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Robot linear path calibration using a multi-degree-of-freedom laser system

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Summary

Investigate the application of standard linear measurements, typically used on machine tools, for the calibration of robot motion.

In order to extract position and pose variation efficiently, a new Multi-degree of freedom (MDoF) measuring system, namely a Renishaw XM-60 laser system, has been used.

Main topics:

- Little bit of history on non-Cartesian and XM-60 measurement
- Compensation results on a small 6-axis robot
- Possibilities for continuous motion measurement

Non-Cartesian measurement

Calibration of a delta non-Cartesian machine configuration + 2 rotary axes

- Project required validation of new calibration method.
- Target uncertainty of +/- 6 µm based on tightest tolerance specifications for the machine
- Existing calibration using large volume metrology flexible but higher uncertainty.
- Standard MT test procedures to be applied (Renishaw XL80 interferometer, IBS R-Test, Artefacts).

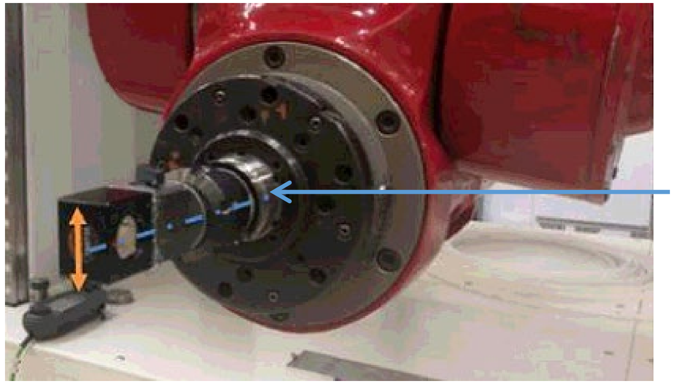
For Cartesian machine, uncertainty in tool length caused by position of optics relative to the spindle datum is very small since it is essentially a second order effect.

For Non-Cartesian machine the uncertainty is much greater as the transformations using the tool length are first order and depend on the magnitude of the angular motions.

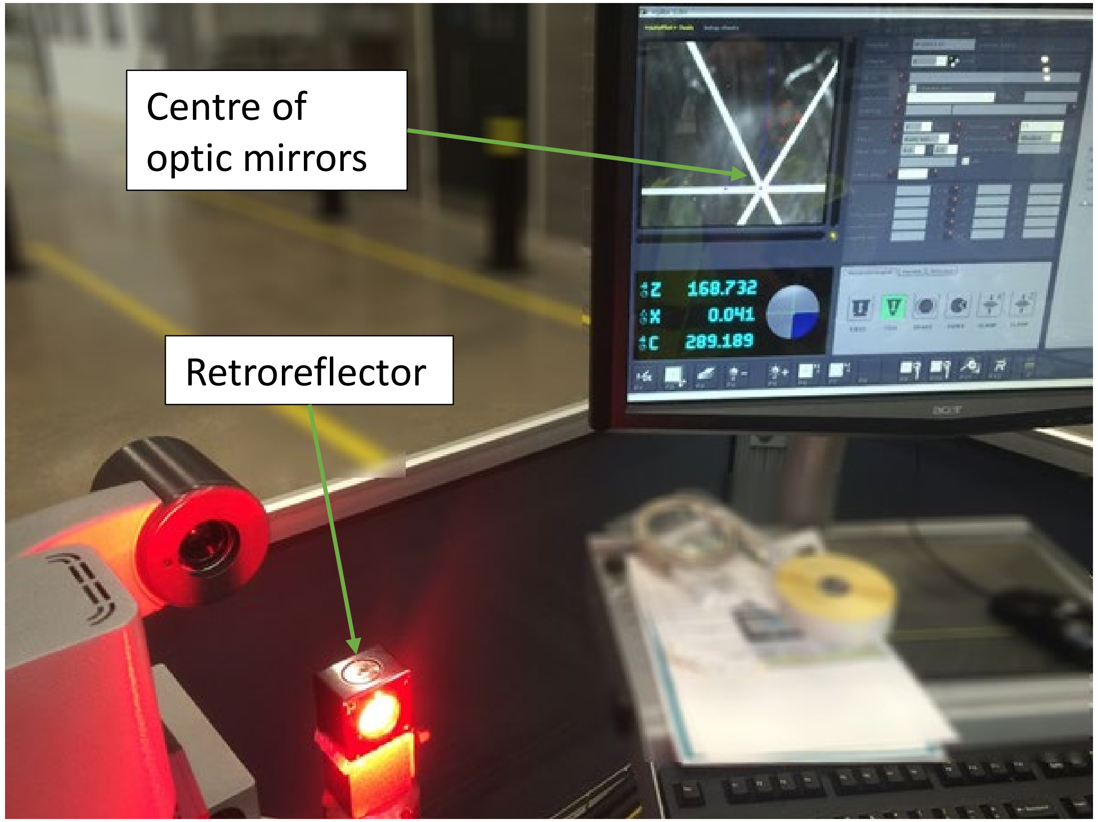
TCP considerations

In order to reduce uncertainty associated with coordinate transformation, the tool length and centre (Tool Centre Point) need to be measured/set.

- Tool setter used for tool length, using corner cube centre.
- Optic rotation used to find centre (control of spindle angle)
- Combined uncertainty from set-up and XL-80 < +/-6 µm



Spindle axis



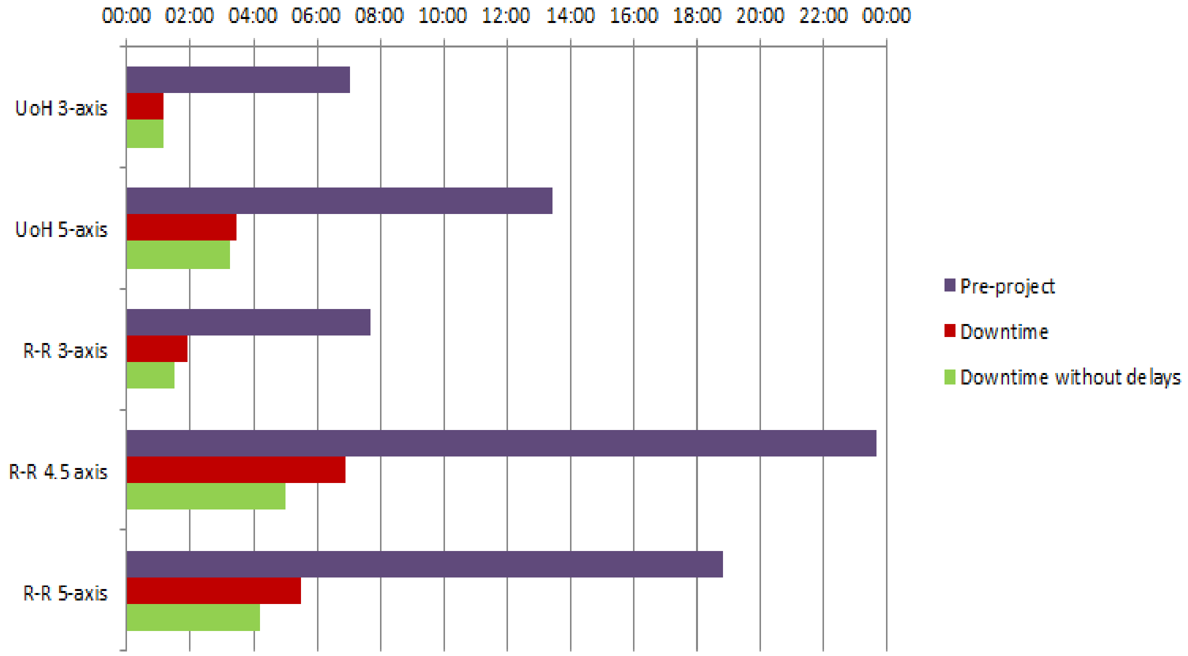
Centre of optic mirrors

Retroreflector

Rapid measurement with XM-60

Industrial project (SAMULET) with MAJOR AEROSPCE MANUFACTURER to reduce multi-axis machine tool calibration time

- Significant impact from XM-60 for the linear axes
- Effective training of maintenance engineers at many RR sites.
- Development of Standard Operating Procedures (SoPs) for 2, 3 and 5 axis machines
- Very efficient
  - < 45mins for 3-axis *6DoF (+10mins for squareness)
  - < 8r shift for full 5-axis machine.
- > 80 % reduction in downtime in some cases.



