3D METROLOGY CONFERENCE

3DMC presentation

Autocalibration of complex mechatronic systems: Machine tools and robots

by Brahim Ahmed Check & Unai Mutilba

18/09/2025

Tekniker
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

Outline

Outline

- **WHO WE ARE - TEKNIKER**
- **INTRODUCTION**
- **MACHINE TOOL CALIBRATION**
- **ROBOT CALIBRATION**

WHO WE ARE

R&D Centre
(not-for-profit Private Foundation) |
Applied research spanning 45 years

Our mission is to deliver growth and wellbeing to society at large via R&D&I and to further the competitiveness of the business fabric in a sustainable manner

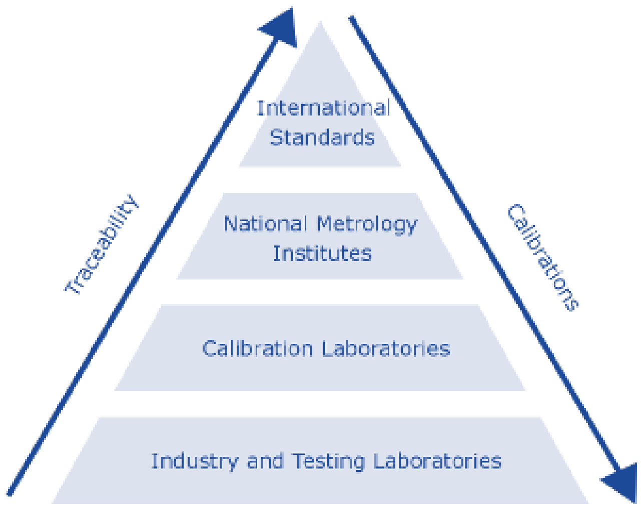
Specialised in **Manufacturing**

Outline

Introduction

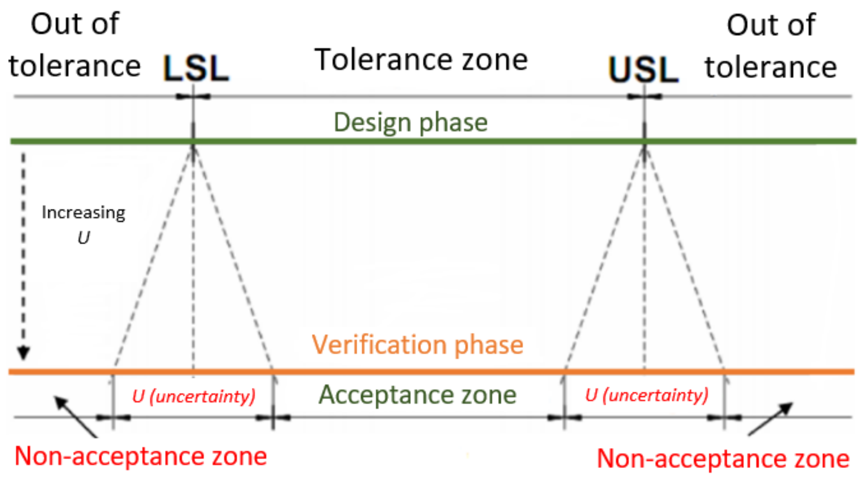
TRACEABILITY

Property of a measurement result whereby the **result can be related to a reference** through a **documented unbroken chain of calibrations**, each contributing to the measurement uncertainty



UNCERTAINTY

The measurement uncertainty is a **non-negative parameter associated with the result of a measurement**, which **characterises the dispersion of values that can be reasonably attributed to that measurement result.**



Introduction

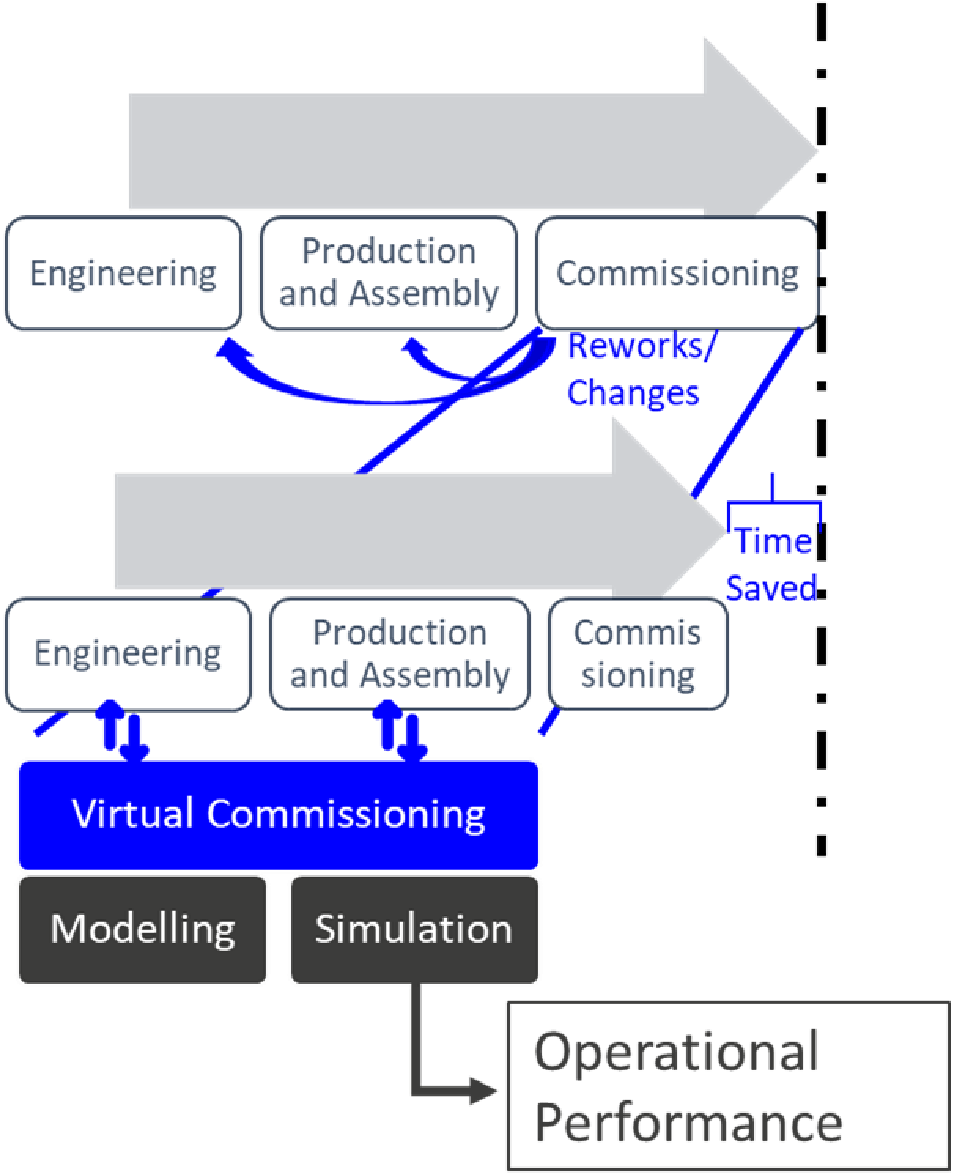
Virtual commissioning

TRADITIONAL

Simulation techniques for validating and optimizing the automation and control systems of machines, robots or industrial plants before physical commissioning.

Errors can be identified and corrected, efficiency improved, and implementation costs and times minimized

Safe virtual environment to test various situations and solutions



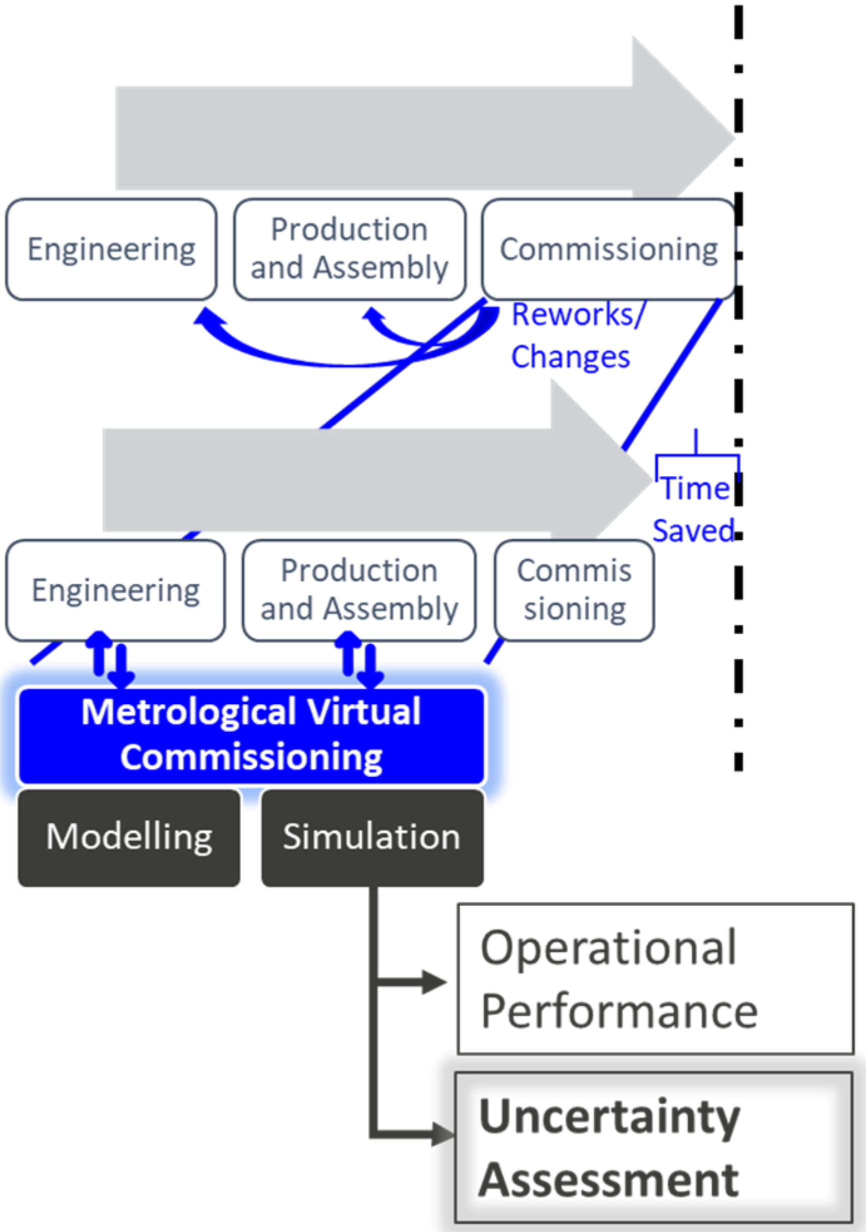
Virtual commissioning + Metrology

METROLOGICAL

Combines virtual commissioning with metrology to ensure models are both functionally accurate and metrologically correct.

