High-speed 6DoF Tool Monitoring using a Low-cost Photogrammetric System

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3D Imaging, Metrology & Photogrammetry Applied Coordinate Technologies

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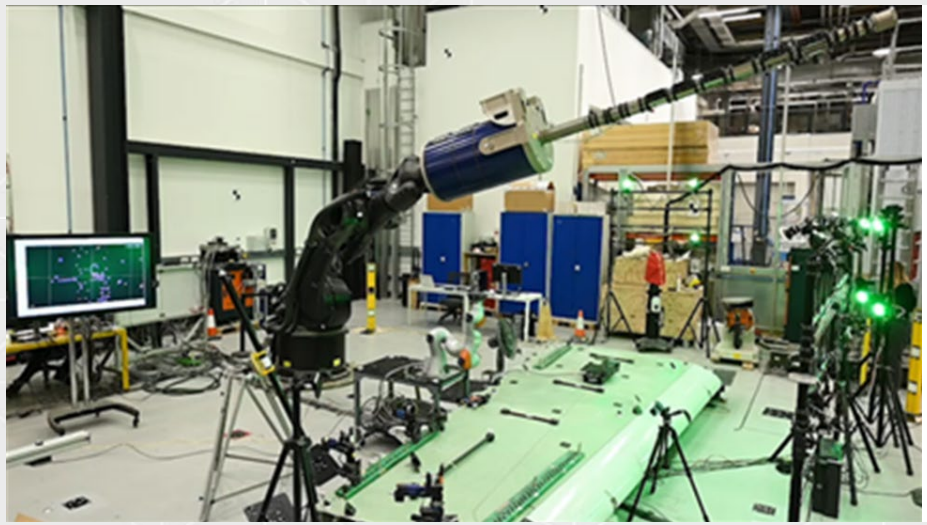
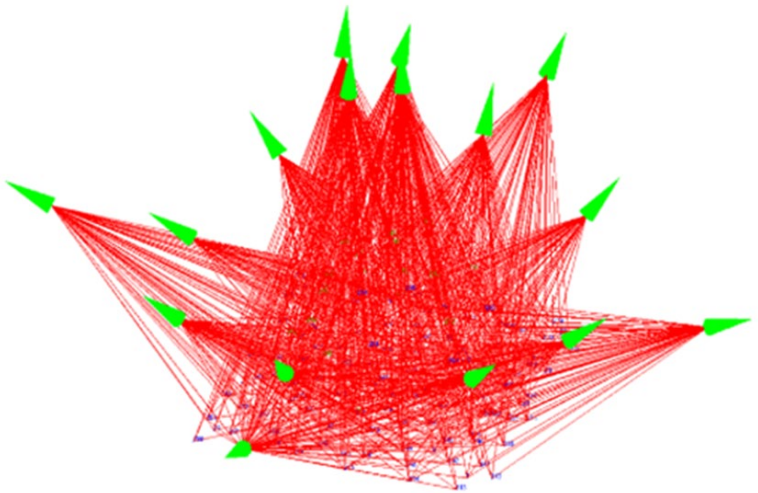
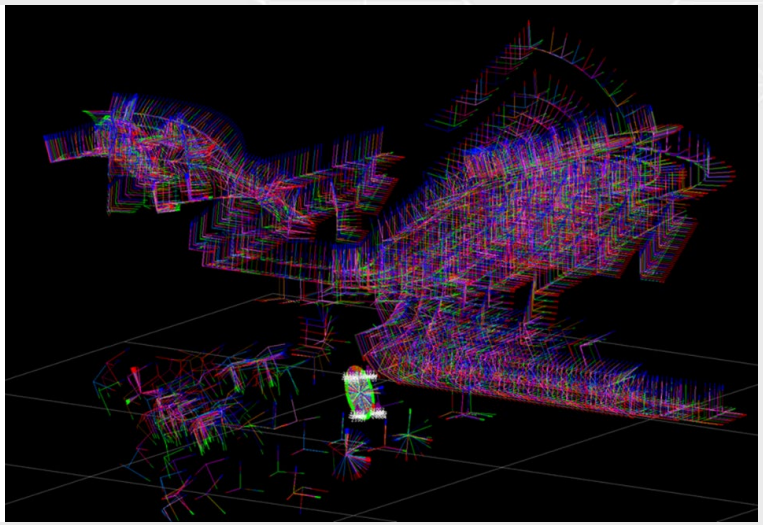
The DYNAMITE Project

DYNamic Applications of large volume Metrology in Industry of Tomorrow Environments - an EU funded project bringing together a number of companies across different countries to improve measurement capabilities in manufacturing environments. Focuses on enhancing the ability to measure size, location, orientation and shape of large objects, assemblies, or large working-volume devices under dynamic situations.