Robot measurement using XM-60

Scope

- Focus on Path or Trajectory Controller Motion rather than volumetric calibration
    - No calculation of D-H parameters or joint errors in this work.
- Low or repeatable load conditions
- Use of measurement systems designed for Cartesian axes i.e. this work explores the benefits from acquiring MDoF for linear paths in non-linear systems with low uncertainty and ease of setup.

XM60 setup on robot

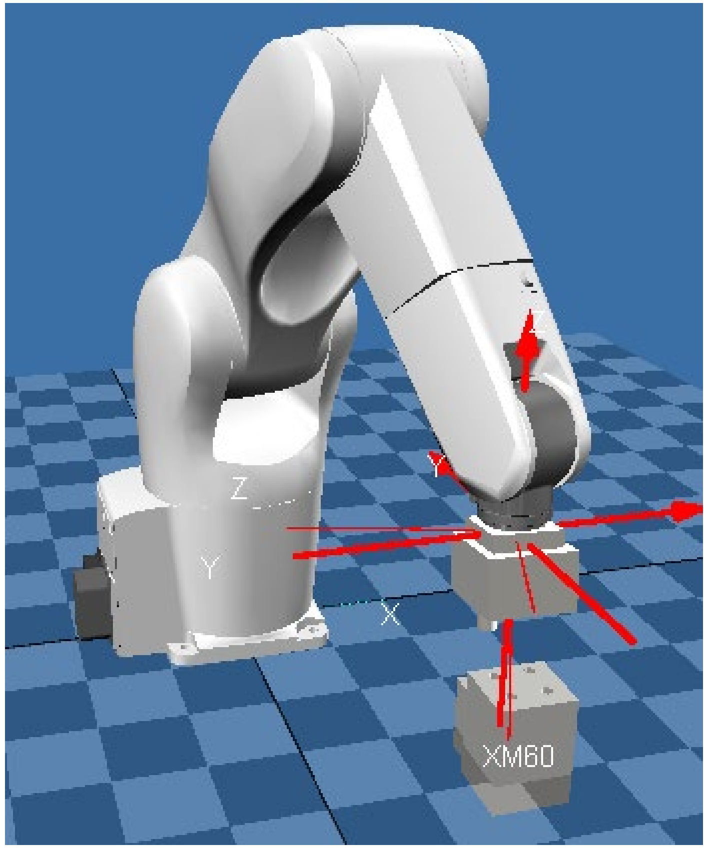
Standard Cartesian coordinate frame setup on a robot (Denso VS068, 7kg)

Denso robot operating mode:

- XY-bisection: moves according to the selected work coordinates. RX/RY/RZ rotate around the work coordinates centered on the tool origin point.
- Attitude (posture) control mode active

Correct tool-centre coordinate required

- Tool length and centre offset using approximate centre of the receiver unit.

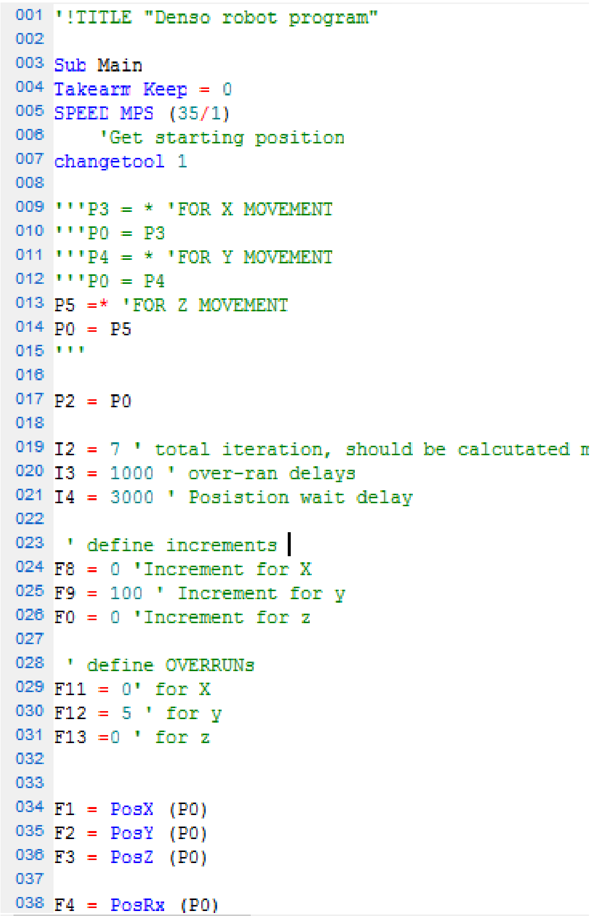


Robot programming

Simple parametric program for all measurements (WINCAPS III)

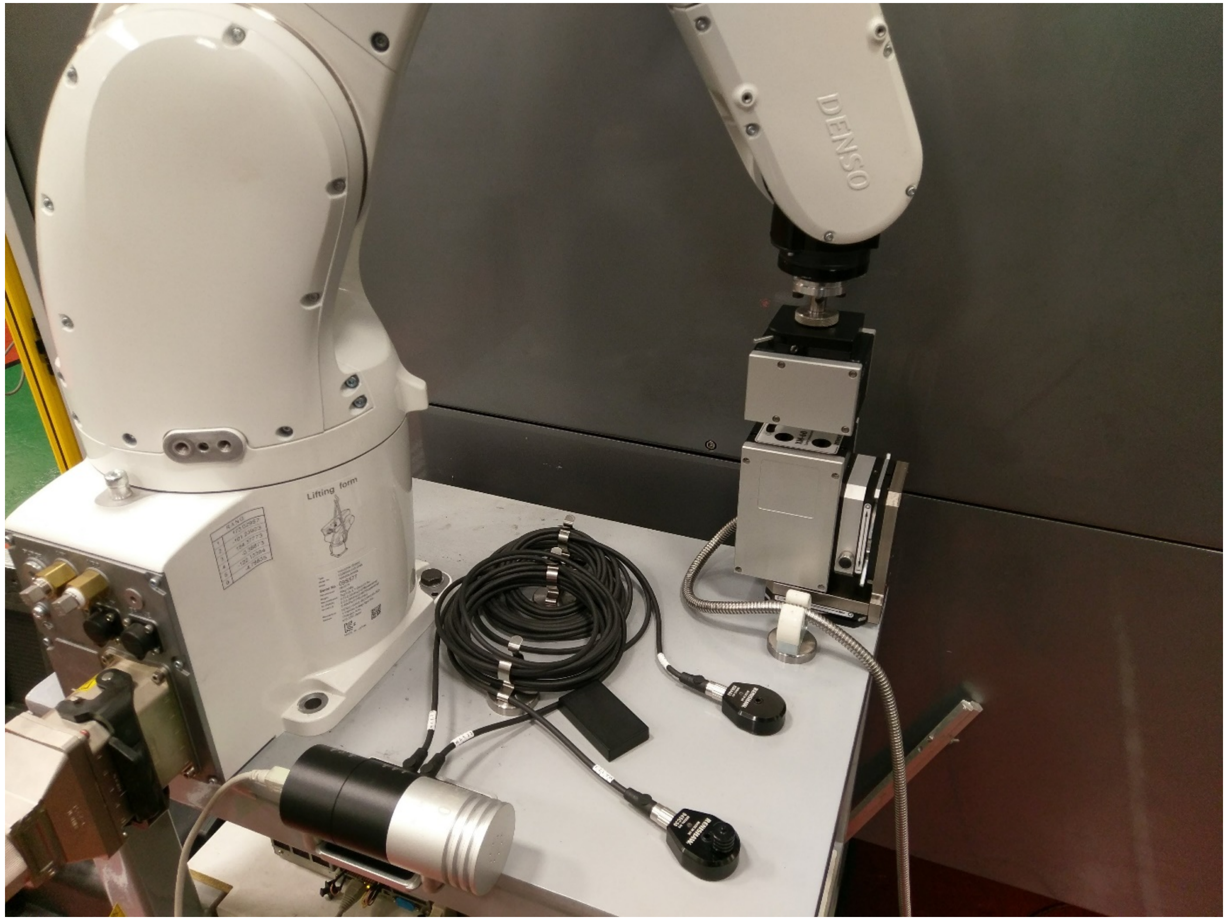
- Target sequence set in accordance with ISO 230 part 2. Typically 50mm step size (>= 11 targets per 500mm)
- Tool loaded with correct offsets for optic setup.