Enables comprehensive validation by testing and optimizing both functionality and measurement accuracy in a virtual environment before physical commissioning

Calibration and measurement systems can be virtually tested and optimized to ensure the actual system meets metrological requirements and standards



Outline

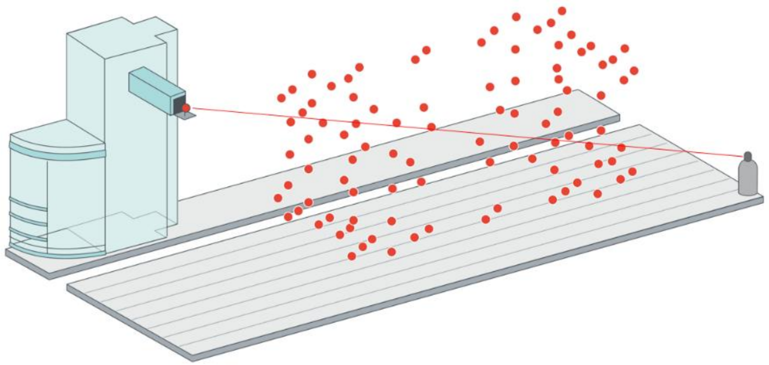
WHO WE ARE - TEKNIKER

INTRODUCTION

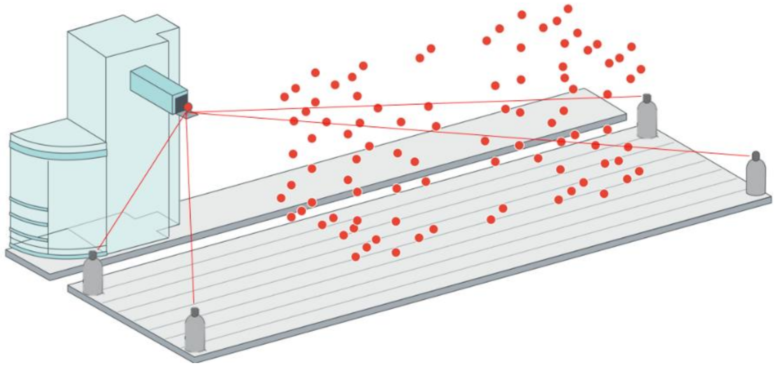
MACHINE TOOL CALIBRATION

ROBOT CALIBRATION

Integrated multilateration - a new approach

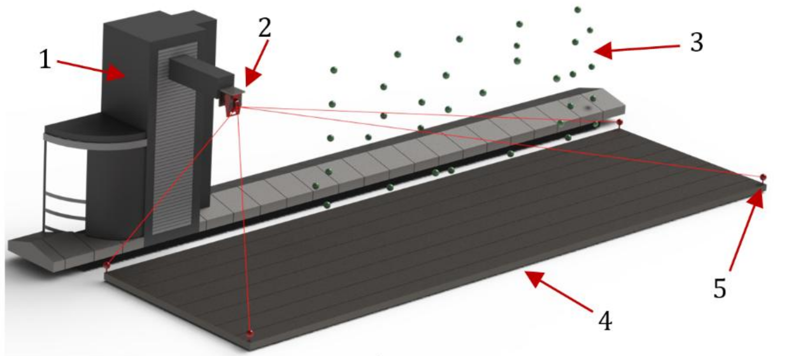


Sequential multilateration approach



Simultaneous multilateration approach

Machine Tool Integrated Inverse Multilateration **(MIIM)**: Presented in GA CIRP Tokyo 2018 [1]



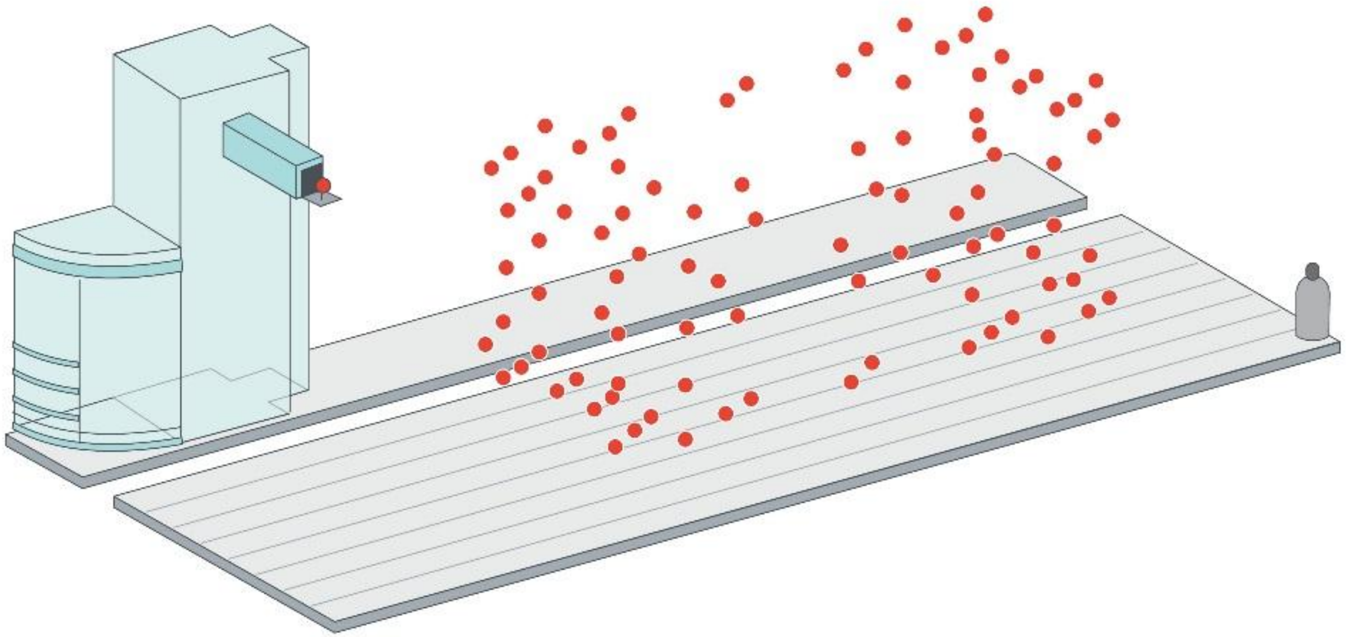
1	Machine tool	4	Machine tool´s table
2	Tracking interferometer	5	Fiducial point (x4)
3	Measurement point grid		

[1] Mutilba U, Yagüe-Fabra JA, Gomez-Acedo E, Kortaberria G, Olarra A (2018) Integrated multilateration for machine tool automatic verification. CIRP Ann 67 (1):555–558.

MT calibration

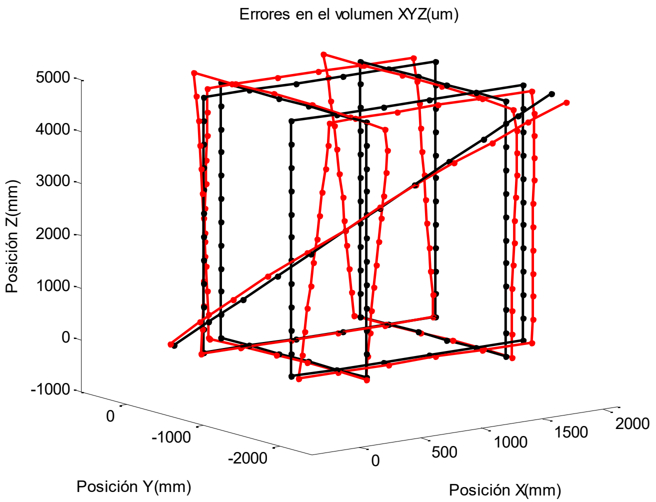
Multilateration based approach for large scale MT error mapping

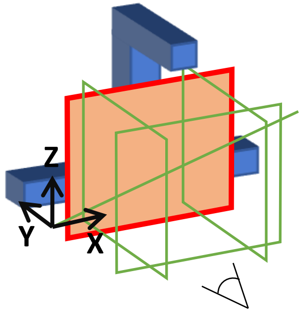
Interferometric or absolute displacement measurements between tracking interferometers that are fixed to the machine base and a reflector, fixed to the machine spindle, near to the tool centre point (TCP)

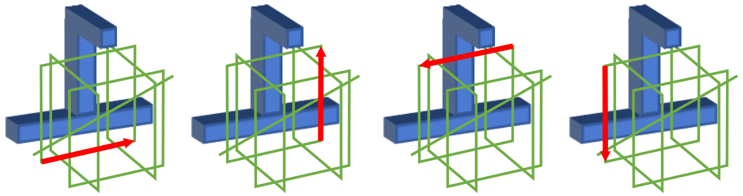


TRADITIONAL MULTILATERATION – laser tracker and electronic levels

Self-developed solution based on a AT901 laser tracker and levels







TRADITIONAL MULTILATERATION – laser tracer

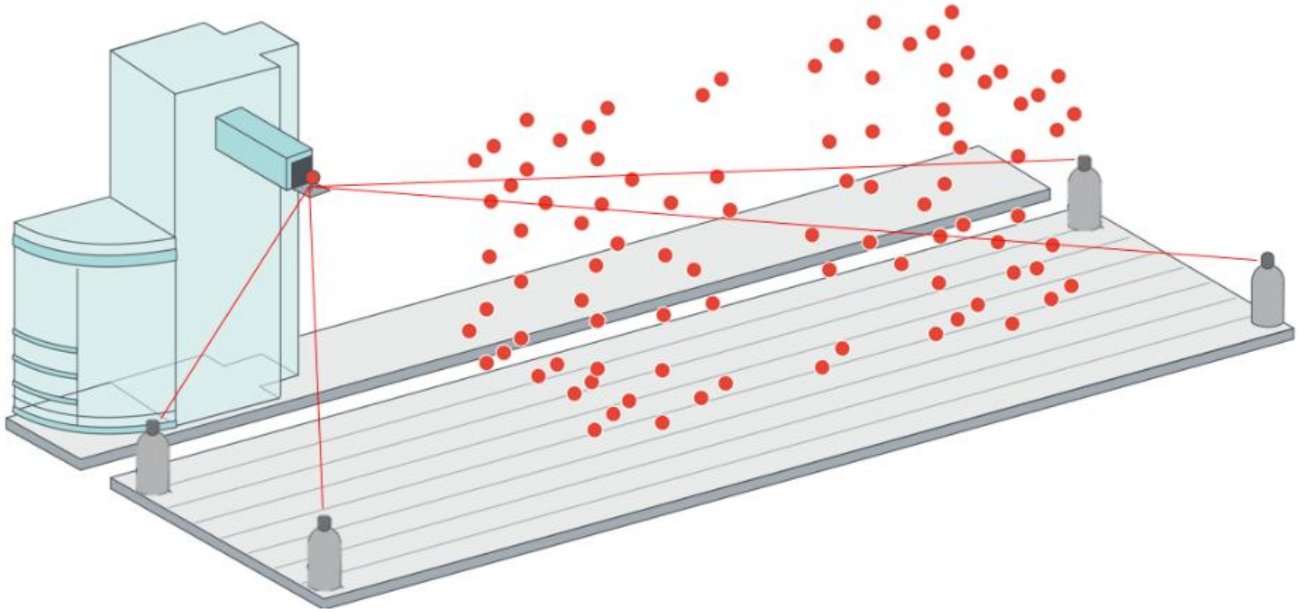
Laser tracer technology from ETALON AG

TRADITIONAL MULTILATERATION – laser tracer

MT calibration

Simultaneous multilateration approach

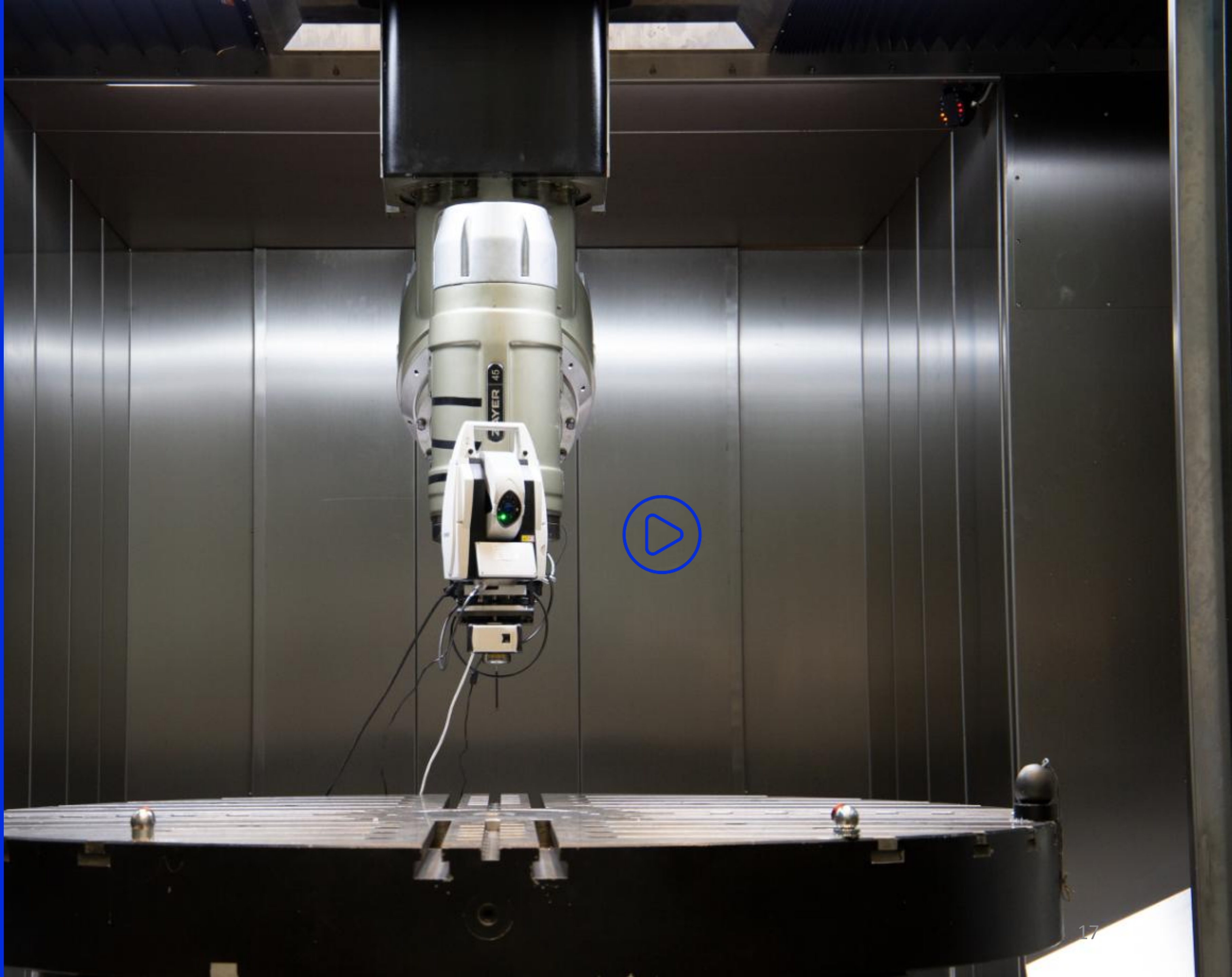
Interferometric or absolute displacement measurements between tracking interferometers that are fixed to the machine base and a reflector, fixed to the machine spindle, near to the tool centre point (TCP)