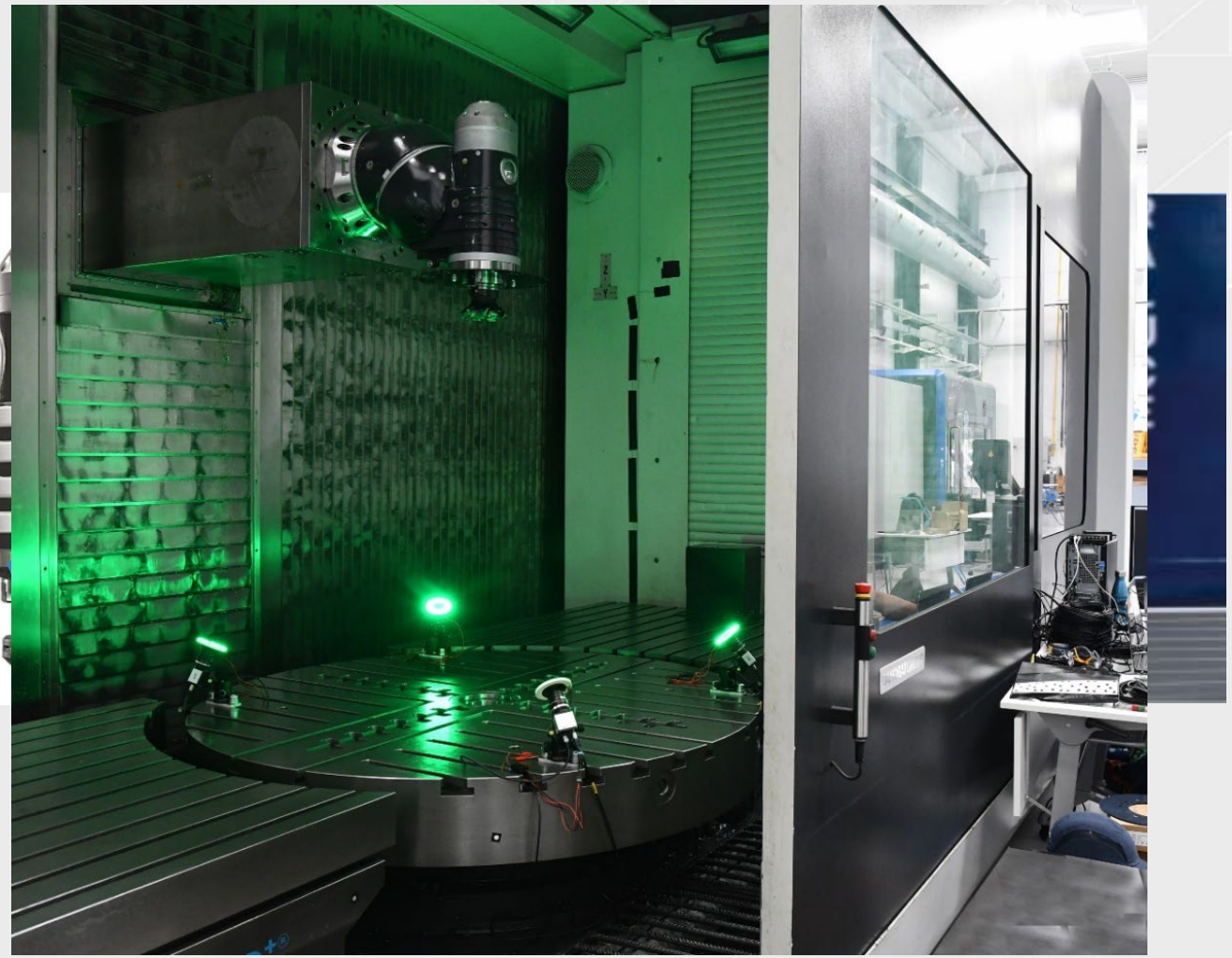


In the low-cost photogrammetry space this project has demonstrated 6DoF solutions scalable in volume, complexity, and number of tracked objects, tracking 50+ 6DoF solutions in parallel within a common spatial and temporal reference system at different frequencies and accuracies. This work investigates the high speed measurement capabilities of this approach.

Testbed System

System Characteristics and Measurement Challenges

- SORALUCE milling machine (FMT) Large multi-axis cutting machine.
- Spindle error analysis: Cutting tool has a maximum speed of 3000 RPM.
- Measure the main dimensions of heads: Testing volume of 1 m^3 over central turntable.



Multi-image photogrammetric sensor networks

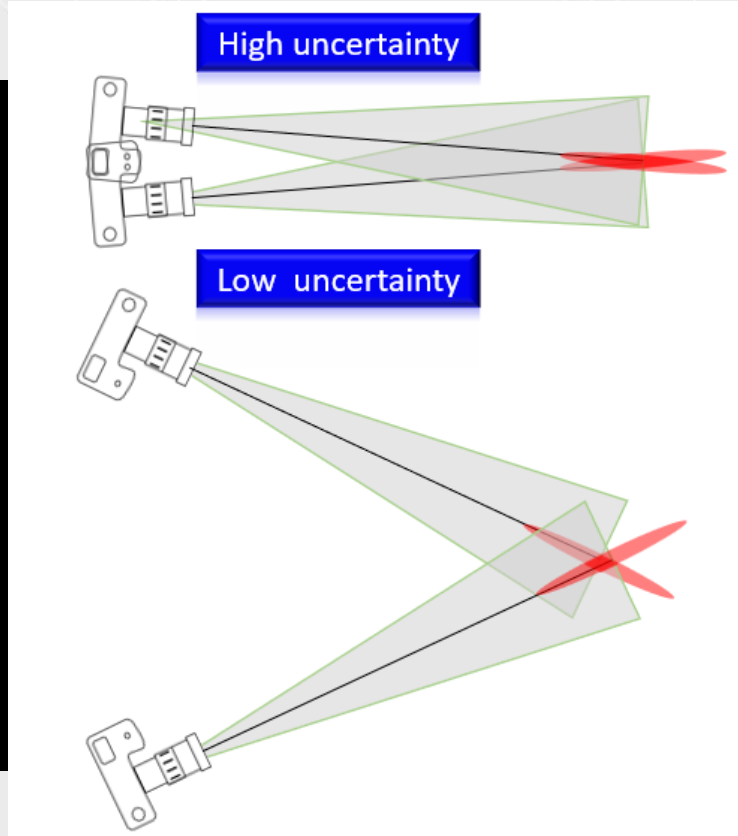
- Point matching across multiple images allows for 3D reconstruction.
- All overlapping points can be simultaneously processed as part of a single network – does not require individual point measurement.
- Uncertainty estimation through least squares “bundle adjustment”.
- Quality of angular measurements, number of lines of sight and network geometry affect the quality and robustness of the results.