XM-60 setup for new path typically less than <u>10 minutes</u>.



```
'!TITLE "Denso robot program"

Sub Main
Takearm Keep = 0
SPEED MPS (35/1)
    'Get starting position
changetool 1

'''P3 = * 'FOR X MOVEMENT
'''P0 = P3
'''P4 = * 'FOR Y MOVEMENT
'''P0 = P4
P5 =* 'FOR Z MOVEMENT
P0 = P5
'''

P2 = P0

I2 = 7 ' total iteration, should be calcutated
I3 = 1000 ' over-ran delays
I4 = 3000 ' Posistion wait delay

 ' define increments
F8 = 0 'Increment for X
F9 = 100 ' Increment for y
F0 = 0 'Increment for z

 ' define OVERRUNs
F11 = 0' for X
F12 = 5 ' for y
F13 =0 ' for z


F1 = PosX (P0)
F2 = PosY (P0)
F3 = PosZ (P0)

F4 = PosRx (P0)
```

Two Z axis setup examples



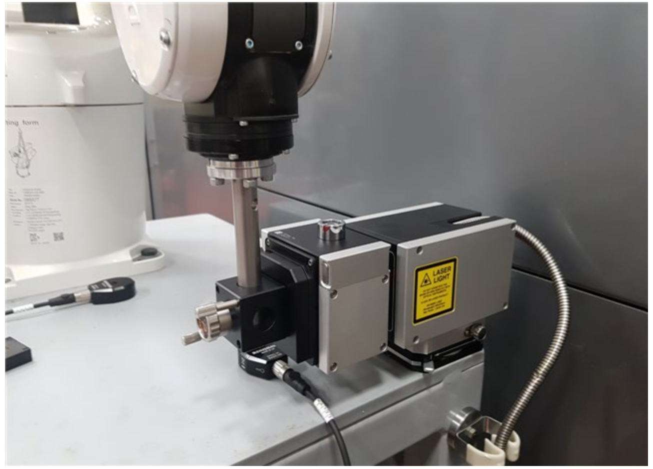
Example XM-60 result 1

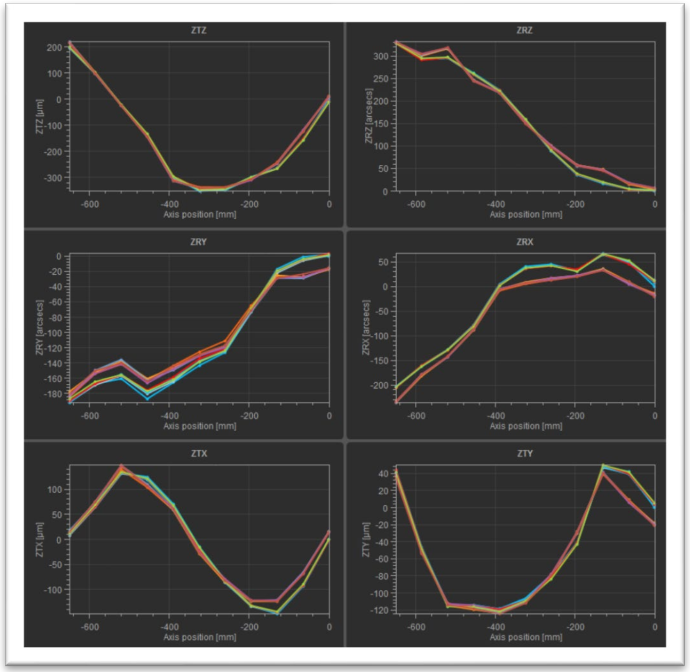
5 bi-directional runs at 3000mm/min equivalent feedrate.

500mm traverse in X direction

Error range from 160 to 500 µm and 200 to 300 arc-second for positioning and angular motion errors respectively.

Repeatability of <15µm and <12arc-seconds for positioning and angular motion errors respectively.