Traditional multilateration has strong limitations:

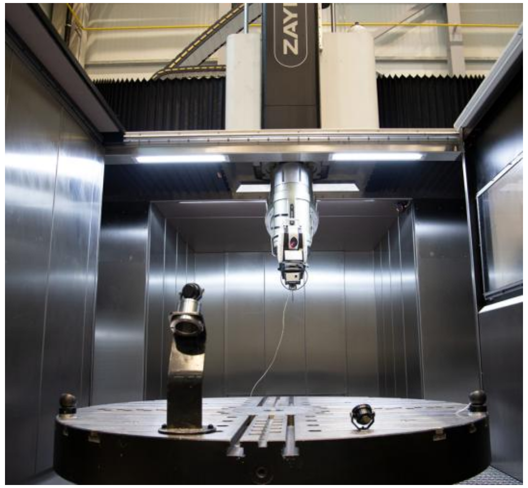
- **Four tracking interferometers** are needed
  - Sequential multilateration: A unique tracking interferometer is available
    - **Human intervention** is needed for manipulation: Manual intervention to move the tracking interferometer to the next position
    - **MT repeatability**
    - **Time-consuming** approach
    - **Thermal drift**
  - Simultaneous multilateration: Four tracking interferometers are available
    - **High-cost** solution.

SELF-DEVELOPED AND AUTOMATIC VOLUMETRIC ERROR MAPPING APPROACH

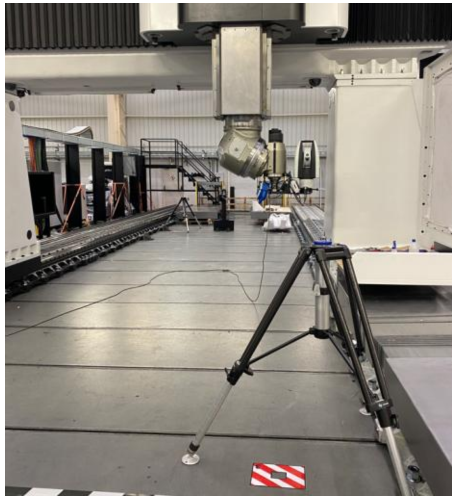


Integrated multilateration - a new approach

Different MT configurations – in collaboration with ZAYER



ZAYER ARION G



ZAYER THERA

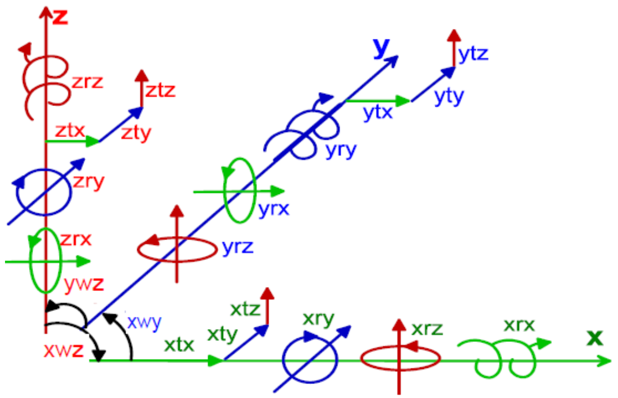
ZAYER ARES

ZAYER ZERO

More to come…

Error modelling and compensation of MTs

In MTs, 21 components of error kinematic models



$$E = P + A * X + A_p * X_p$$

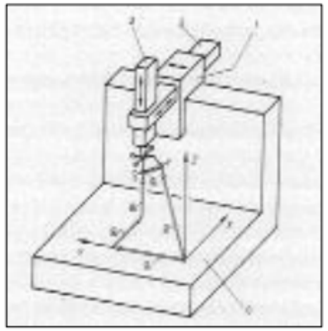
- E: error vector at position $X+X_p$
- P: translatorical errors
- A: rotatorical errors
- X_p: probe-offset vector
- X: position of reference probe

$$A = \begin{bmatrix} 0 & -ywx - xrz & +zwx + xry + yry \\ 0 & 0 & -zwy - xrx - yrx \\ 0 & +xrx & 0 \end{bmatrix}$$

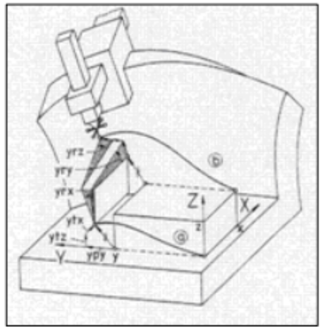
$$A_p = \begin{bmatrix} 0 & -xrz - yrz - zrz & +xry + yry + zry \\ +xrz + yrz + zrz & 0 & -xrx - yrx - zrx \\ -xry - yry - zry & +xrx + yrx + zrx & 0 \end{bmatrix}$$

$$X = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad X_p = \begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} \qquad P = \begin{bmatrix} xtx + ytx + ztx \\ yty + xty + zty \\ ztz + xtz + ytz \end{bmatrix}$$

Ideal



Real



For each linear axis X, Y and Z in total 6 geometric errors can appear (T: Translatory R: Rotatory) :

- Positioning — XTX YTY ZTZ
- Straightness — XTY XTZ YTX YTZ ZTX ZTY
- Yaw — XRZ YRZ ZRX
- Pitch — XRY YRX ZRY
- Roll — XRX YRY ZRZ

For 3 linear axes this means 18 error sources in total.

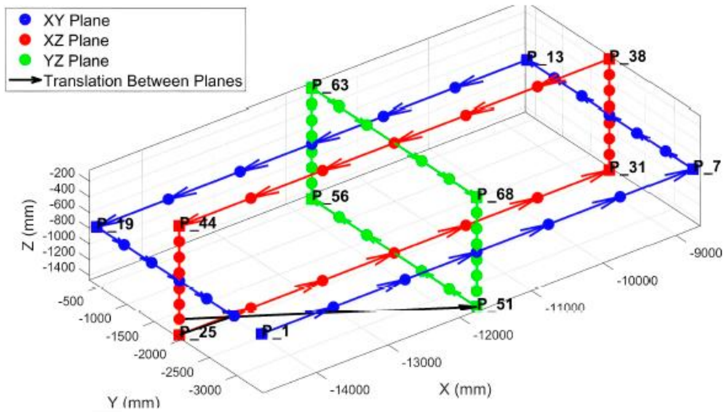
Additionally the 3 squareness errors of the linear axes must be taken into account:

- $x \perp y$ — XWY
- $x \perp z$ — XWZ
- $y \perp z$ — YWZ

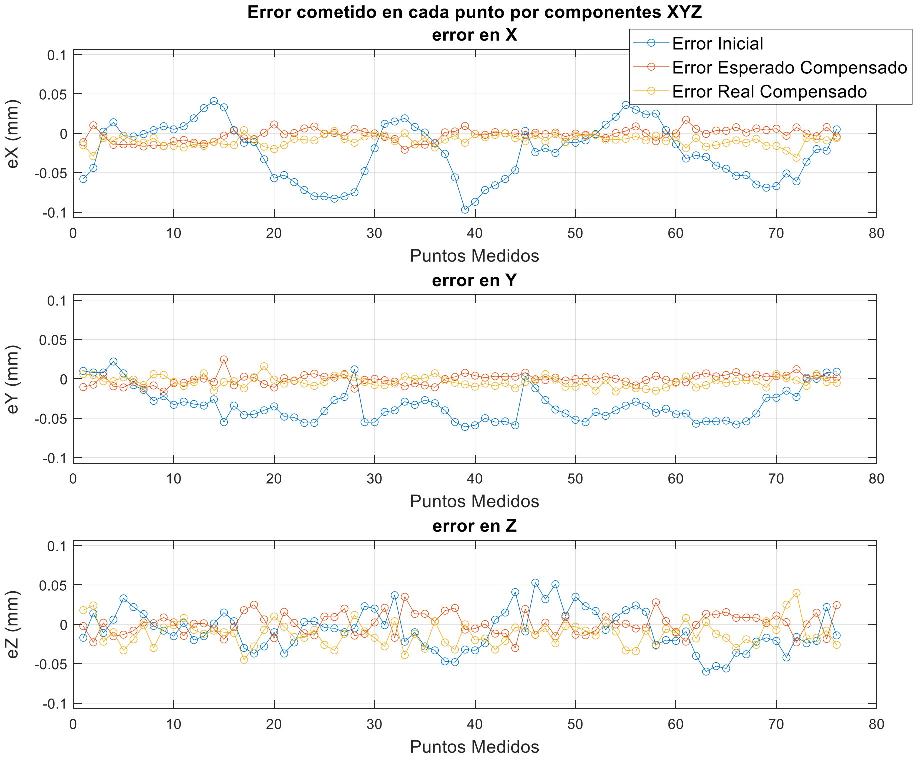
In total 21 geometric errors have to be handeld for a 3-axes machine tool.

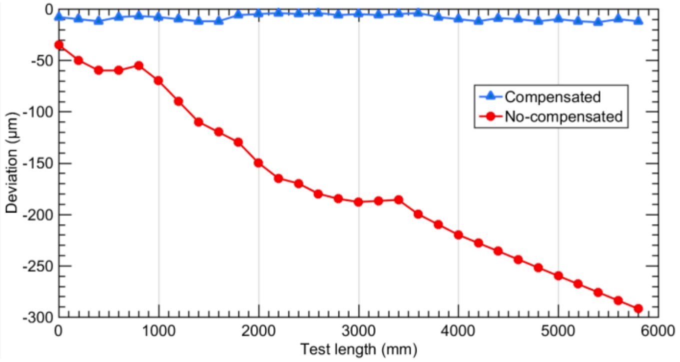
Error modelling and compensation of MTs

Measurement strategy

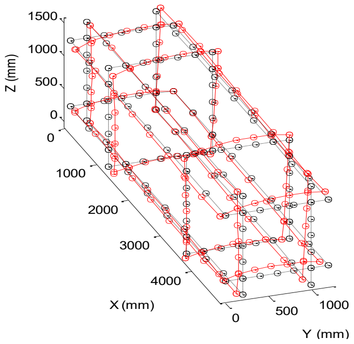


Some results

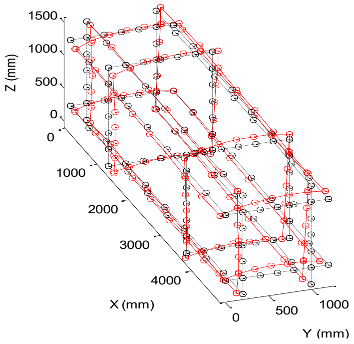




Thermal characterisation of MTs



9:00



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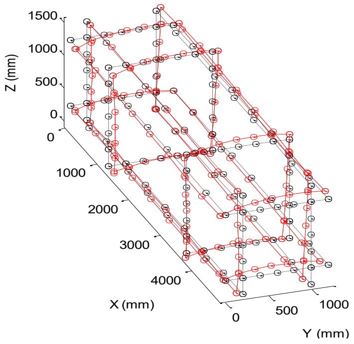