Single Camera, Multi-Pose

- A very large number of images may be included, strengthening results.
- Limited to static object measurement.

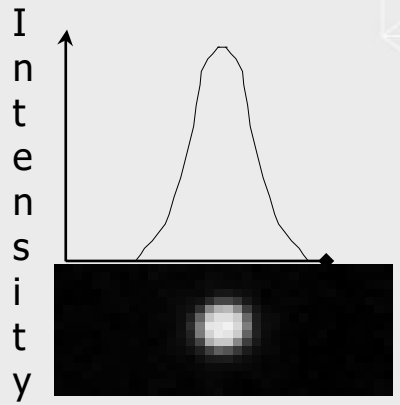
Multi-Camera Single pose

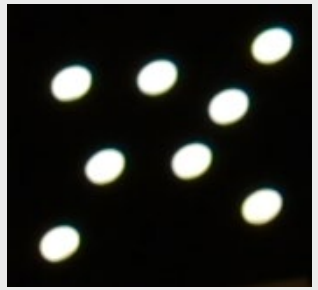
- Images captured simultaneously, allowing for dynamic measurement.
- Movement may affect lines of sight, altering coordination capability.
- Other challenges include maintaining traceable scale; thermal changes in object, camera and environment; and air turbulence.

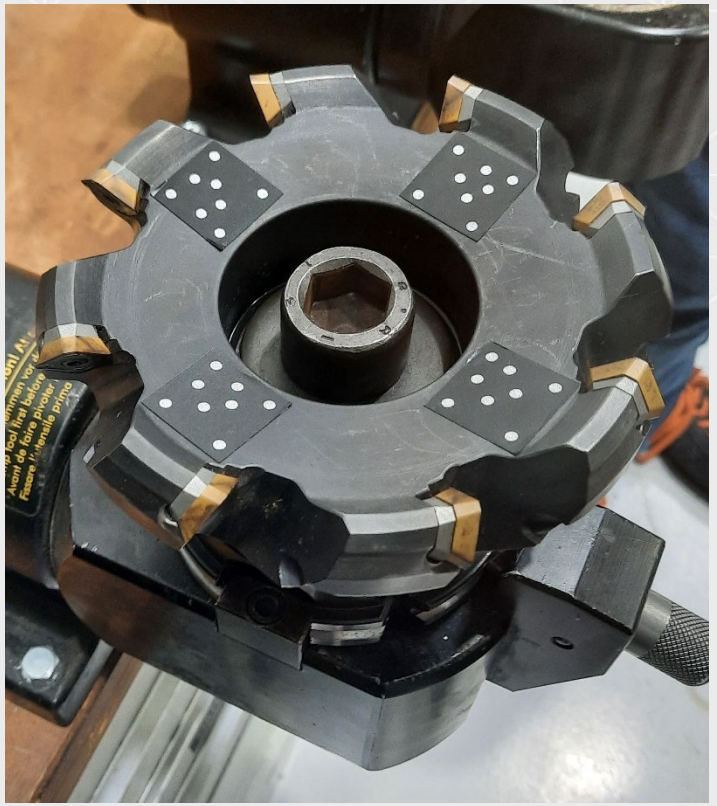


Targeting

- IDEKO's VSET used for static measurement.
- UCL's VMS used for dynamic measurement.
- Both systems use high contrast circular targets allowing for identification of the centre point to sub-pixel accuracy in images.
- VSET uses barcode targets allowing single targets to be uniquely identifiable.
- VMS uses coded target blocks where sets of 8 targets are uniquely identifiable.
- VSET detects and handles individual VMS targets as arbitrary uncoded targets.