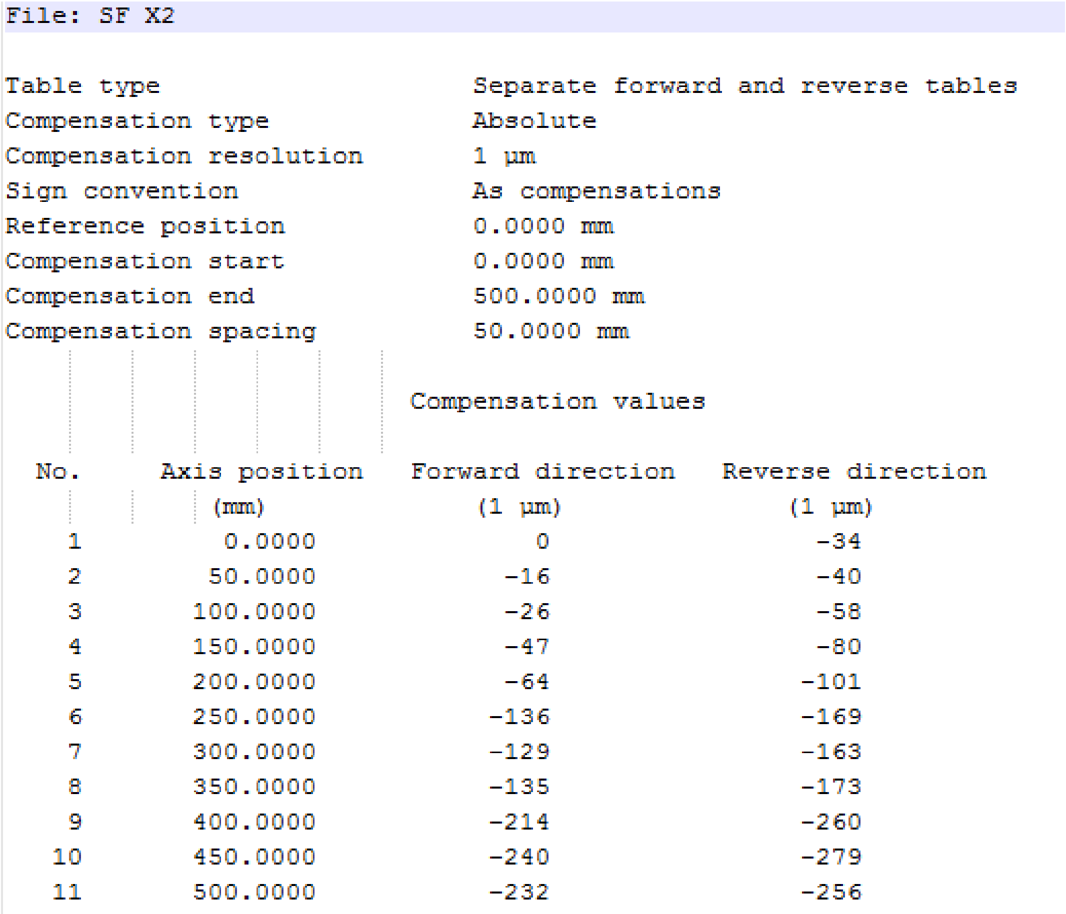


Error compensation

Compensation files exported from CARTO software for all axis error motions.

Data formatted into arrays for robot control software.

- Control based compensation using D-H parameters not part of this work.
- Part program modification established method of compensation.



```
File: SF X2

Table type                  Separate forward and reverse tables
Compensation type           Absolute
Compensation resolution     1 µm
Sign convention             As compensations
Reference position          0.0000 mm
Compensation start          0.0000 mm
Compensation end            500.0000 mm
Compensation spacing        50.0000 mm

                                   Compensation values

 No.       Axis position     Forward direction    Reverse direction
                (mm)              (1 µm)               (1 µm)
   1          0.0000               0                  -34
   2         50.0000             -16                  -40
   3        100.0000             -26                  -58
   4        150.0000             -47                  -80
   5        200.0000             -64                 -101
   6        250.0000            -136                 -169
   7        300.0000            -129                 -163
   8        350.0000            -135                 -173
   9        400.0000            -214                 -260
  10        450.0000            -240                 -279
  11        500.0000            -232                 -256
```

Error compensation

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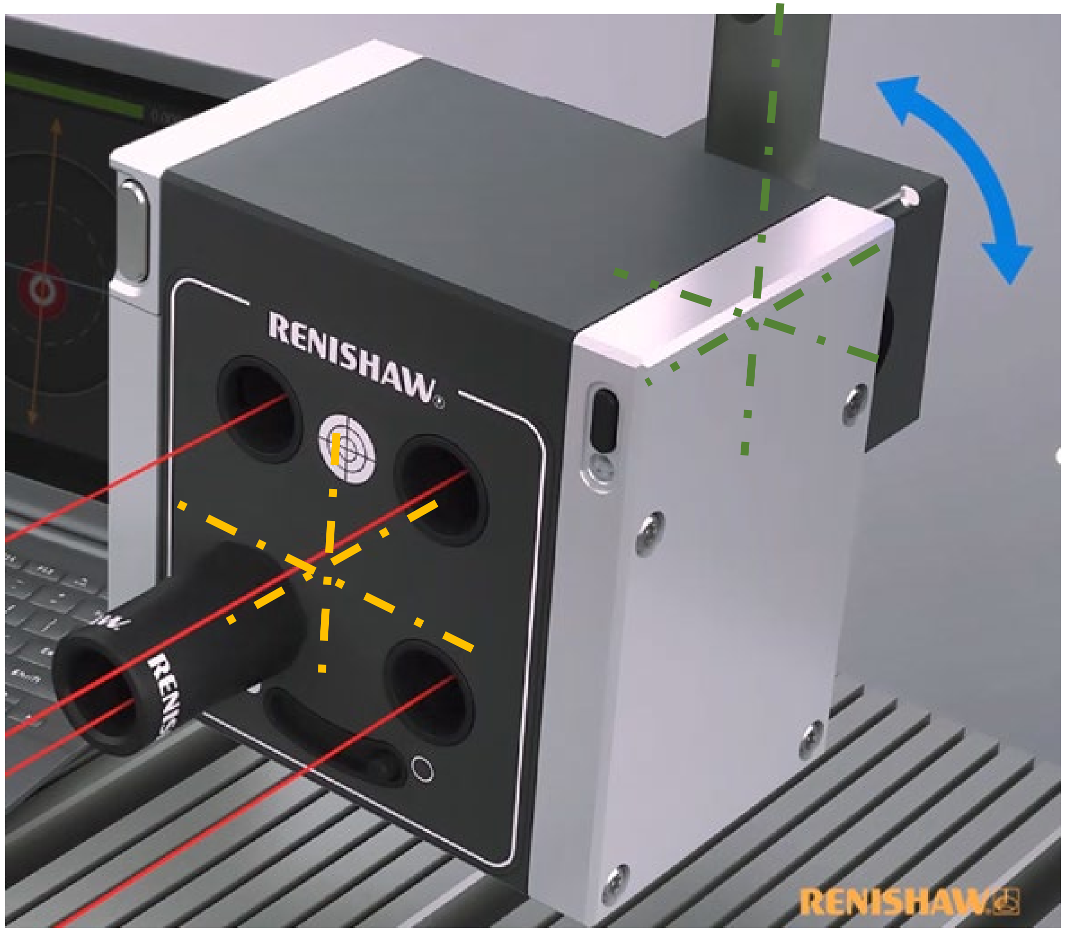
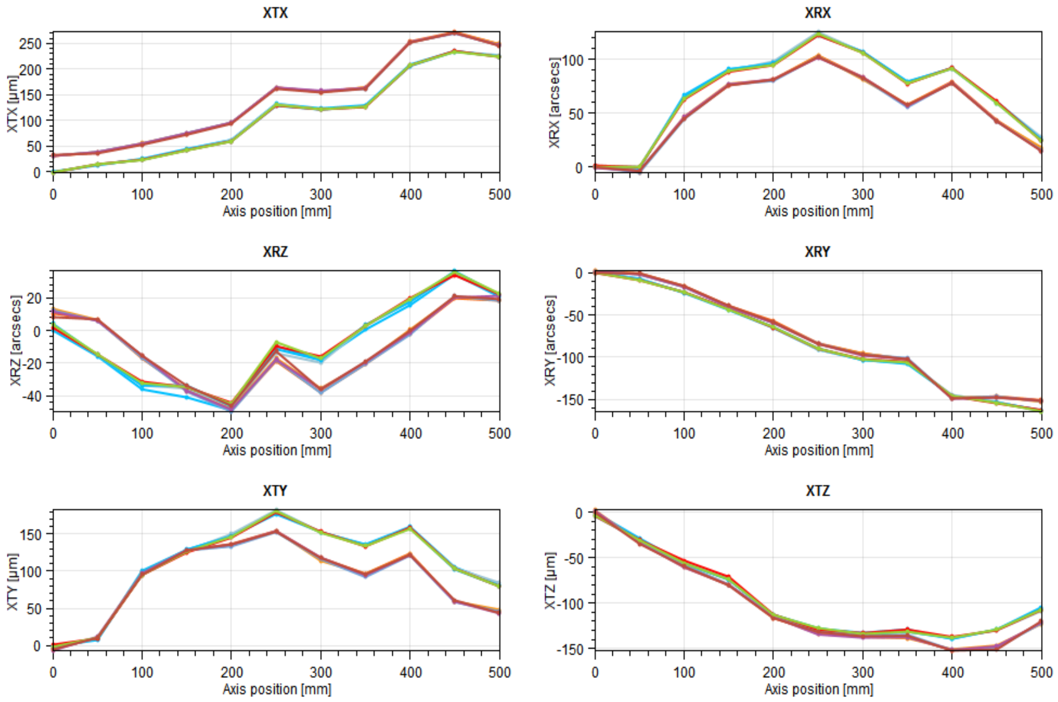
Although roll and straightness axes are co-axial, the exact location relative to the mounting bracket was not known.

