability** of the positioning is in the **sub-micron range**, generally in the order of the **surface roughness**
- **Stability zone** is limited
- Requires a **repeatable preload**
- Stiffness if limited by **hertzian contacts** and by the **rigid bodies' rigidity**
- **More stiffness** when the **contact radius is increased**

Kelvin clamp





Maxwell clamp

EPFL

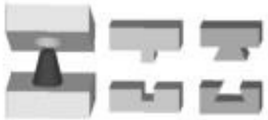
Common coupling methods

Pinned Joints

No Unique Position

Flexural Kin. Couplings

Kinematic Constraint

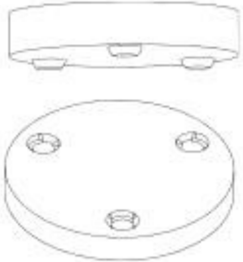


Elastic Averaging

Non-Deterministic

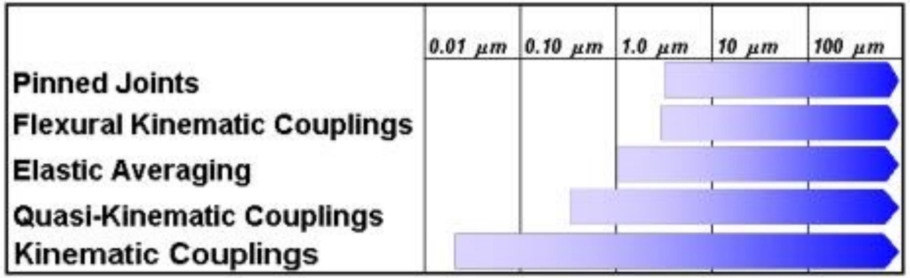