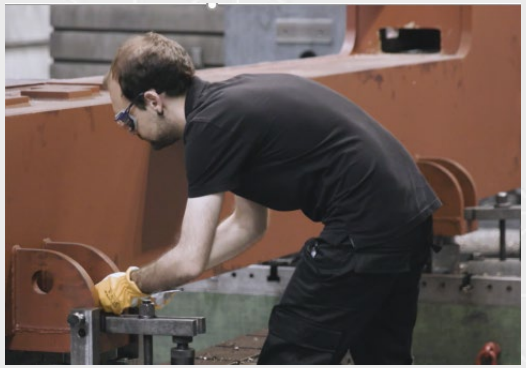


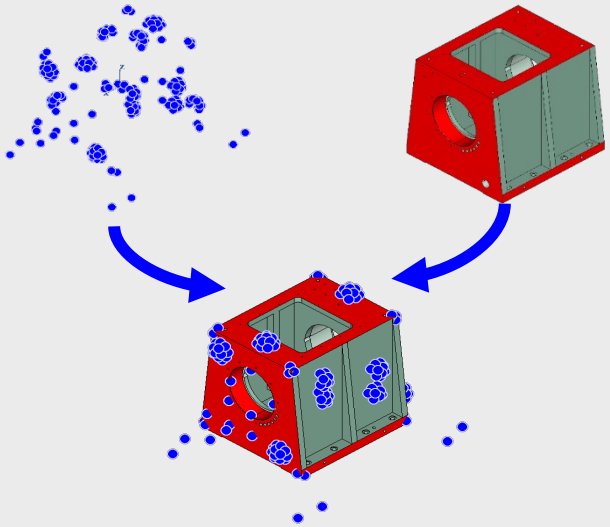


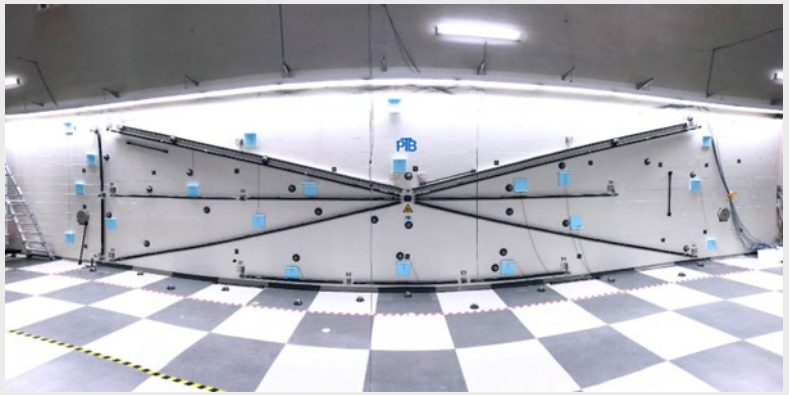
IDEKO VSET System

Modular design for the alignment of large-scale parts

- **VSET MEASURING** Measure the over stock before milling
- **VSET FITTING** Compare the measurement with the design
- **VSET ALIGNMENT** Align the part to the machine axis