- Compensation for angular error motions causes additional displacement errors
    - Typically <20µm. Would be reduced/eliminated with more accurate optic centre
- Angular compensation followed by the measurement and compensation of positioning and straightness error motions.

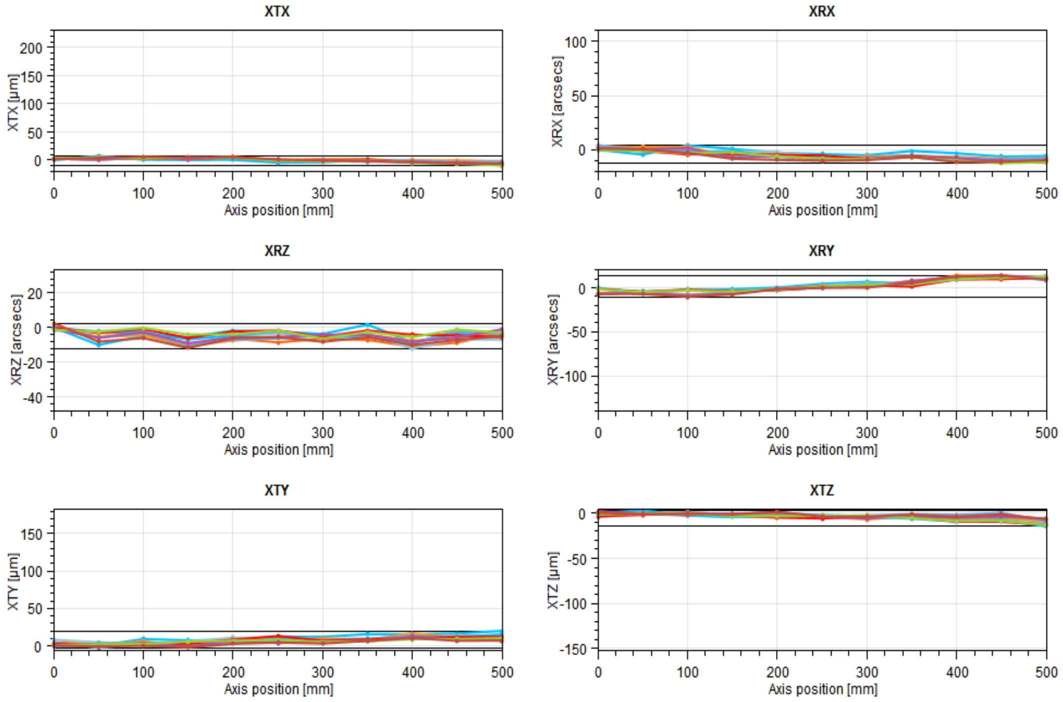


Compensation result 1 (X axis)

Before



After



Result 1 summary

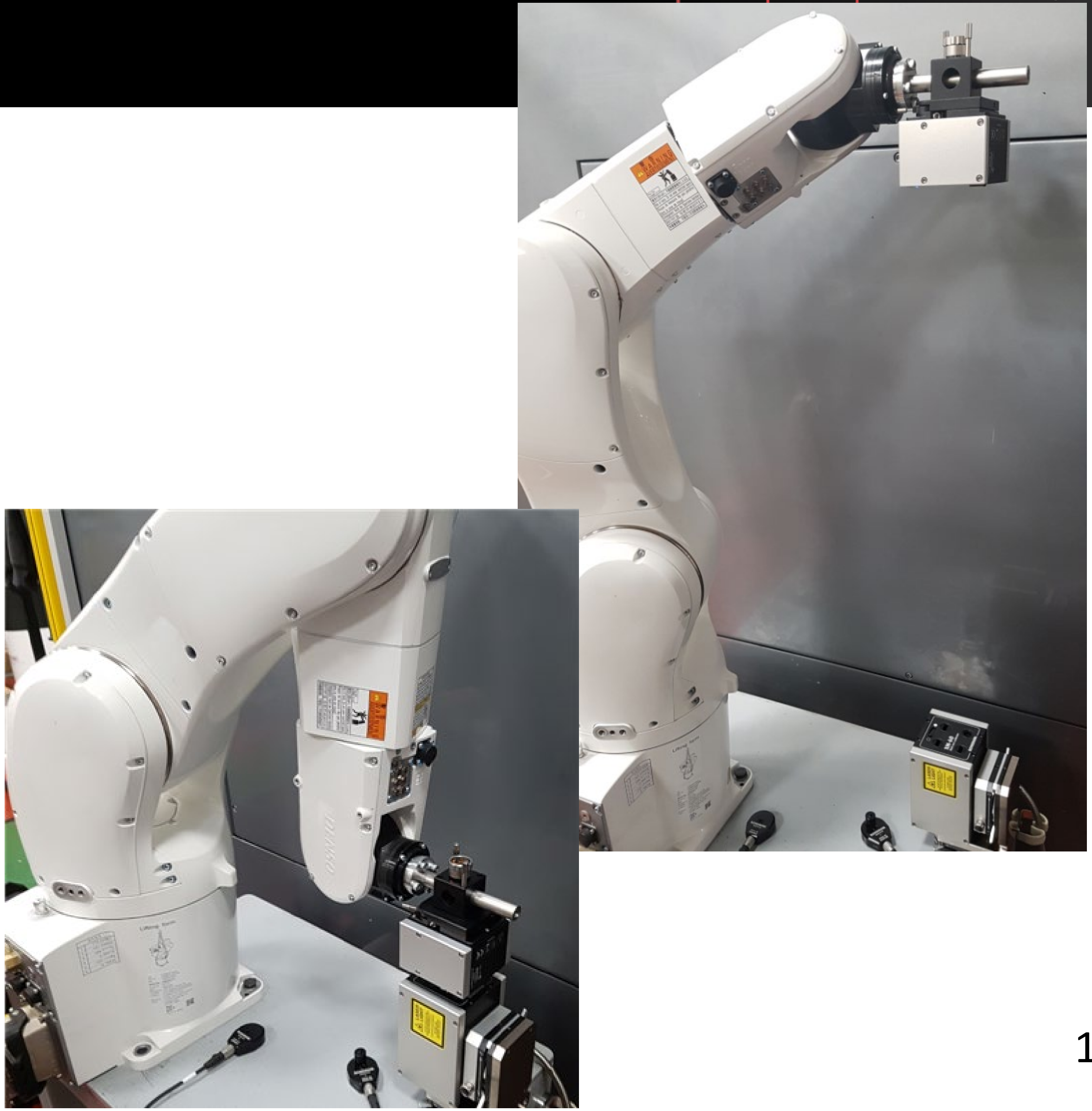
Error	Type	Before (µm/arc-sec)	After (µm/arc-sec)
XTX	Positioning	270	20
XTY	Straightness (horiz)	190	25
XTZ	Straightness (vert)	150	20
XRX	Angular (roll)	130	15
XRY	Angular (pitch)	160	20
XRZ	Angular (yaw)	85	15