Kinematic Couplings

Kinematic Constraint



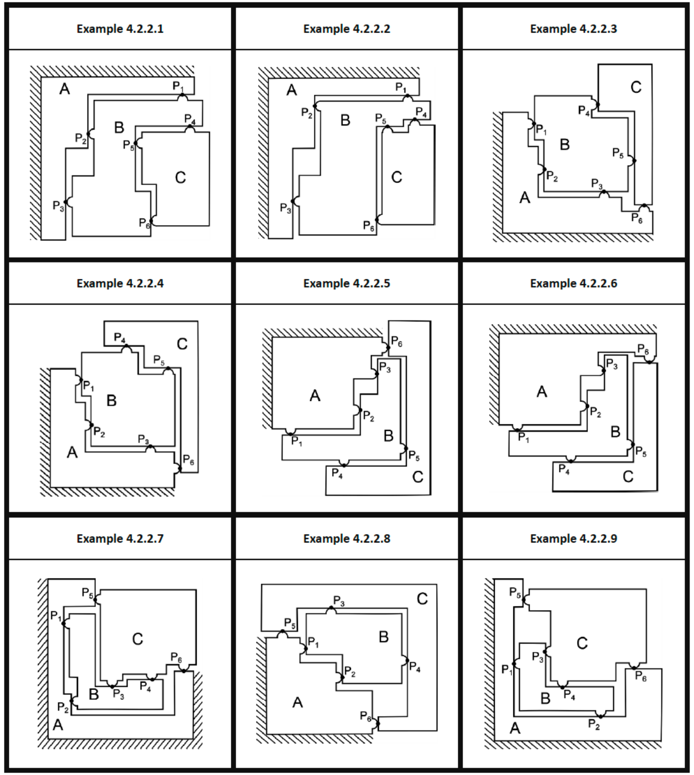
Quasi-Kinematic Couplings

Near Kinematic Constraint



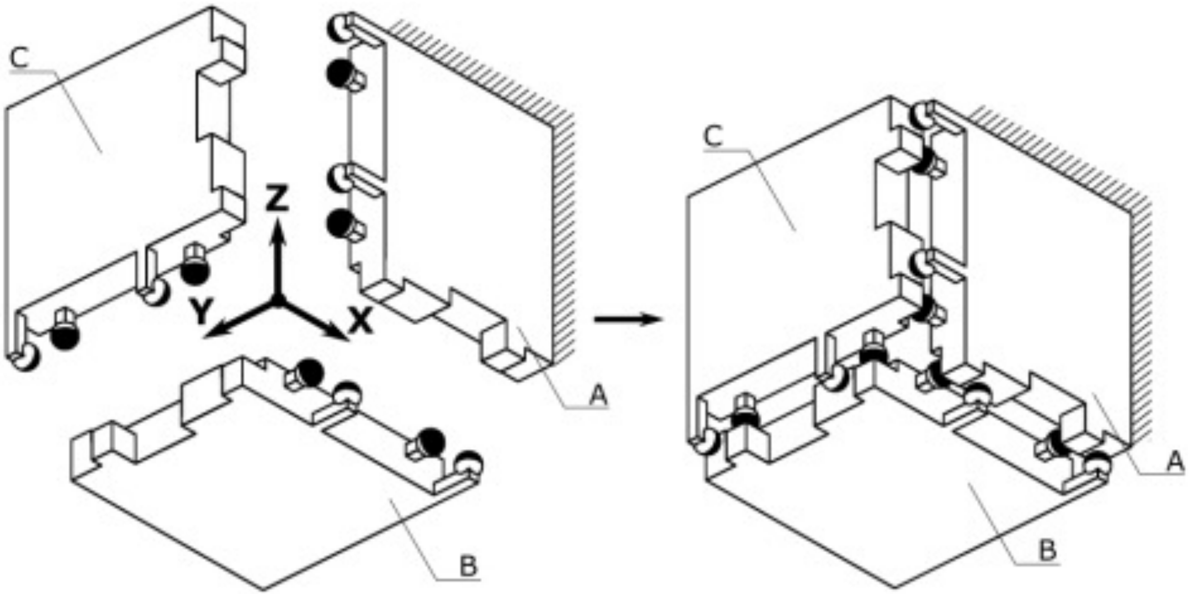
Source: Precision Engineering Research Group, MIT

Kinematic coupling (3 bodies – 2D)



J. Kruis, “Design, analysis, testing and applications of two-body and three-body kinematic mounts”, EPFL thesis n° 7005, 2016

Kinematic coupling (3 bodies – 3D)



J. Kruis, “Design, analysis, testing and applications of two-body and three-body kinematic mounts”, EPFL thesis n° 7005, 2016

Kinematic coupling (3 bodies - 3D)