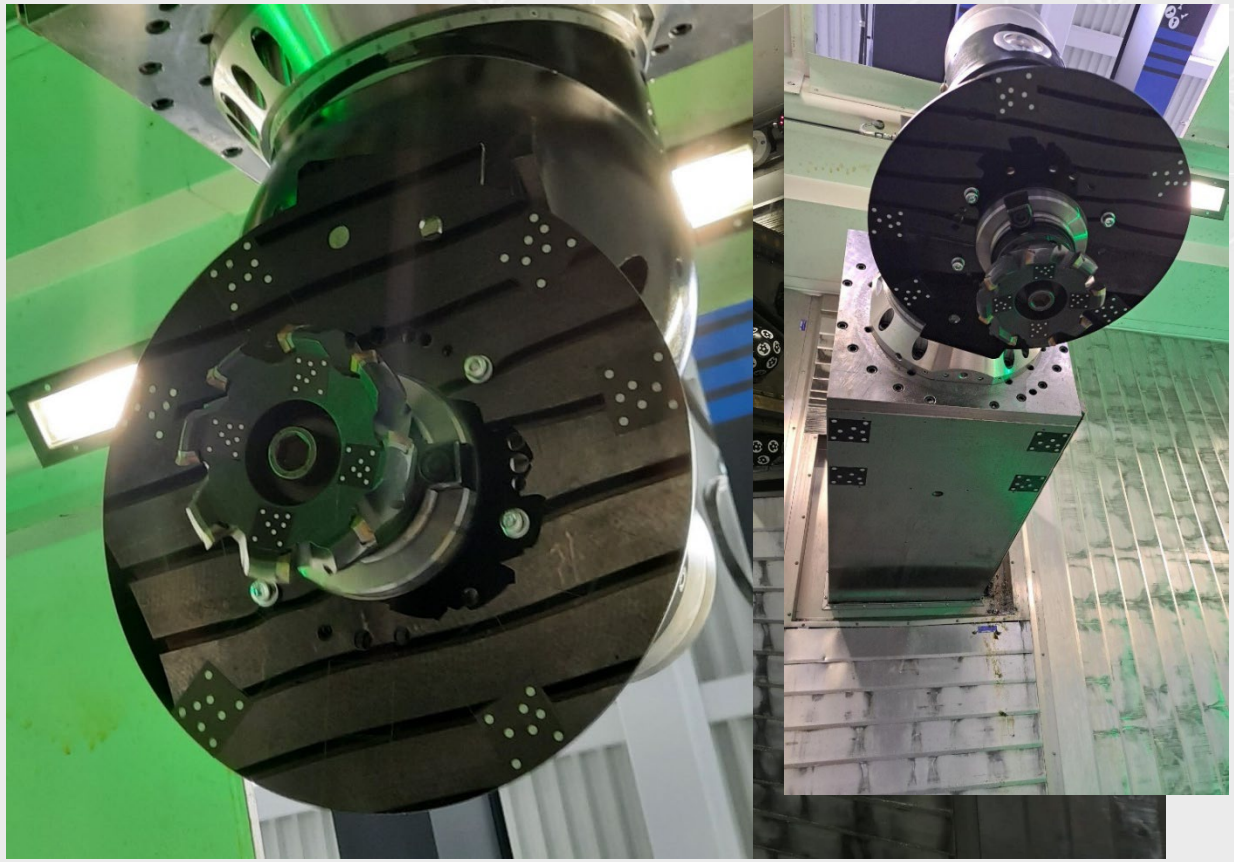




Performance validation at PTB reference wall 12 m Uncertainty 0.22 mm *K*=2

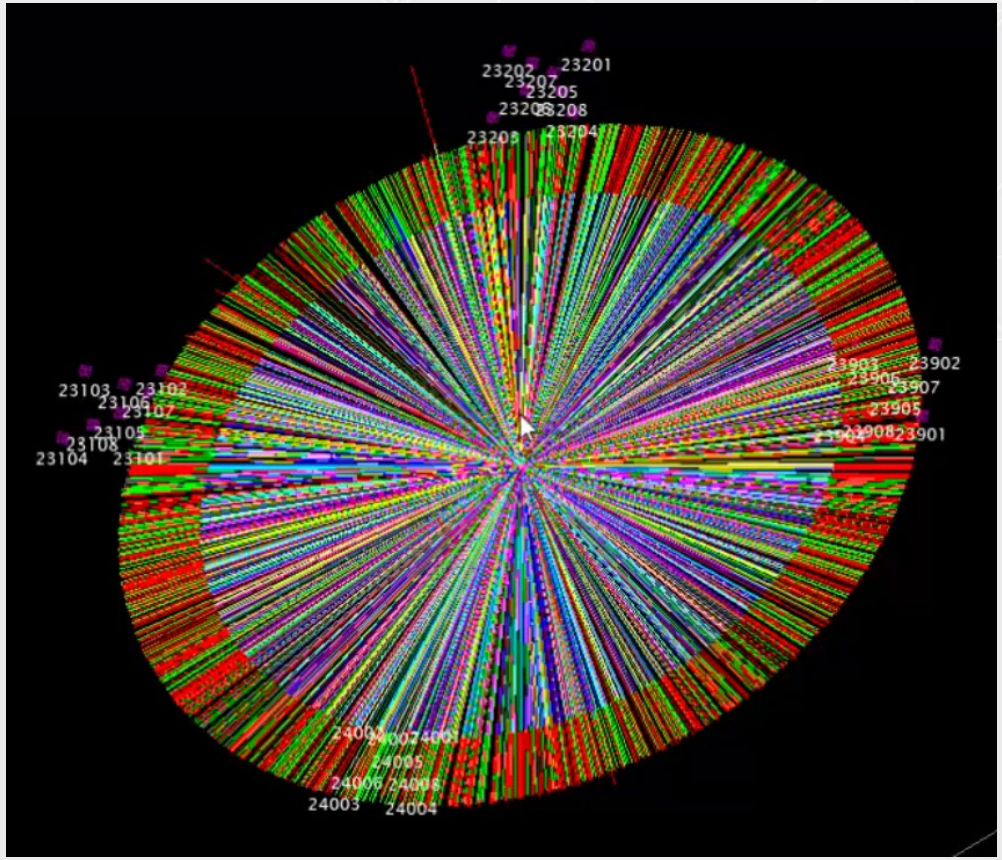
The Characterisation Process

- VMS targets are stuck to the machine in three groups. Each group defines an individually trackable object: the cutting tool; a ring around the tool head, and the boom arm.
- A dense network of Magnetic VSET targets are arranged around the machine.
- Scale bars with VSET targets provide scale to the network.
- The VSET measurement provides a point cloud of the measured targets.
- The VMS target groups are extracted from the point cloud to define a reference coordinate set for the 6 Degree of Freedom Tracking of each object of interest.

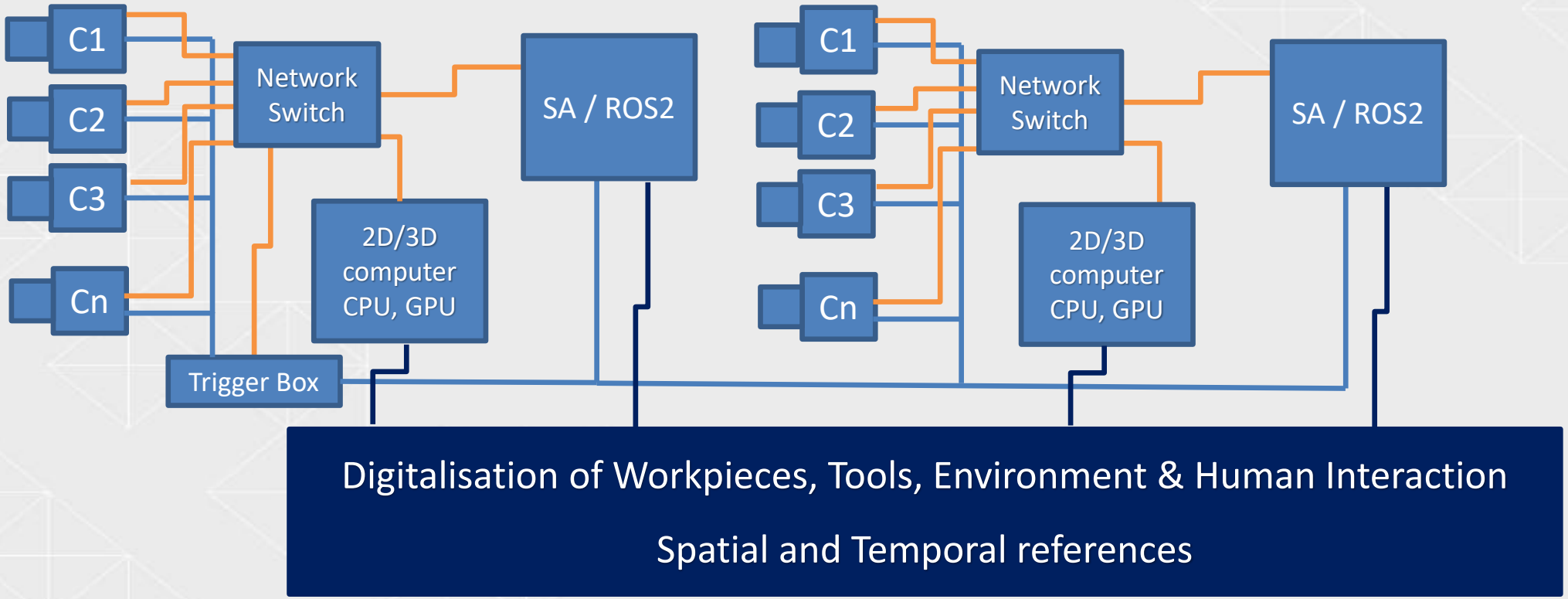


Measurement System Requirements

- Ability to “freeze” image motion with a tool rotating at 3000rpm.
- Minimal image distortion – global camera shutter.
- Short exposure [< 0.1ms]
- High level of light return from retroreflective targets.
- Use of image gain and amplification to increase visibility with minimal noise.
- Camera synchronisation.
- Data transfer and processing.
- Previous ‘50 object’ demo system tested concept with a spinning fan.