Compensation result 2

Longer 650mm traverse range in Z axis direction

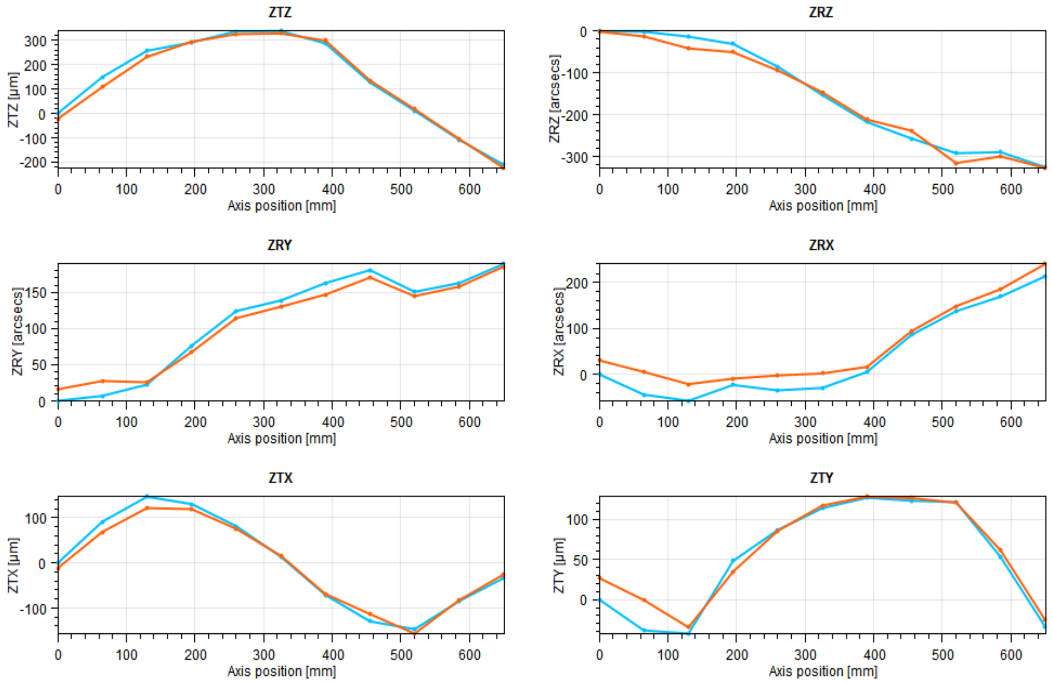
Significant rotation of most joints

- >160° rotation of 4th and 6th joints, > 100° of 3rd and 4th

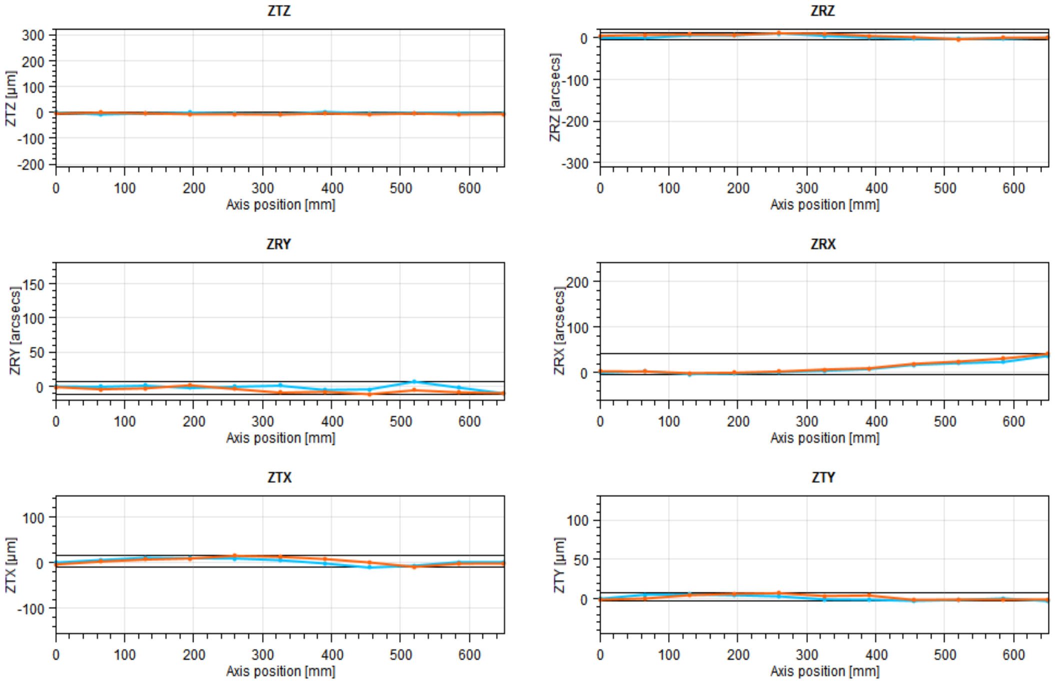


Compensation result 2 (Z axis)

Before



After



Result 2 summary

Error	Type	Before (µm/arc-sec)	After (µm/arc-sec)
XTX	Positioning	550	15
XTY	Straightness (horiz)	300	25
XTZ	Straightness (vert)	165	10
XRX	Angular (roll)	330	15
XRY	Angular (pitch)	300	40
XRZ	Angular (yaw)	190	20

Considerations and further work

Average reduction in error of 90% for linear path position and orientation.

Rapid setup of new linear paths.

Further work

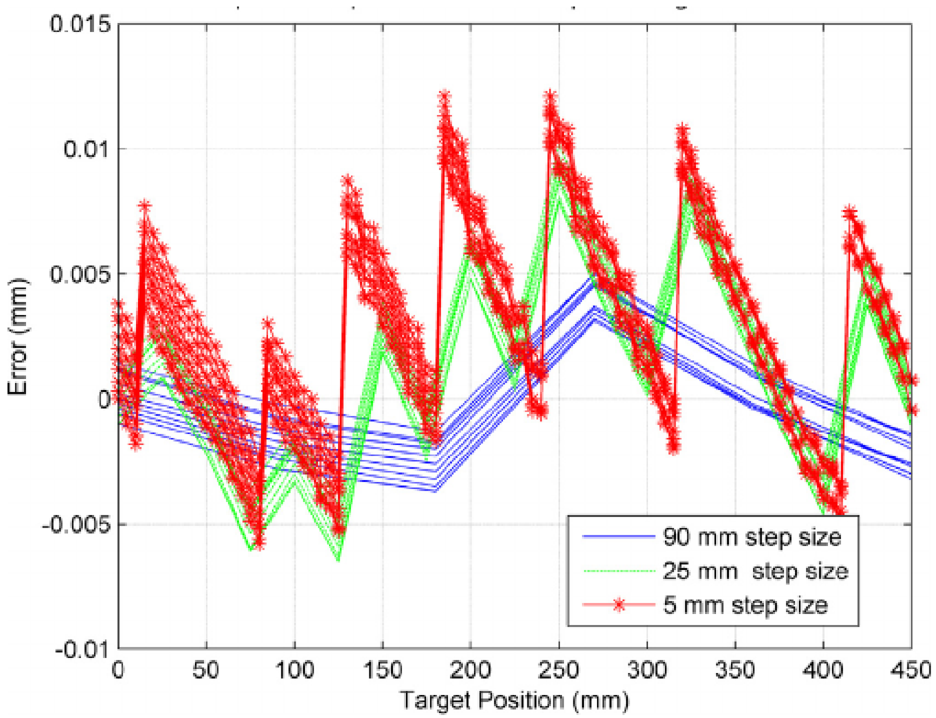
- Determine error propagation as tool offsets and orientations vary from that set during the measurement.
  - Could be variation in tool length or end effector offsets and angles.
  - Cartesian trajectory the same or similar but joint angles vary.
- Potential for diagnostics using continuous motion measurements.