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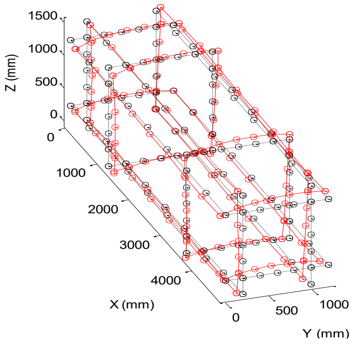

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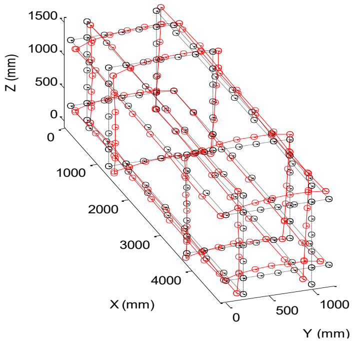
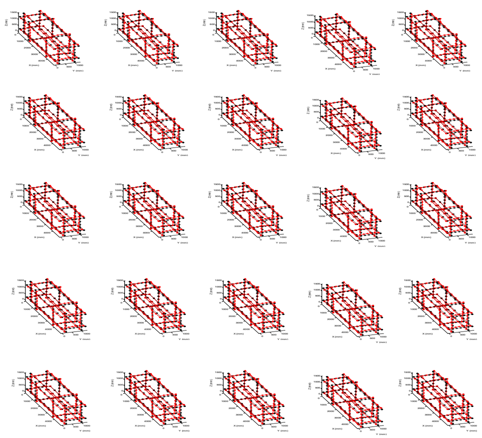
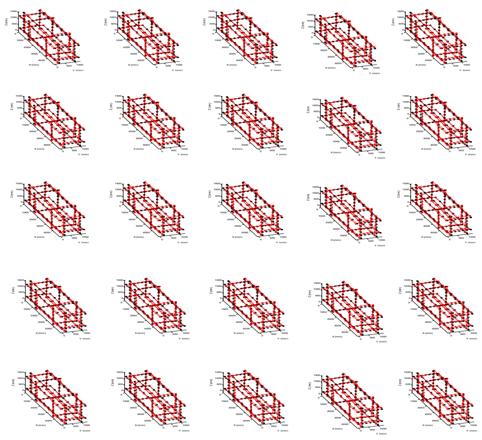


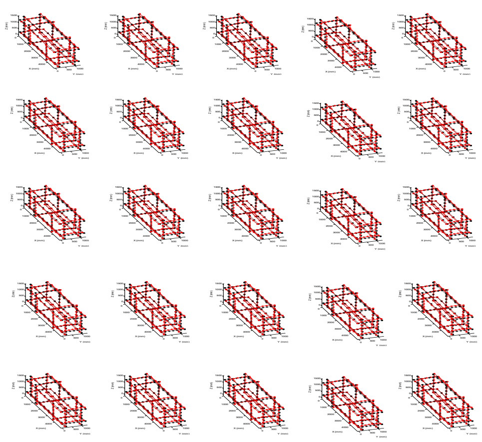
12:00



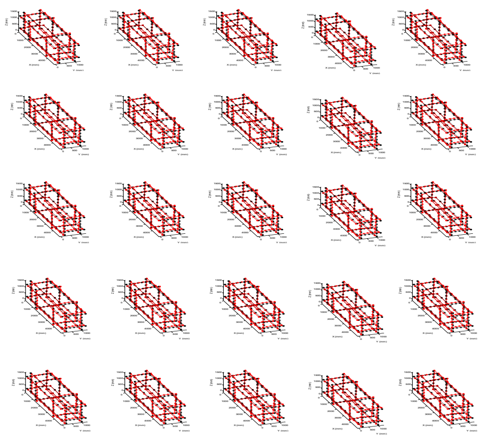
Monday



Tuesday

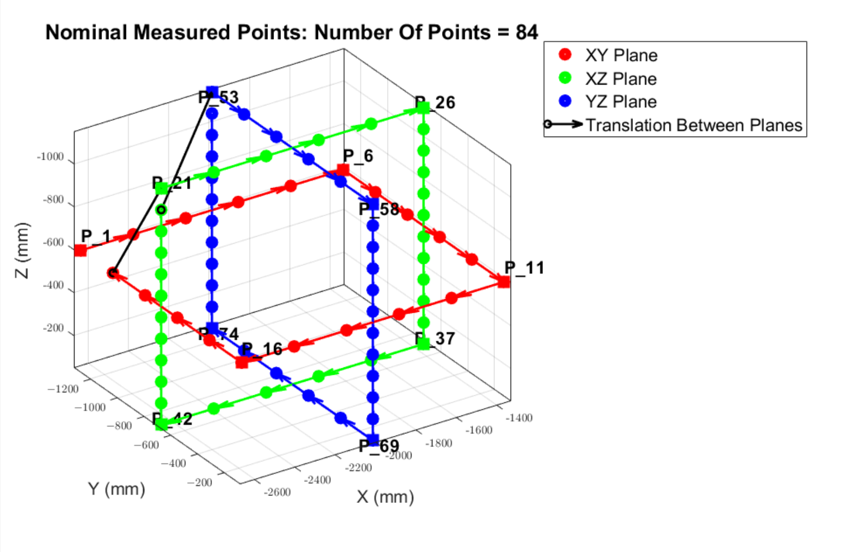


Wednesday



Thursday

Thermal characterisation of MTs



Measurement setup:

Machine tool: ZAYER ZERO model (non-controlled environment)

CNC: Heidenhain.

MIIM setup:

AT960 LEICA laser tracker integrated on the MT head.
4 wide-angle retro-reflectors: Two on the table and two on a height.

Measurement volume:

X: -2.650 ÷ -1.350 (1.300 mm) step 260 mm.

Y: -1.300 ÷ -100 (1.200 mm) step 240 mm.

Z: -1.150 ÷ -50 (1.100 mm) Step 100 mm.

Point cloud: 84 points

Measurement sequence:

1st: Plane XY : XX↑ YY ↑ XX ↓ YY↓

2nd: Plane XZ : XX↑ ZZ ↑ XX ↓ ZZ↓

3rd: Plano YZ : YY↑ ZZ ↑ YY ↓ ZZ↓

Total measurement time: Aprox. 10 days(300 repetitions)

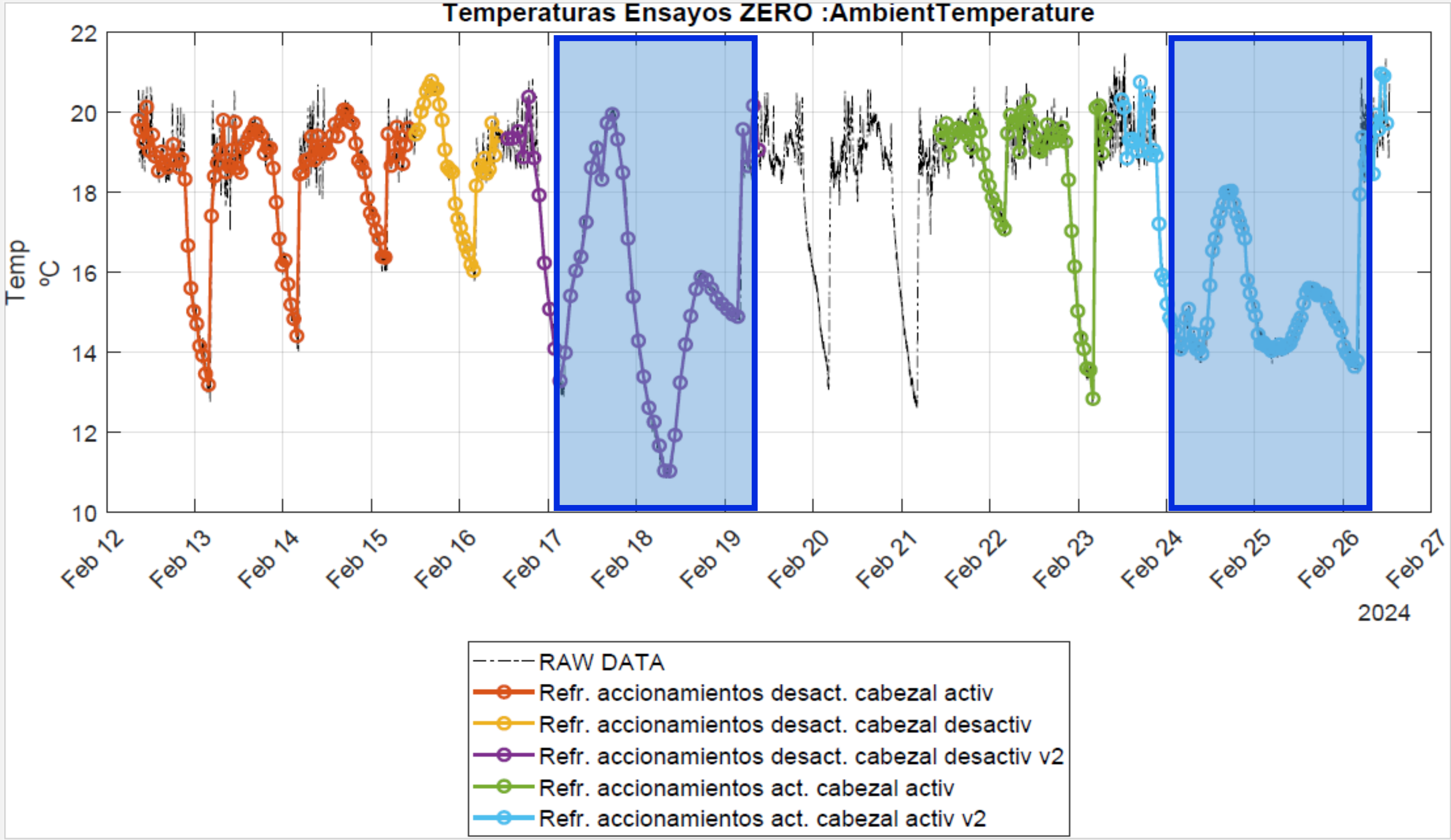
Time resolution: 45 min/volume.

Thermal characterisation of MTs

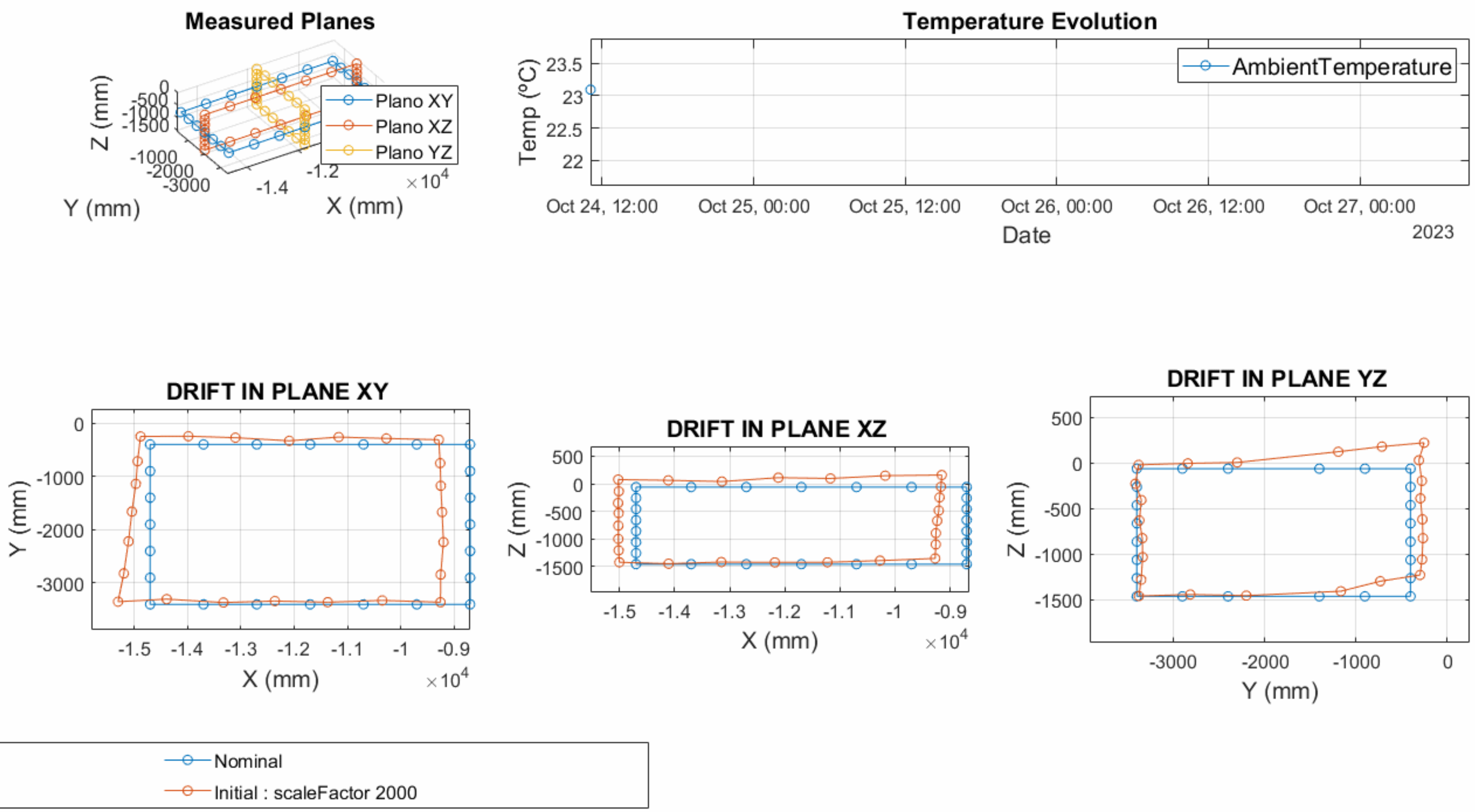
Measurement data:

Temperature: Ambient temperature variation 7ºC (non-controlled environment)

Weekend

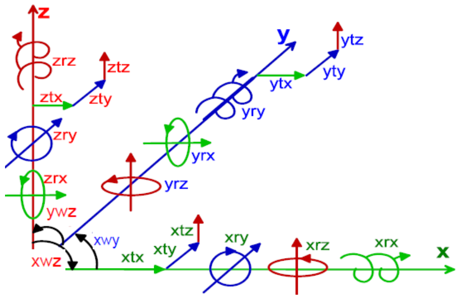


Thermal characterisation of MTs



Thermal characterisation of MTs – coordinate measurements

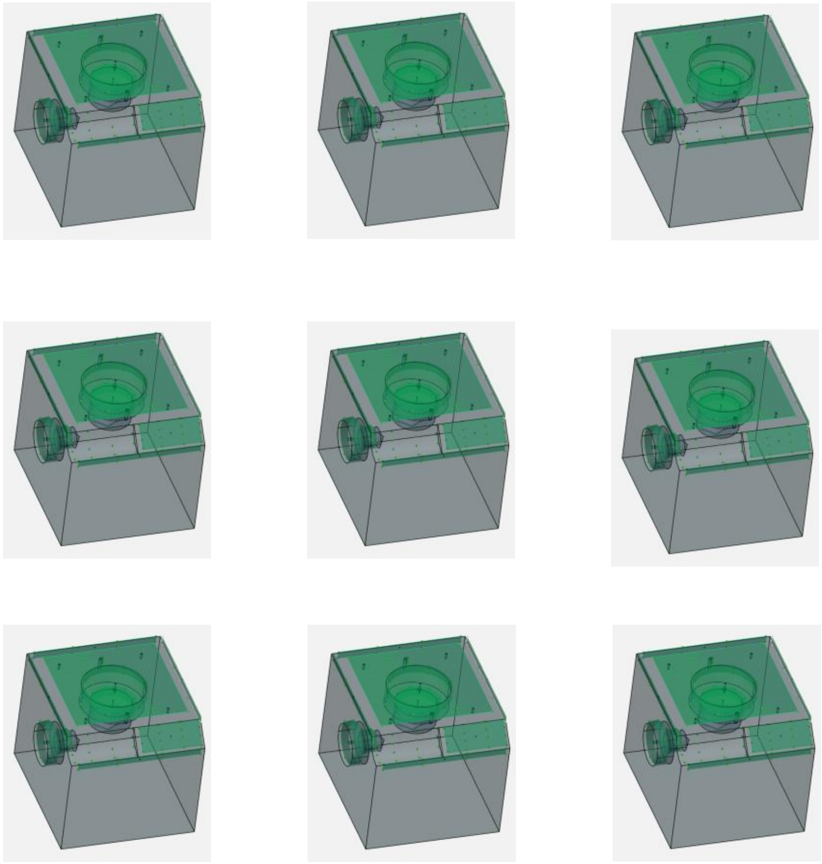
GD&T sensibility to the ambient temperature variation – Ongoing research…



ZEISS Quality Suite

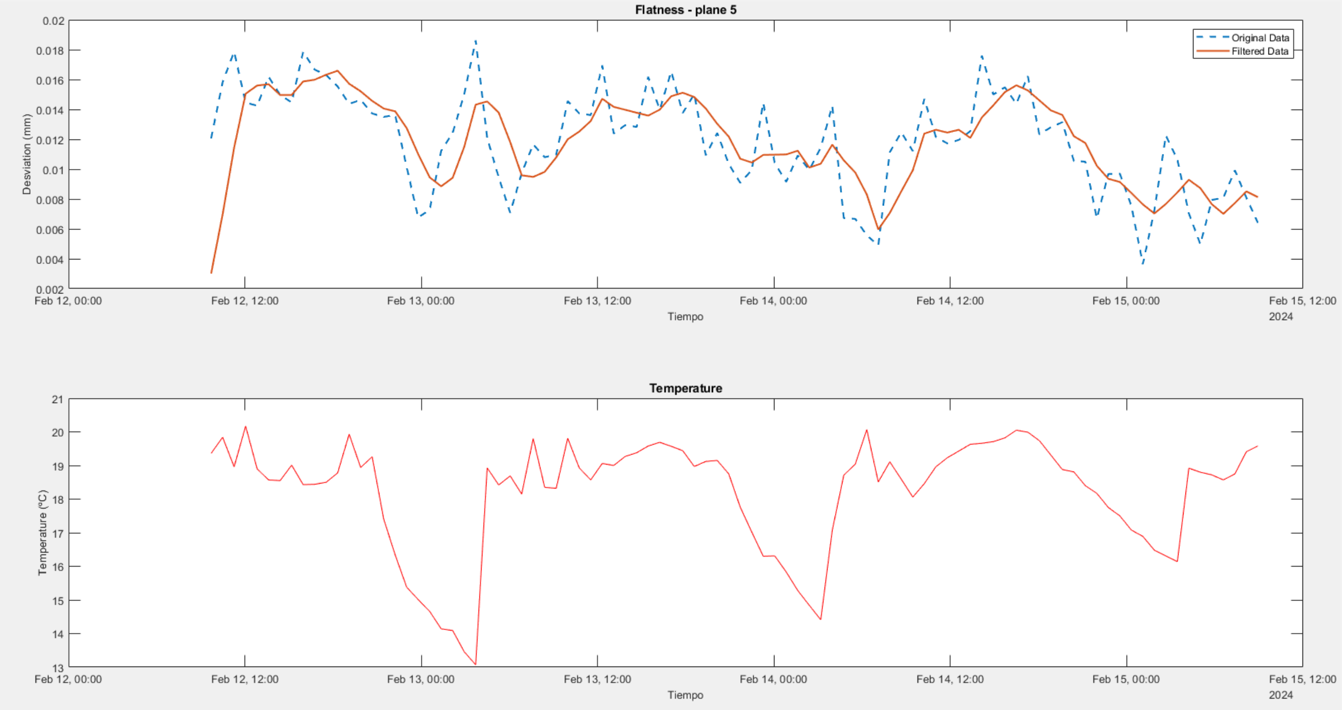
Automatic_processing_GDT.py

```python
# -*- coding: utf-8 -*-

import gom
import os


# Funcion para obtener los archivos txt en el directorio seleccionado
def get_rot_count(dir):
    num_file = 0

    # Get all files in folder dir
    array_files = os.fsencode(dir)

    # Definir una lista vacia
    array_files_txt = []

    # Create selected txt file list and number of files
    for file in os.listdir(array_files):
        filename = os.fsdecode(file)
        if filename.endswith(".txt") :
            num_file +=1
            array_files_txt.append(filename)
            continue
        else:
            continue

    # Verify data of the function
    print('Numero archivos .txt = ')
    print("\t",num_file,"\n")

    print('Lista de los archivos .txt seleccionados=')
    print("\t",array_files_txt,"\n")

    print('Numero de elementos en la lista de archivos.txt seleccionados = ')
    print("\t",len(array_files_txt),"\n")

    return array_files_txt, num_file
```

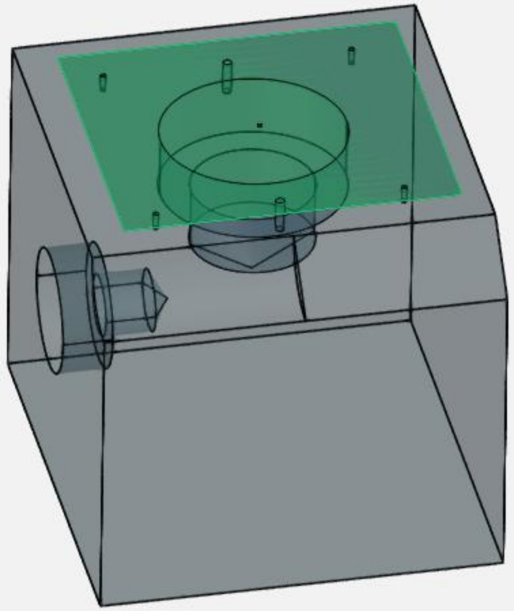


Thermal characterisation of MTs – coordinate measurements

Some preliminary results:

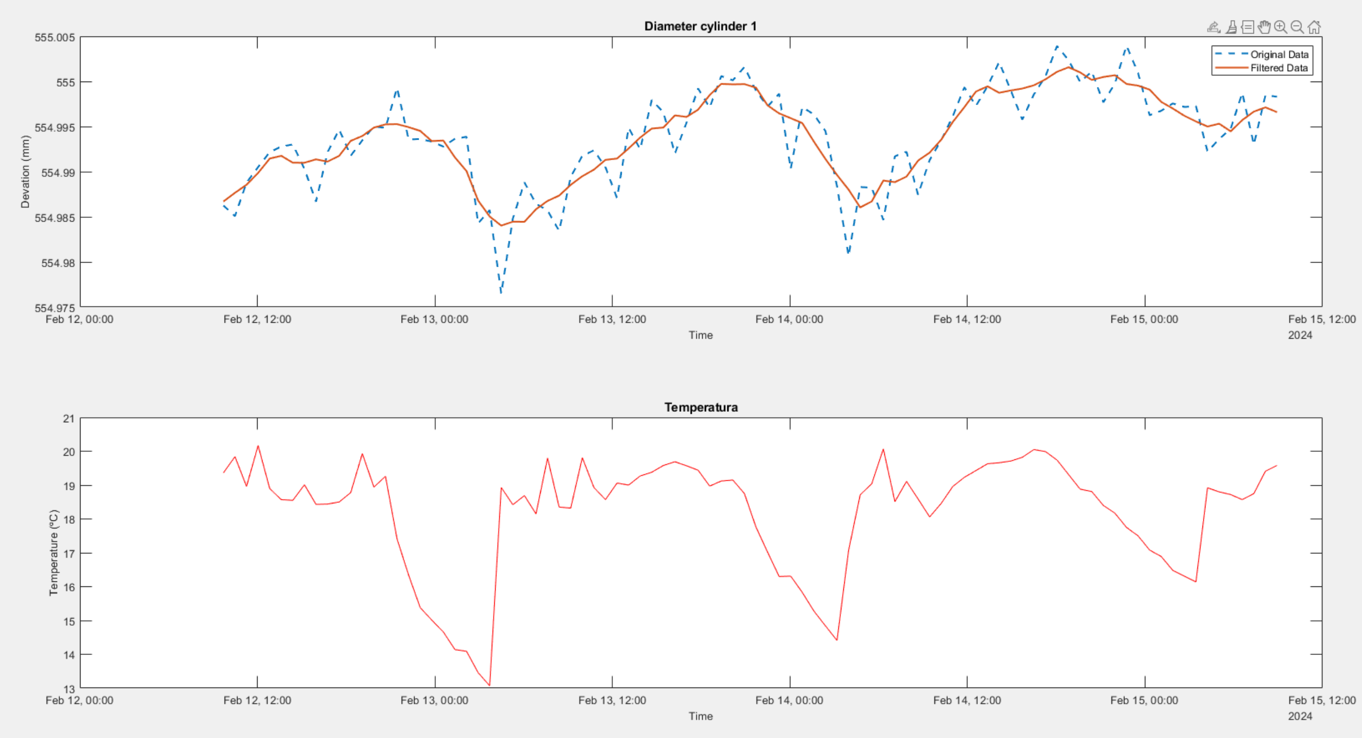


Flatness upper plane

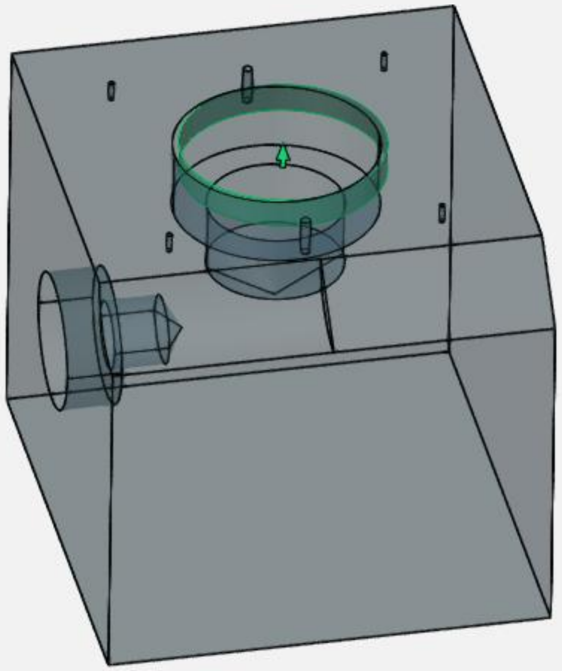


Thermal characterisation of MTs – coordinate measurements

Some preliminary results:



Diameter – upper plane



Outline

WHO WE ARE - TEKNIKER

INTRODUCTION

MACHINE TOOL CALIBRATION

ROBOT CALIBRATION

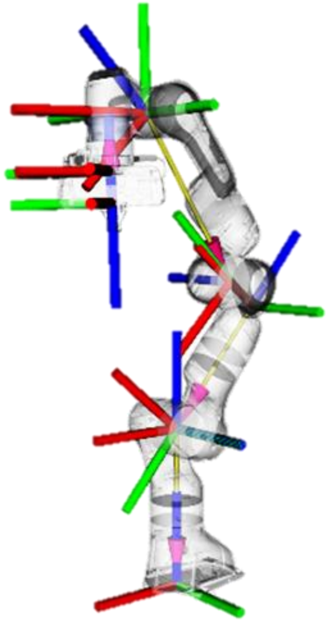
ROBOT CALIBRATION

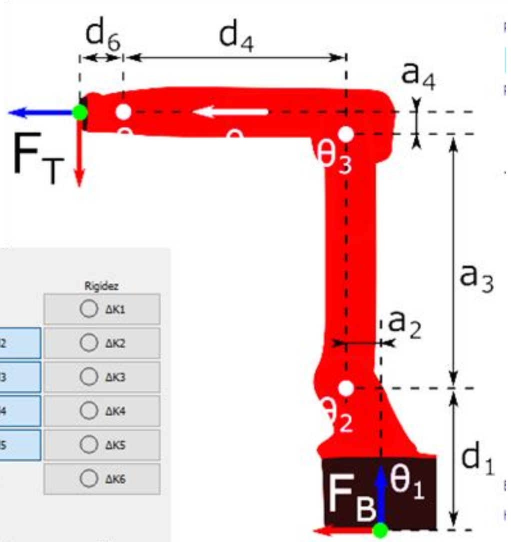
WHAT IS IT ABOUT?

Determination of the real DH kinematic parameters and elastic model

Defined by theoretical values

Not ensured during component manufacturing





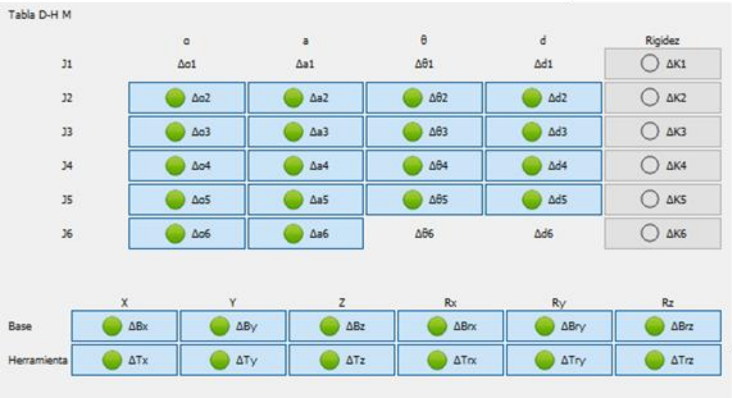


Tabla D-H M

	α	a	θ	d	Rigidez
J1	Δα1	Δa1	Δθ1	Δd1	ΔK1
J2	Δα2	Δa2	Δθ2	Δd2	ΔK2
J3	Δα3	Δa3	Δθ3	Δd3	ΔK3
J4	Δα4	Δa4	Δθ4	Δd4	ΔK4
J5	Δα5	Δa5	Δθ5	Δd5	ΔK5
J6	Δα6	Δa6	Δθ6	Δd6	ΔK6

	X	Y	Z	Rx	Ry	Rz
Base	ΔBx	ΔBy	ΔBz	ΔBrx	ΔBry	ΔBrz
Herramienta	ΔTx	ΔTy	ΔTz	ΔTrx	ΔTry	ΔTrz

ROBOT CALIBRATION

HOW IT WORKS?

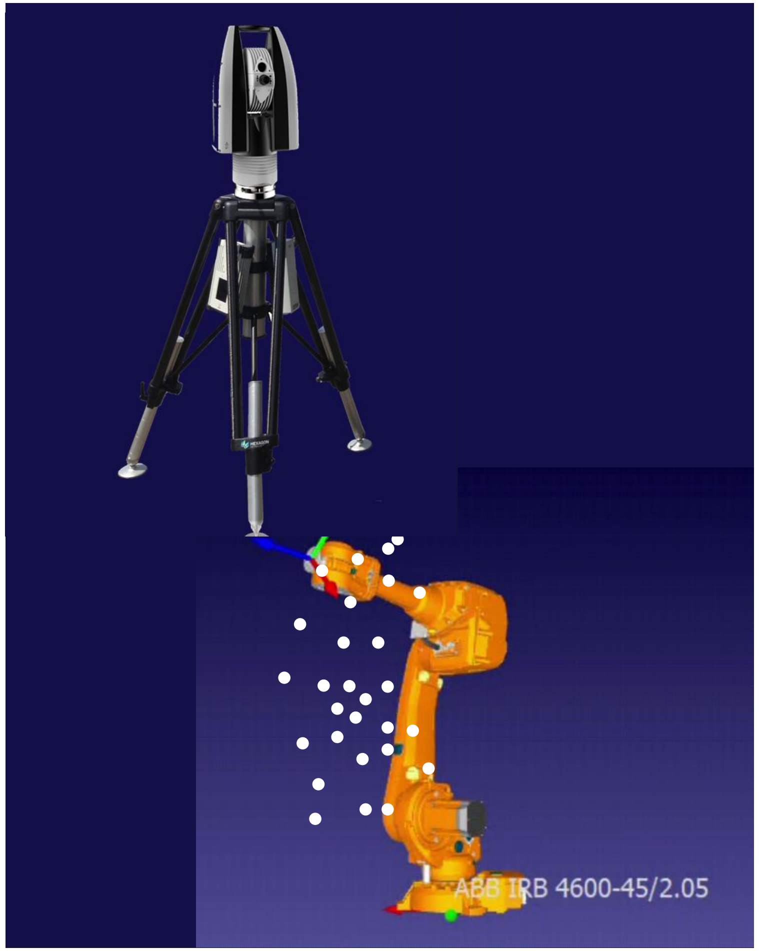
Using an internal or external metrology framework (ISO 9283)

↓

Measurement of the points in the region of interest

↓

Adjustment of the DH parameters minimizing robot error positioning



ROBOT CALIBRATION

WHY IS IT NEEDED?

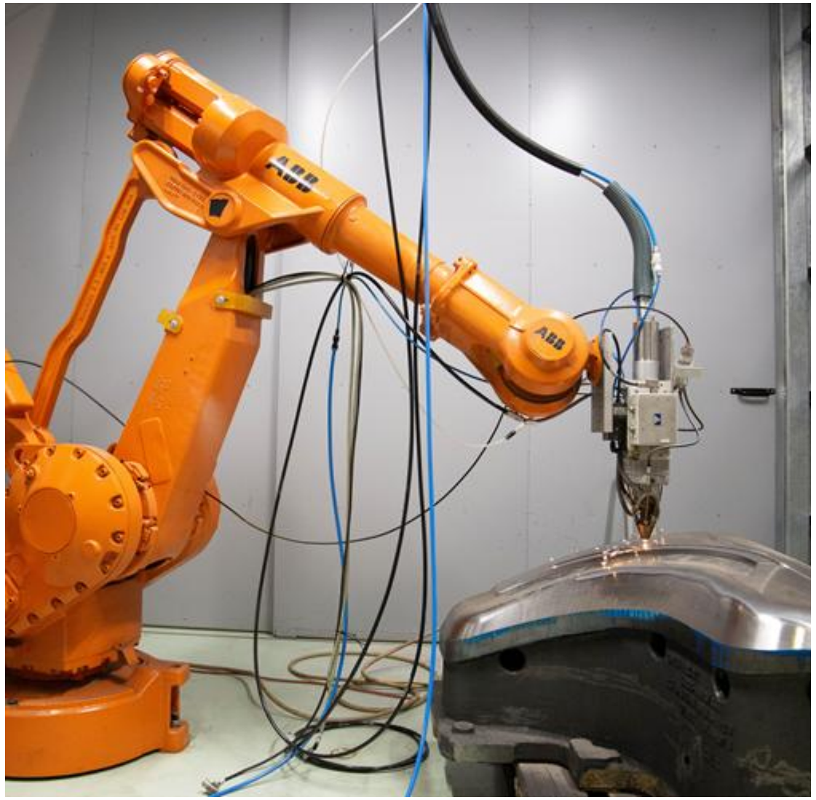
Demanding robot-based manufacturing applications