Example 7.4.2.1

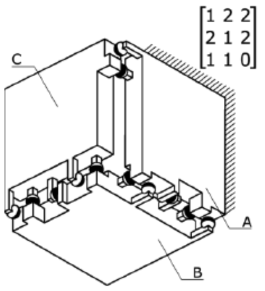


Figure 7.4.2.1

Example 7.4.2.2

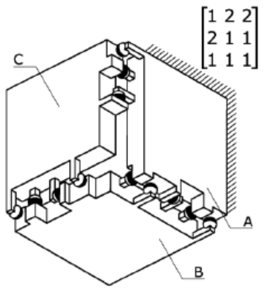


Figure 7.4.2.2

Example 7.4.2.3

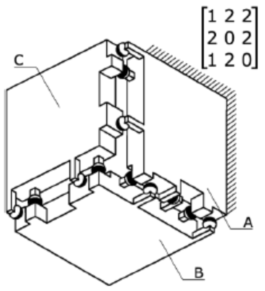


Figure 7.4.2.3

Example 7.4.2.4

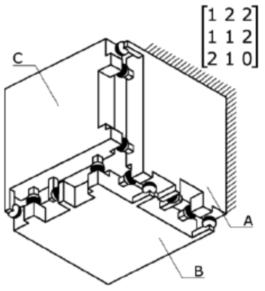


Figure 7.4.2.4

Example 7.4.2.5

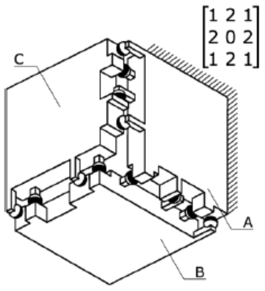


Figure 7.4.2.5

Example 7.4.2.6

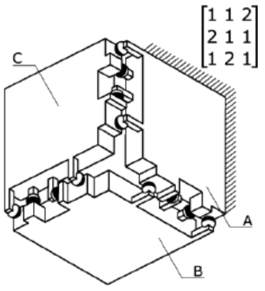


Figure 7.4.2.6

Example 7.4.2.7

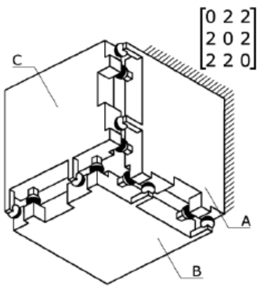
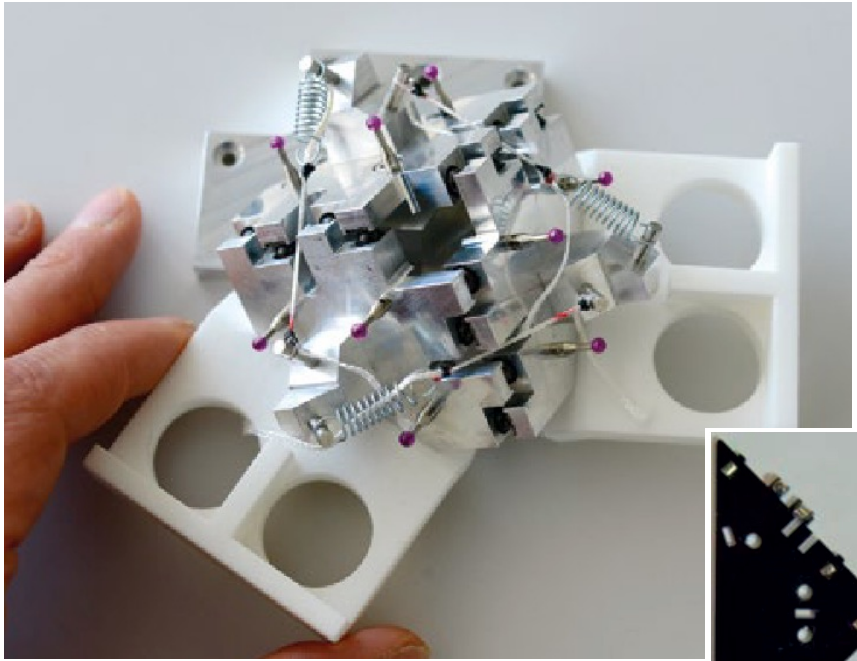
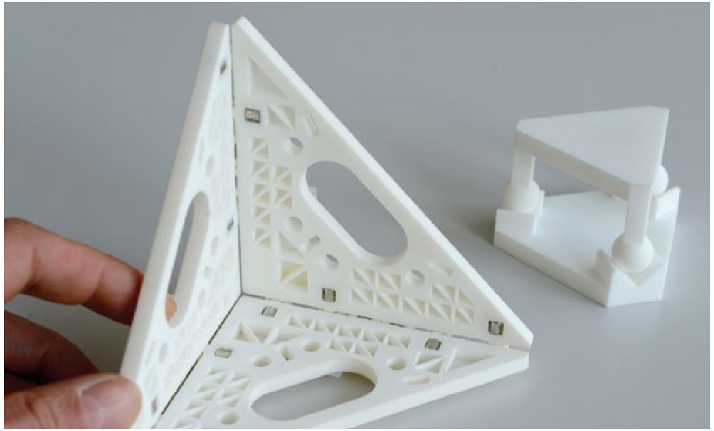