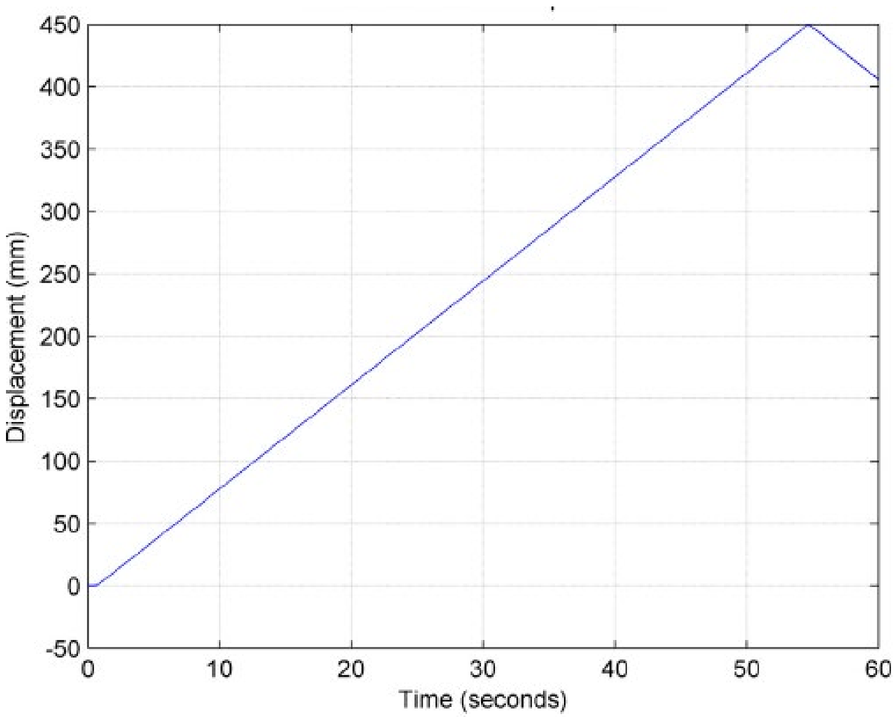
Pseudo static measurement

ISO 230 series of standard are often a compromise between spatial resolution and test time

Easy for aliasing to occur and miss higher frequency components such as feed-drive issues or compensation effects

Continuous motion test rapid but has ambiguity in slope (phase) unless direct feedback is used





J.E. Miller, A.P. Longstaff, S. Parkinson, S. Fletcher, ‘Improved machine tool linear axis calibration through continuous motion data capture’, Precision Engineering, v47, 2017, pp 249-260, https://doi.org/10.1016/j.precisioneng.2016.08.010.

Continuous motion result

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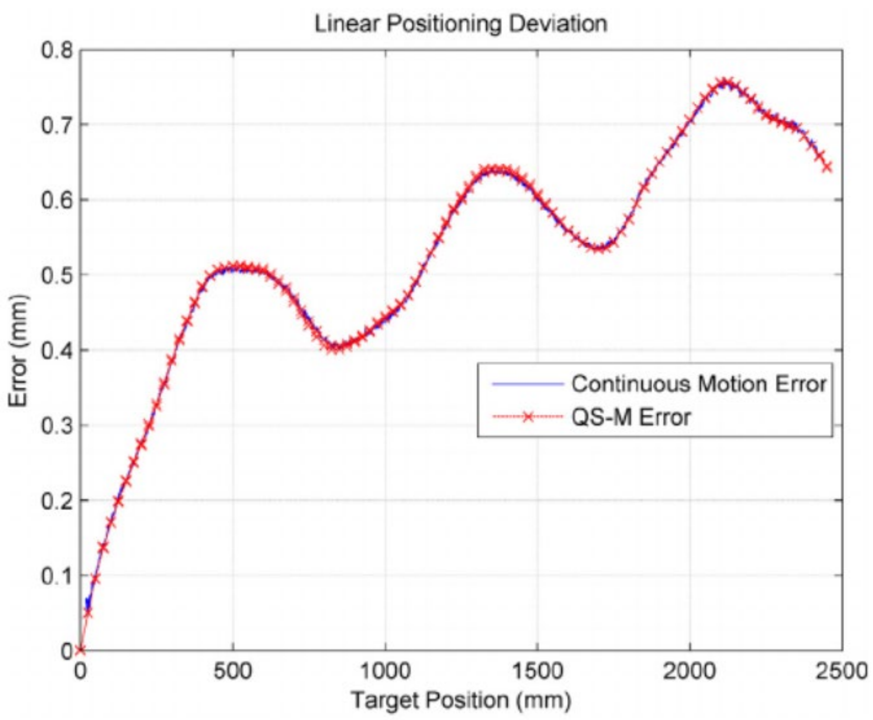
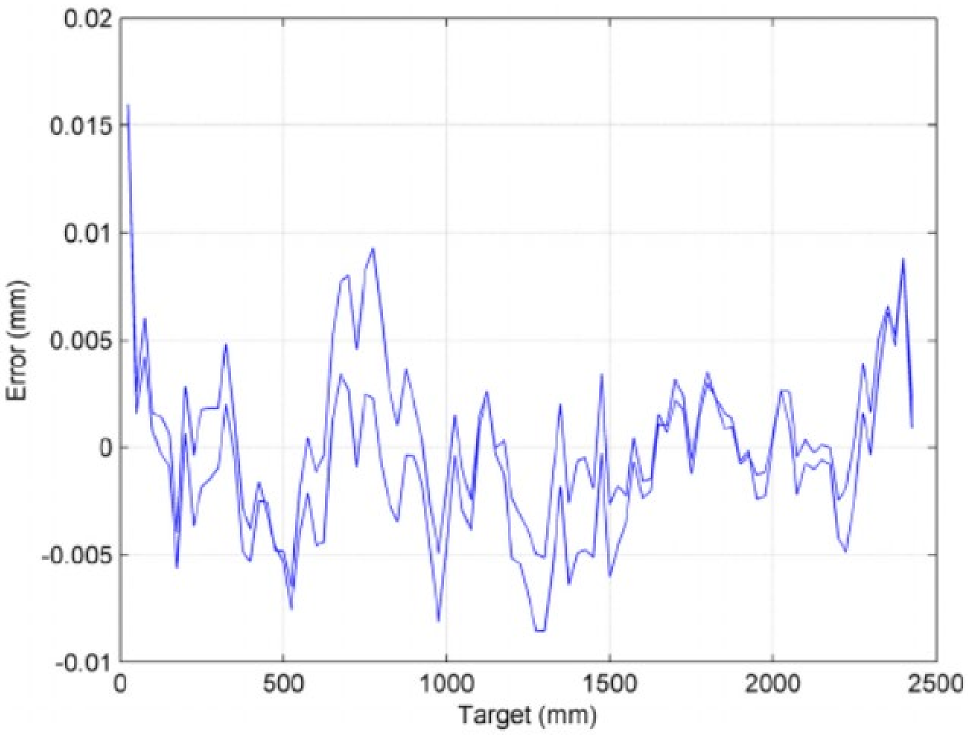
New XL-80 and XM-60 software interfaces for continuous motion (quasi-constant velocity) measurement.