Improvement of the robot absolute accuracy

Robot repeatability 20-50 µm,

Absolute accuracy before calibration 1-2mm

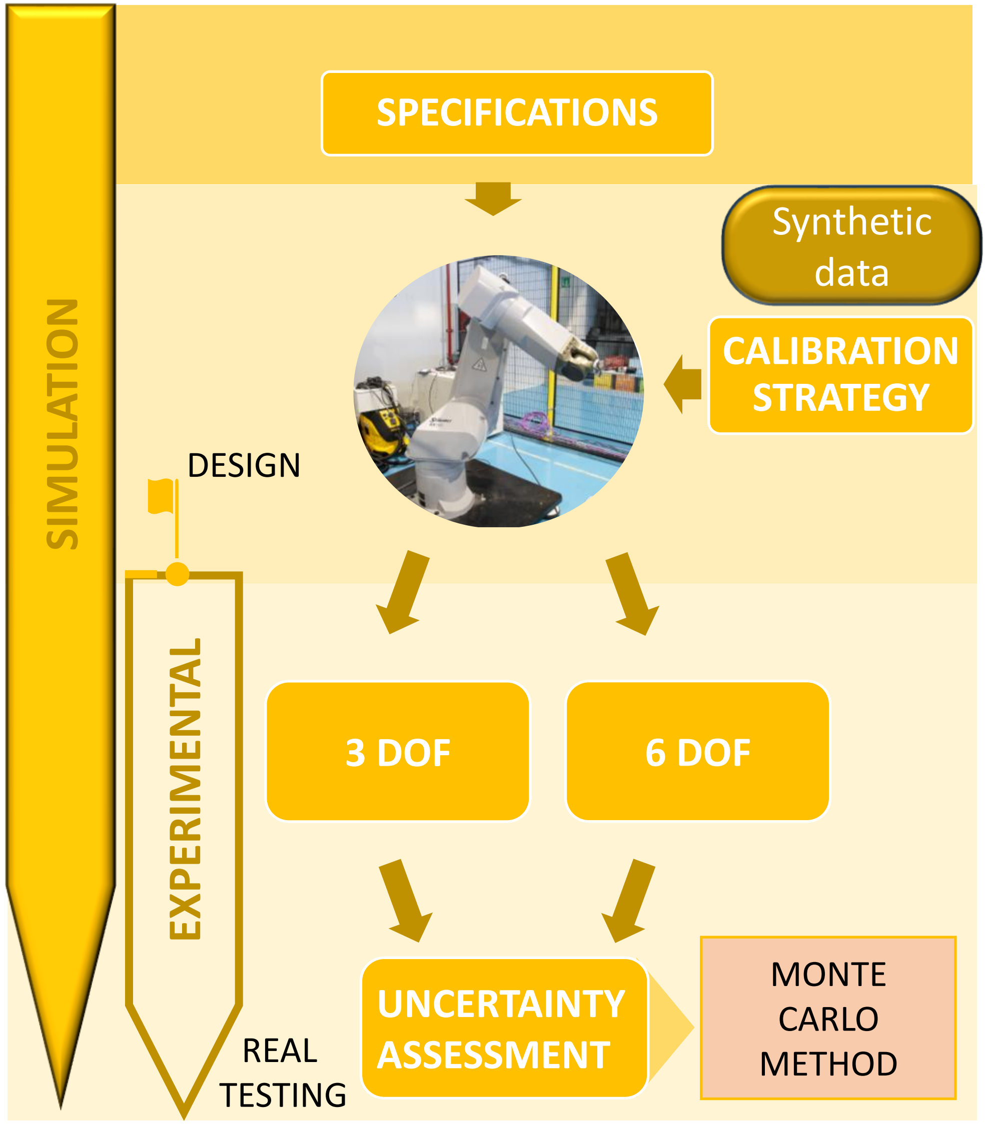
Absolute accuracy improvement after calibration up to 10x



WORKFLOW DIAGRAM

Simulation stages:

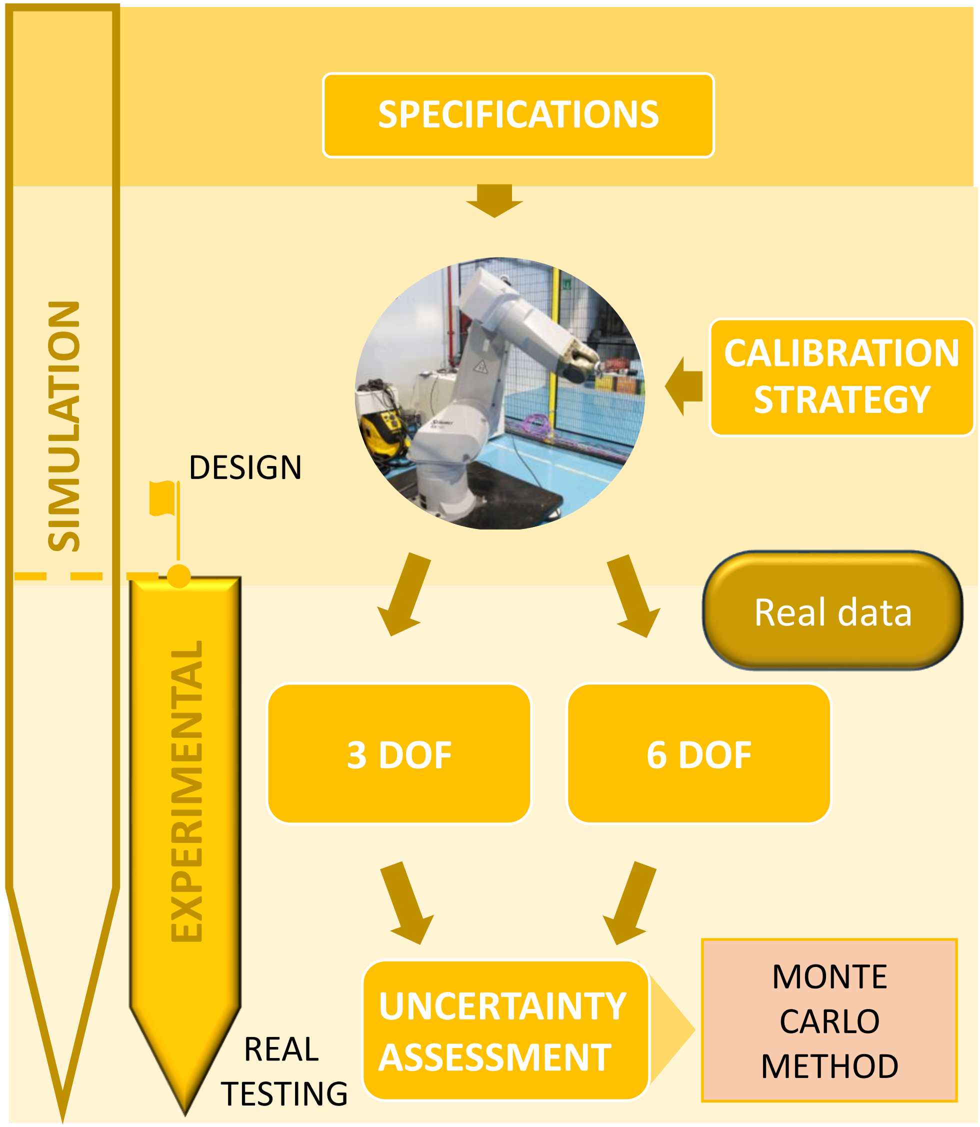
- Develop a dynamic digital twin to simulate real-world behaviors for metrological analysis and optimization.
- Use existing equipment data to generate synthetic data, including uncertainties, for realistic system evaluation.
- Assess overall system uncertainty with synthetic data to ensure compliance with specifications and standards prior to physical deployment.



WORKFLOW DIAGRAM

Experimental stages:

- Transition from virtual optimization to real-world implementation of the auto-calibration solution, using actual data to improve accuracy
- Continuously update the digital twin with operational data to simulate true system performance and uncertainties.
- Integrate real data into the digital twin for precise assessment and refinement, ensuring compliance with metrological standards.



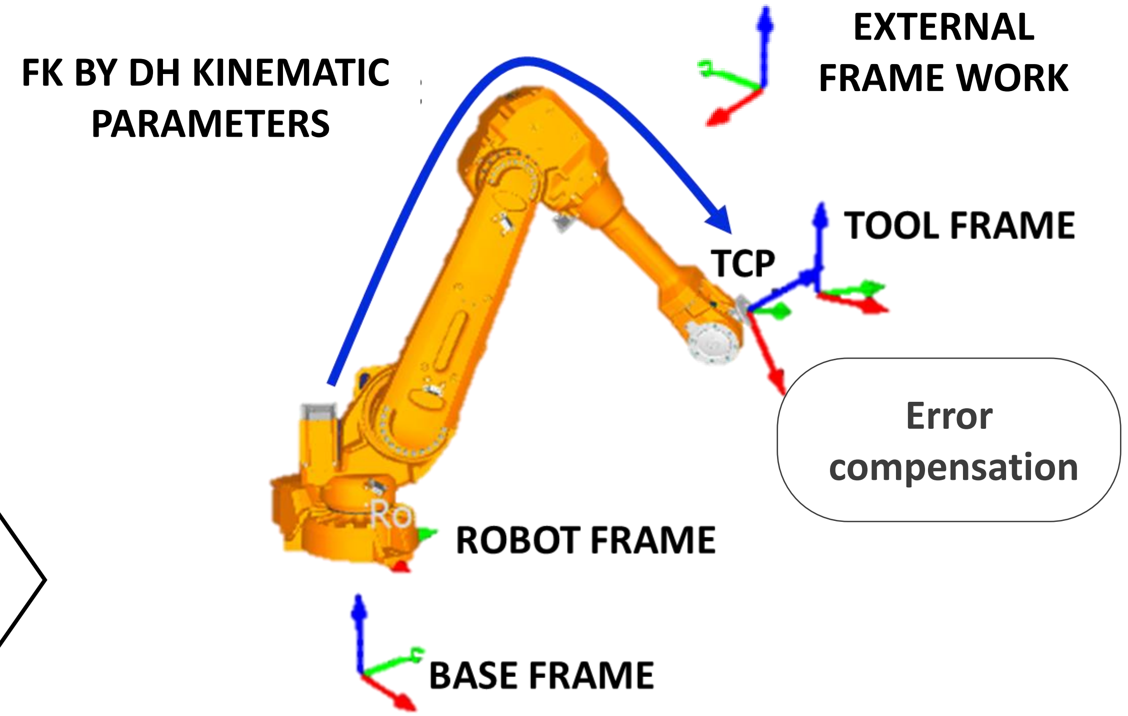
ROBOT COMPENSATION STRATEGIES

CURRENT APPROACHES

Pose error compensation

ON-Line Methods

OFF-Line Methods



ROBOT COMPENSATION STRATEGIES

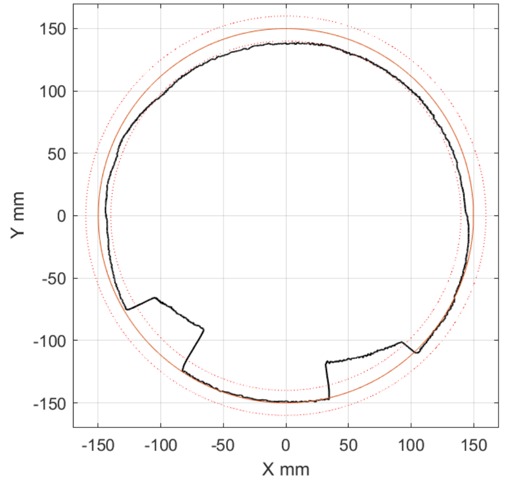
REAL CASE 1

TEKNIKER

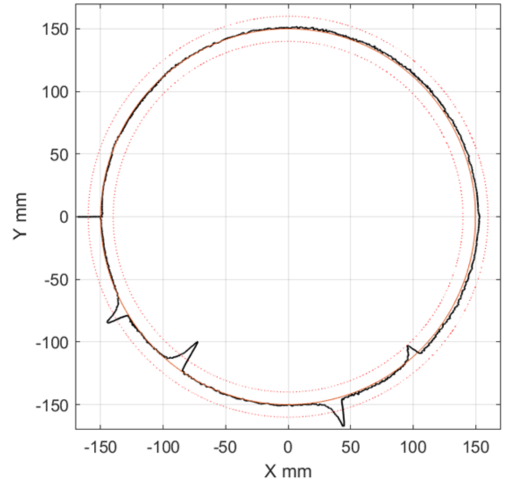
- **RTFP compensation**
- **Laser tracker**
- **1000 Hz**
- **Error in robot repeatability order**