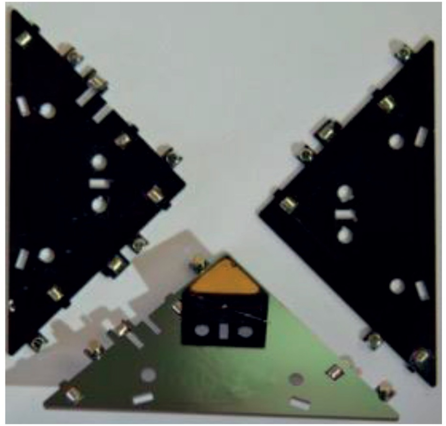
Figure 7.4.2.7

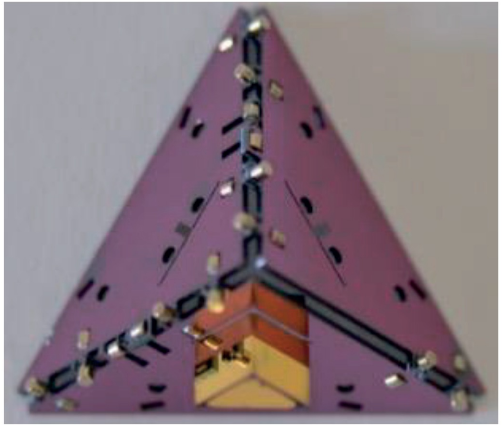
J. Kruis, “Design, analysis, testing and applications of two-body and three-body kinematic mounts”, EPFL thesis n° 7005, 2016

Kinematic coupling (3 bodies – 3D)



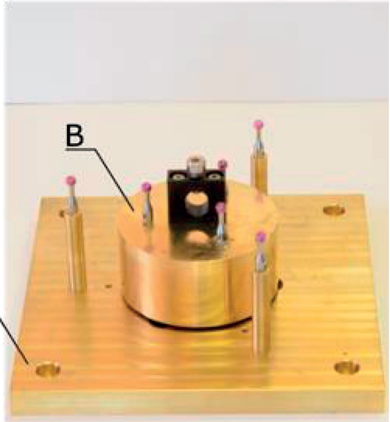


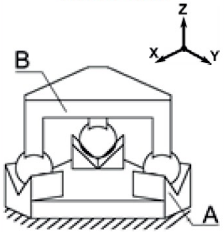
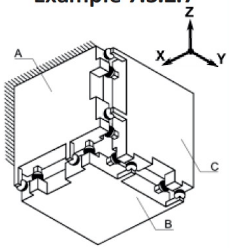


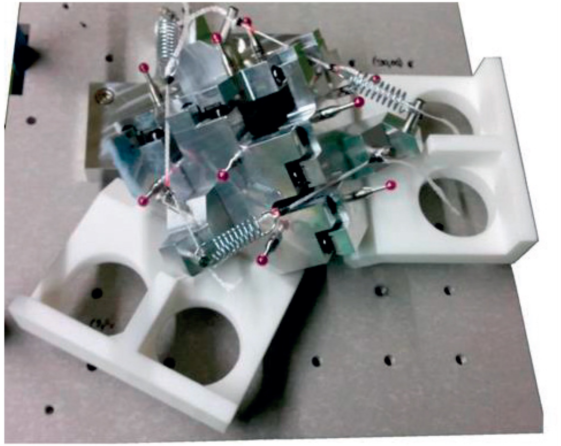


J. Kruis, “Design, analysis, testing and applications of two-body and three-body kinematic mounts”, EPFL thesis n° 7005, 2016

Kinematic coupling (3 bodies - 3D)



		Average		
		Three-Vee 	Example 7.3.2.7 	
			Body	
			B	C
Degree of Freedom (DOF)	D	0.178 µm	0.902 µm	0.712 µm
	α	5 µrad	42 µrad	31 µrad
Number of measurements		10	3	


2 cm

J. Kruis, “Design, analysis, testing and applications of two-body and three-body kinematic mounts”, EPFL thesis n° 7005, 2016

Week 10 exercises and homework

Exercise on MOODLE:

- EXO10_Balancing_II.pdf

Homework:

- No homework