Coarse step QS-M used for slope correction. Method validated on different machine types.

Large machine example:





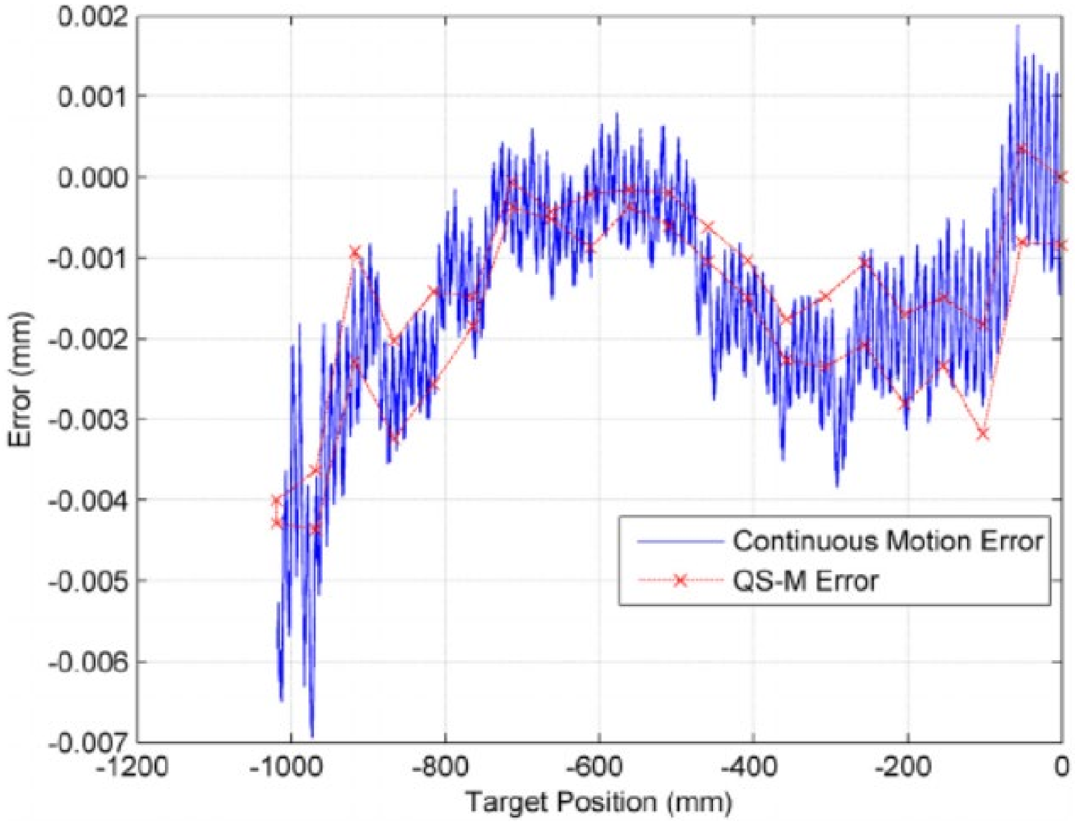
Small machine

Good correlation with standard Quasi-Static measurement (QS-M)

  Within 0.5 µm at 500 mm/min and 0.9 µm at 10000 mm/min

Cyclic error associated with the pitch of the ballscrew easily identifiable

Analysis of the signal can help identify frequencies and magnitude may help localise error sources such as support bearings.



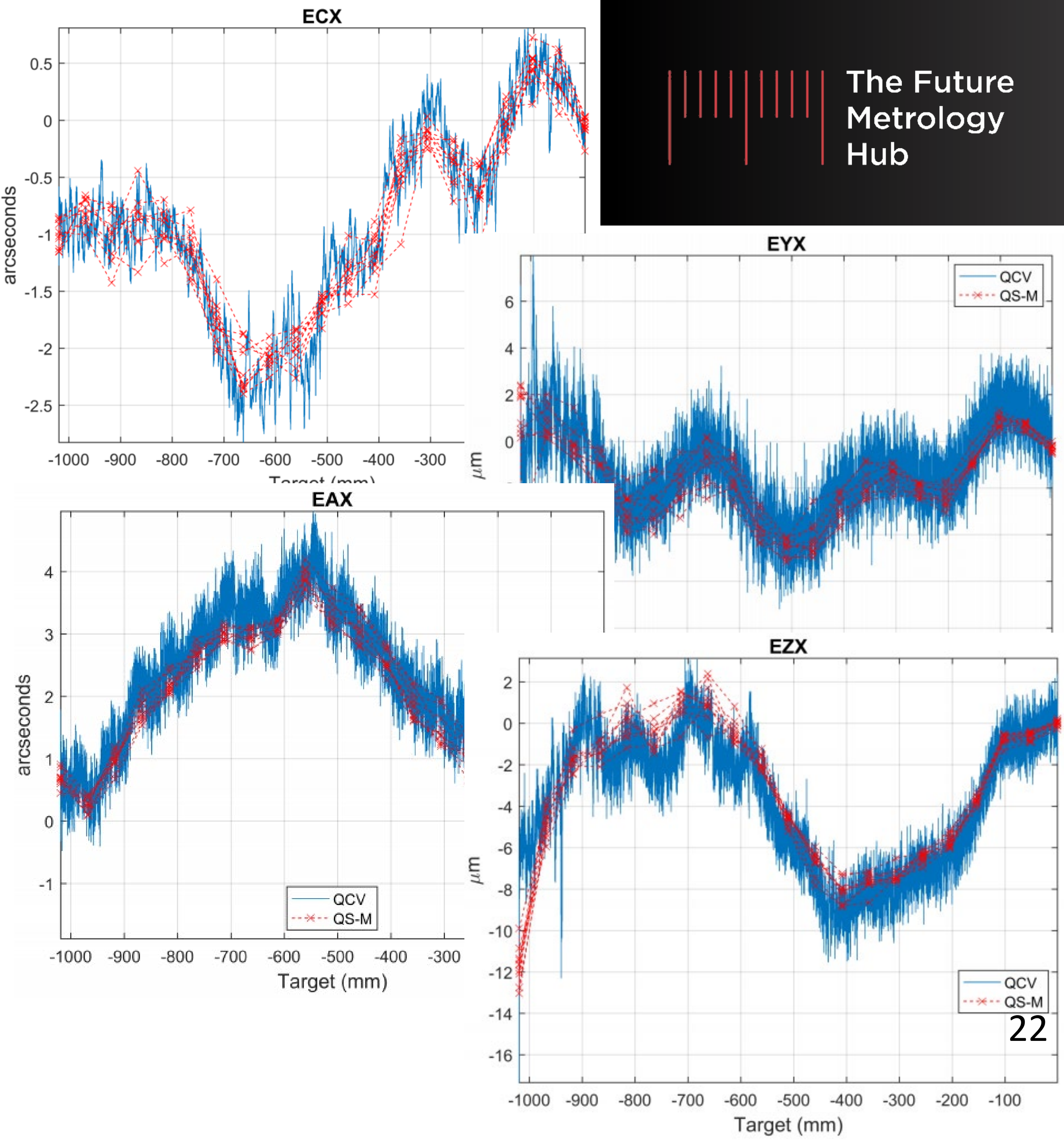
MDoF result example

Small C-frame milling machine.

Single bi-directional qausi-continuous velocity (QC-V) measurement compared with standard QS-M

- RMSE for angles < 0.5 arcseconds and for straightness < 1.4 µm
- Some portion from the small measurement noise in the QCV signal.

Application to robot feeddrive analysis ingoing



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Questions?

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