ON-LINE METHODS

Without Compensation



With Compensation



Robot trajectory

Commanded trajectory

200 µm range error

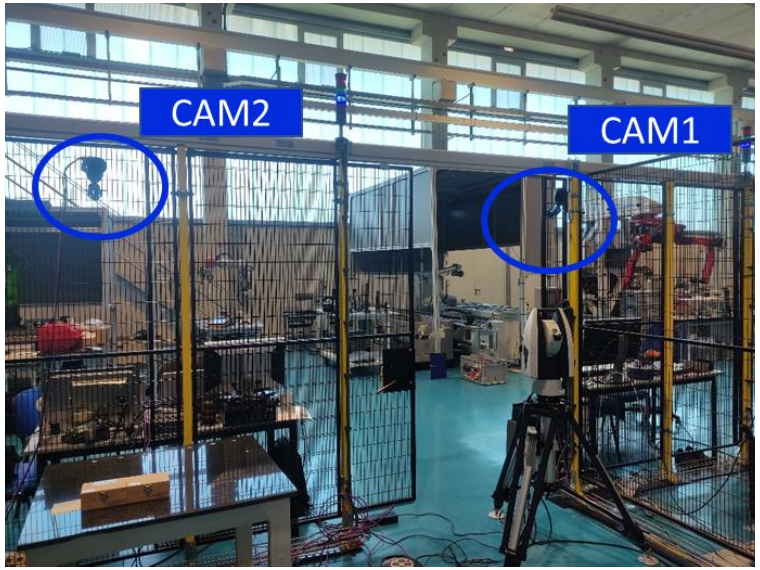
ROBOT COMPENSATION STRATEGIES

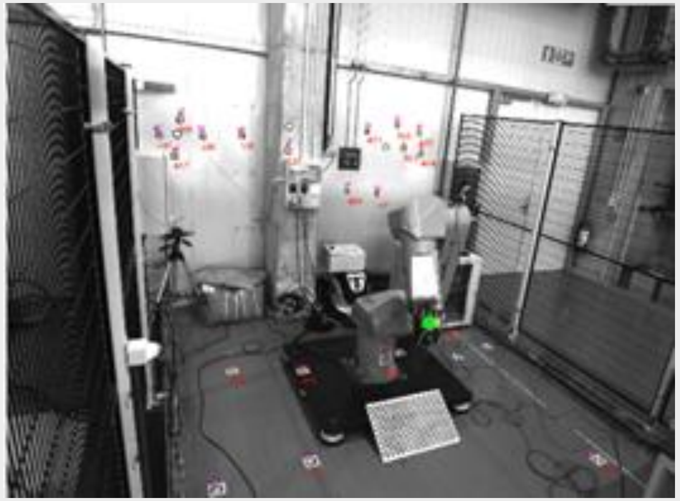
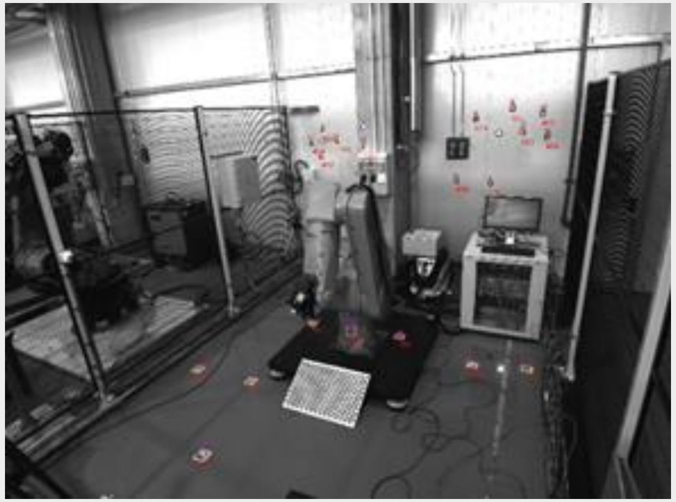
REAL CASE 2

TEKNIKER

- Stereovision system compensation
- 1 Hz
- Reduction of robot error by an order of magnitude

ON-LINE METHODS



Camera 1	Camera 2
	

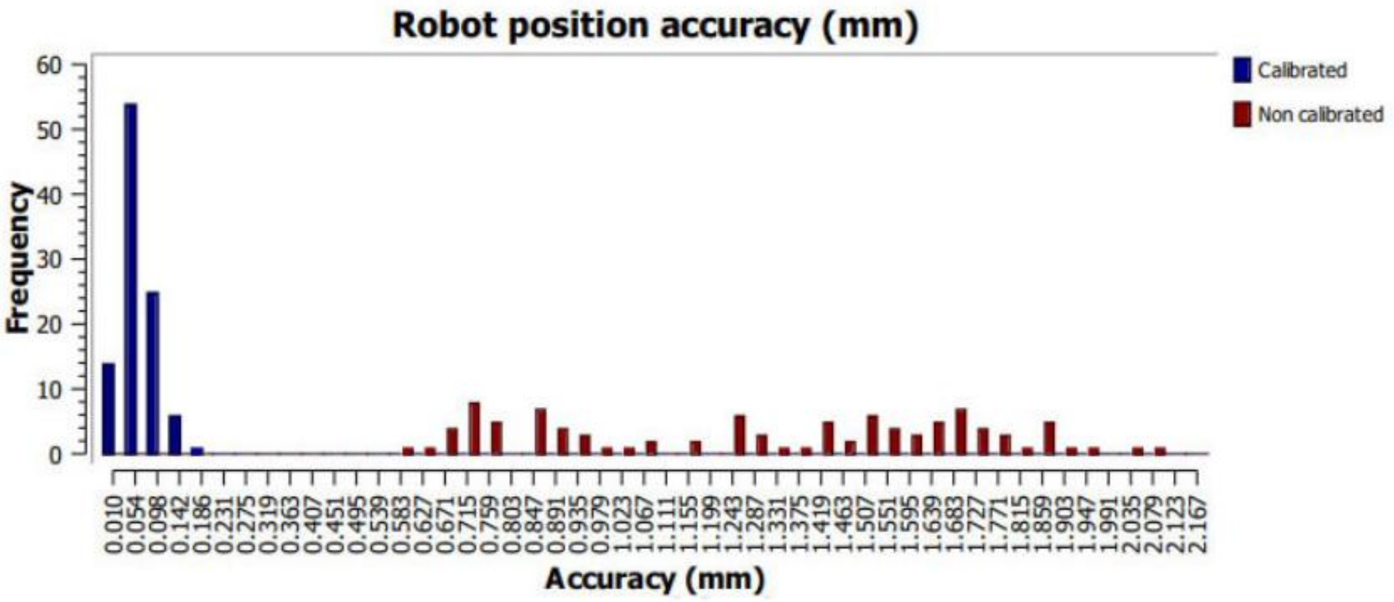
ROBOT COMPENSATION STRATEGIES

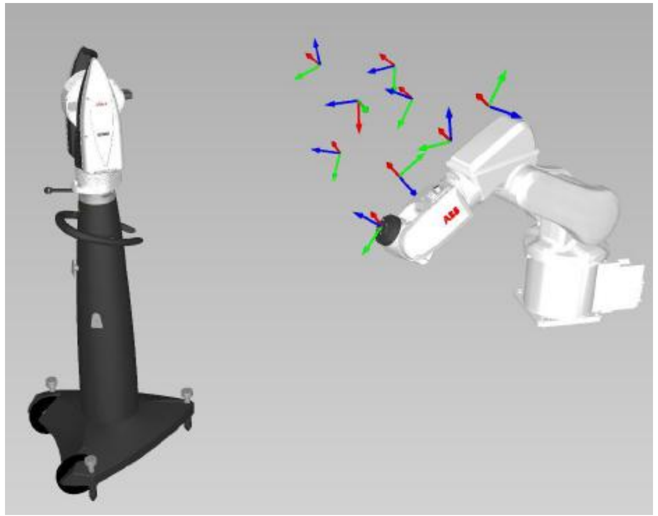
REAL CASE 1

TEKNIKER

- Laser Tracker calibration
- More than 500 robot compatibility
- Reduction of robot error by an order of magnitude

OFF-LINE METHODS





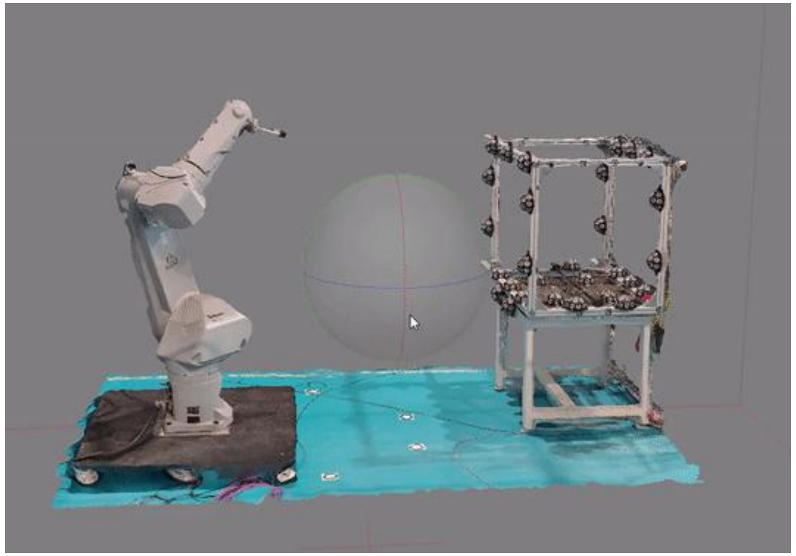
ROBOT COMPENSATION STRATEGIES

REAL CASE 2

TEKNIKER

- **On-board self-calibration by vision system**
- **Reduction of robot error by an order of magnitude**
- **Fast self-calibration <20min**

OFF-LINE METHODS



CAMERA ROBOT INTERFACE

3D ARTIFACT CONFIGURABLE SOLUTION

2D ARTIFACT CHESS BOARD

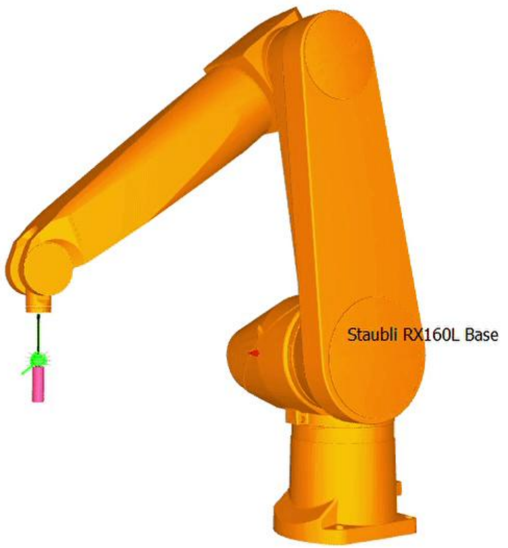
ROBOT COMPENSATION STRATEGIES

REAL CASE 3

TEKNIKER

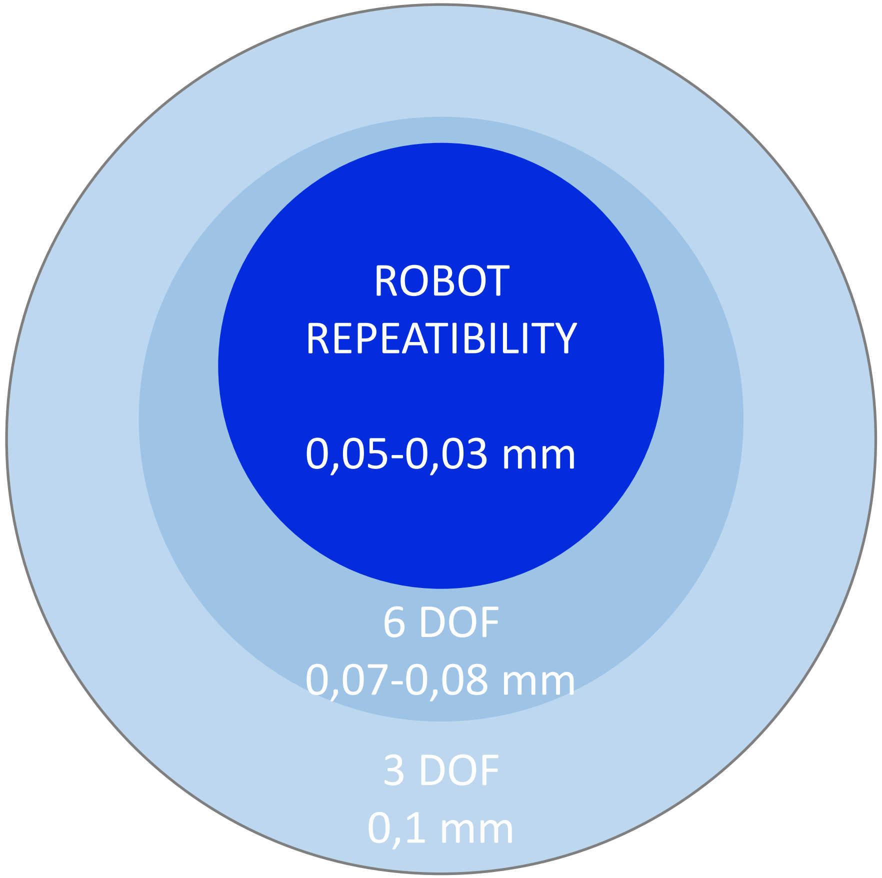
- Probing strategy
- Robot error verification
- Robot self-recalibration
- CNC controller open interaction

OFF-LINE METHODS



EXPECTED ACCURACY

Depending types of calibration



FINAL REMINDERS

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