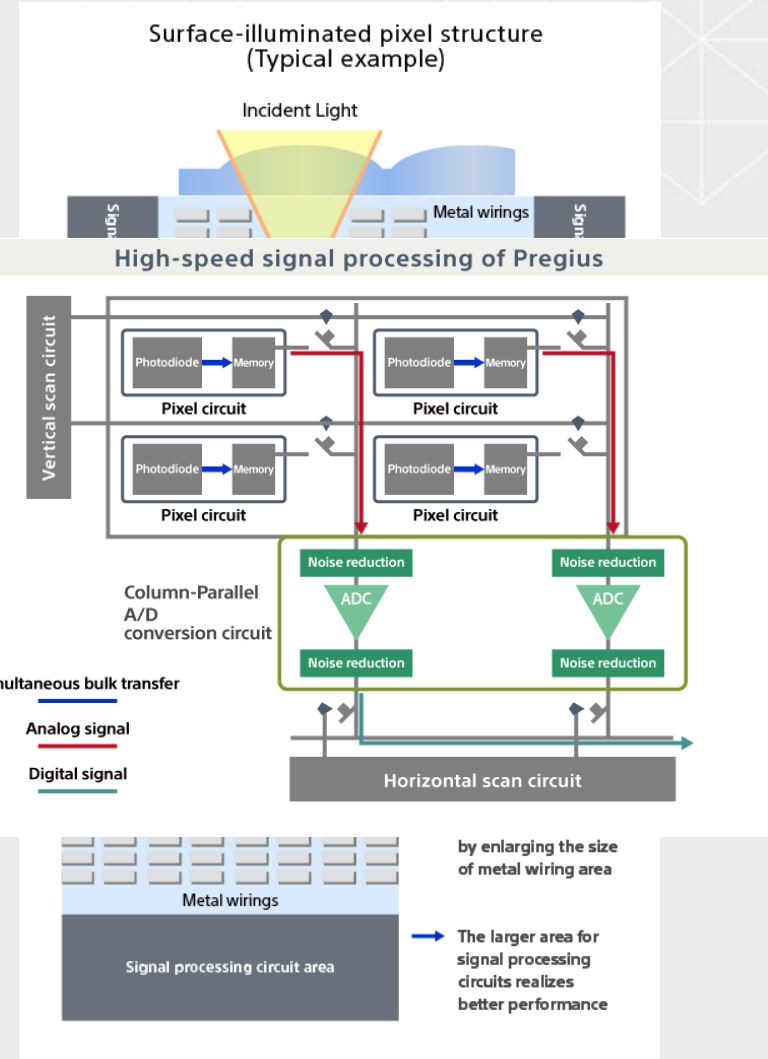
Modular Multi-Sensor System Architecture



Sensor Selection

IDS UI-3290SE-M-GL with Sony Pregius S sensors

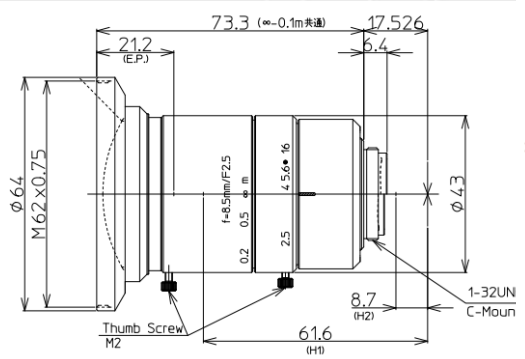
- Uses a global shutter where the full image is captured in a single instant rather than a rolling shutter which scans down the image introducing temporal distortion
- Photodiode arrangement optimises light sensitivity to reduce noise and improve image sharpness
- Delivers >10 M pixels at 10s of frames per second over industry standard USB3.2 connection
- Paired with fibre optic USB and dedicated capture card for rapid data transfer with zero loss over 60m cable lengths.

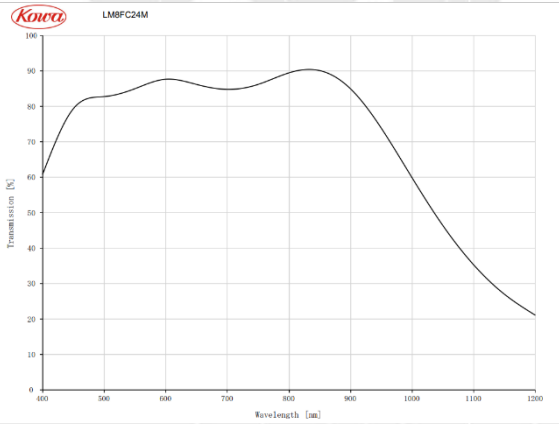


Lens and Lighting

Kowa fixed focal length "C" mount lens

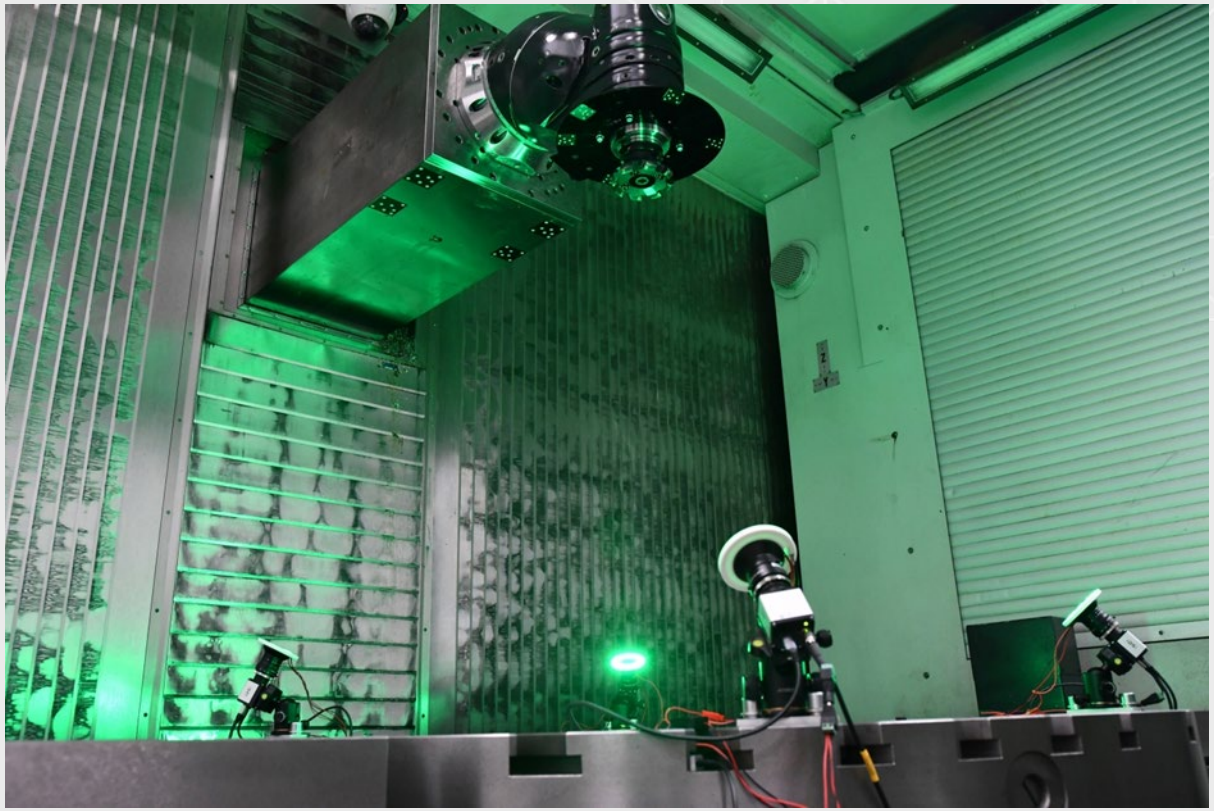
- Matched to sensor dimensions, pixel size and optics
- Angle of view
- Focal length
- Physical stability over time
- Equipped with double "Angel Eye" light rings – Green to match peak sensor sensitivity
- Lens features high transmission and image sharpness in the green wavelength





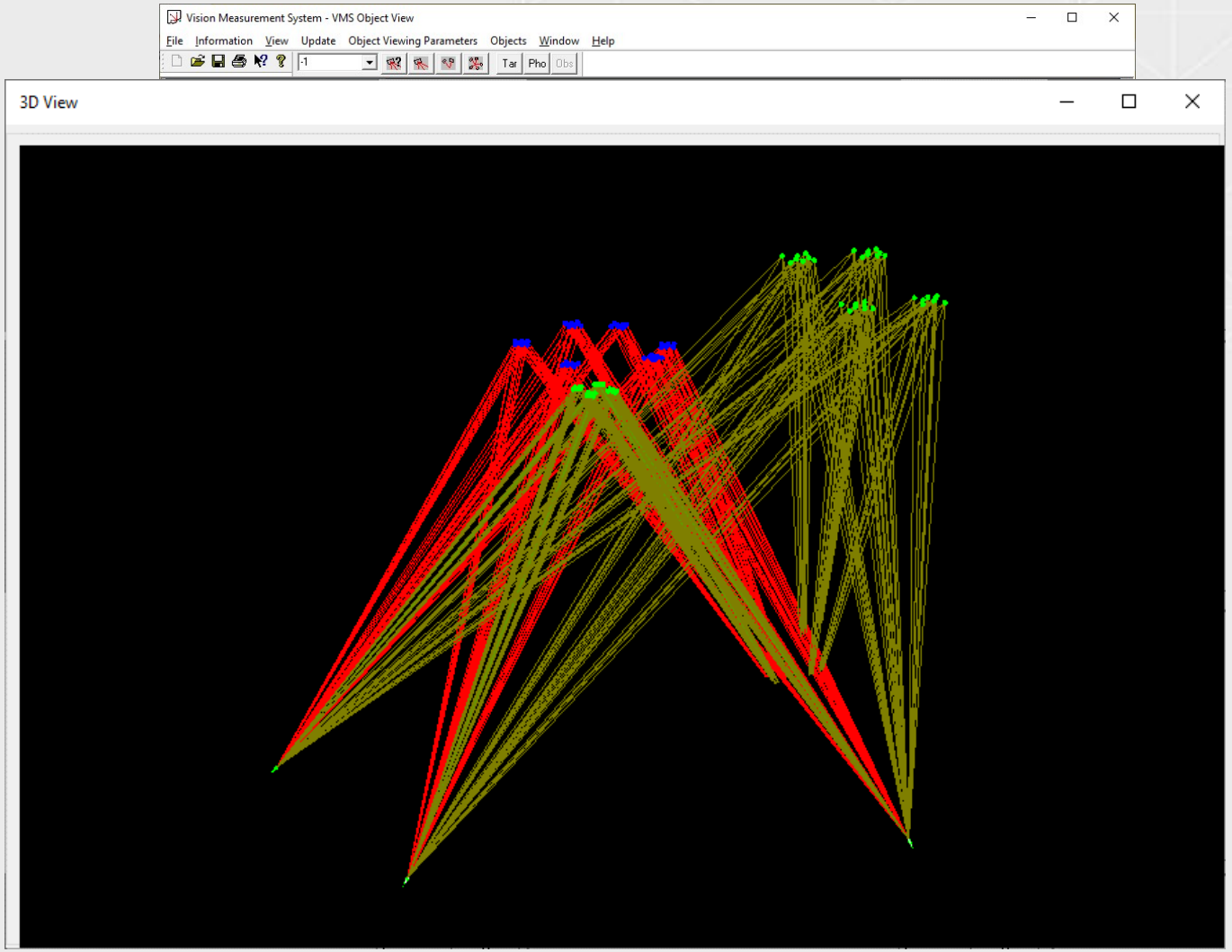
Setting up a coordinate reference system for a multi-camera system

- Design camera network to achieve coverage and overlapping lines of sight and mitigate occlusions.
- Balance the quality, number and geometry of the angular measurements to achieve required accuracies.
- Define physical coordinate reference system.
- Tune cameras for optimal data capture.
- Calibrate cameras.
- Bundle adjustment in VMS provides coordinate of photogrammetric reference points and their uncertainties.
- Capture of joints across multiple poses allows for alignment of axis to centre of rotation.



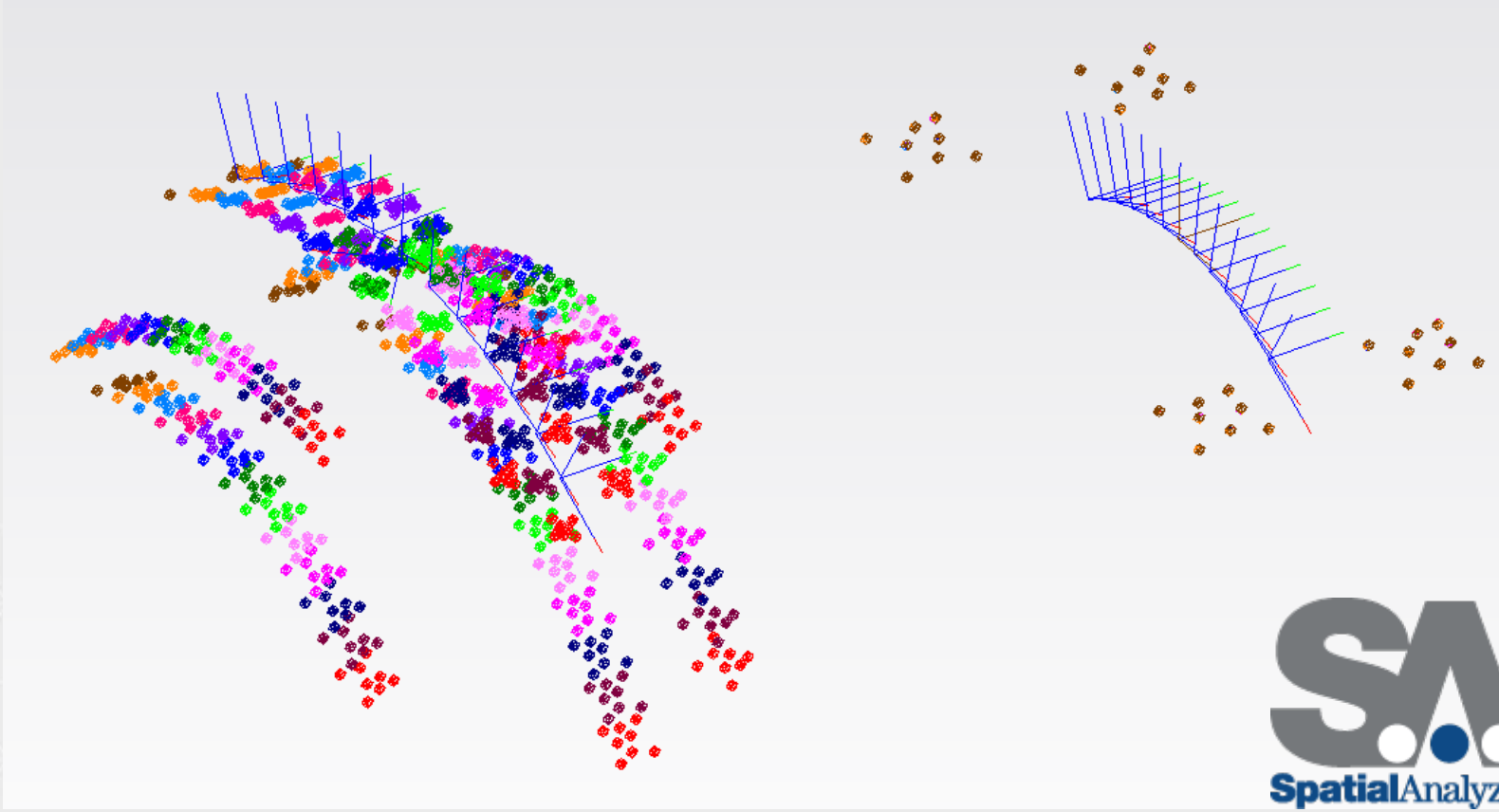
Camera Calibration and Static Measurement

- Calibration images captured of characterised robot moving through a series of poses.
- Calibration image processing carried out in VMS.
- Efforts made to incorporate multiple segments of the machine by locking joint positions.
- Calibration results achieved an image coordinate RMS of 0.34 µm [1/10th pixel].
- With Cameras calibrated, static measurements of the machine agreed with VSET results with a mean precision of 9.23 µm



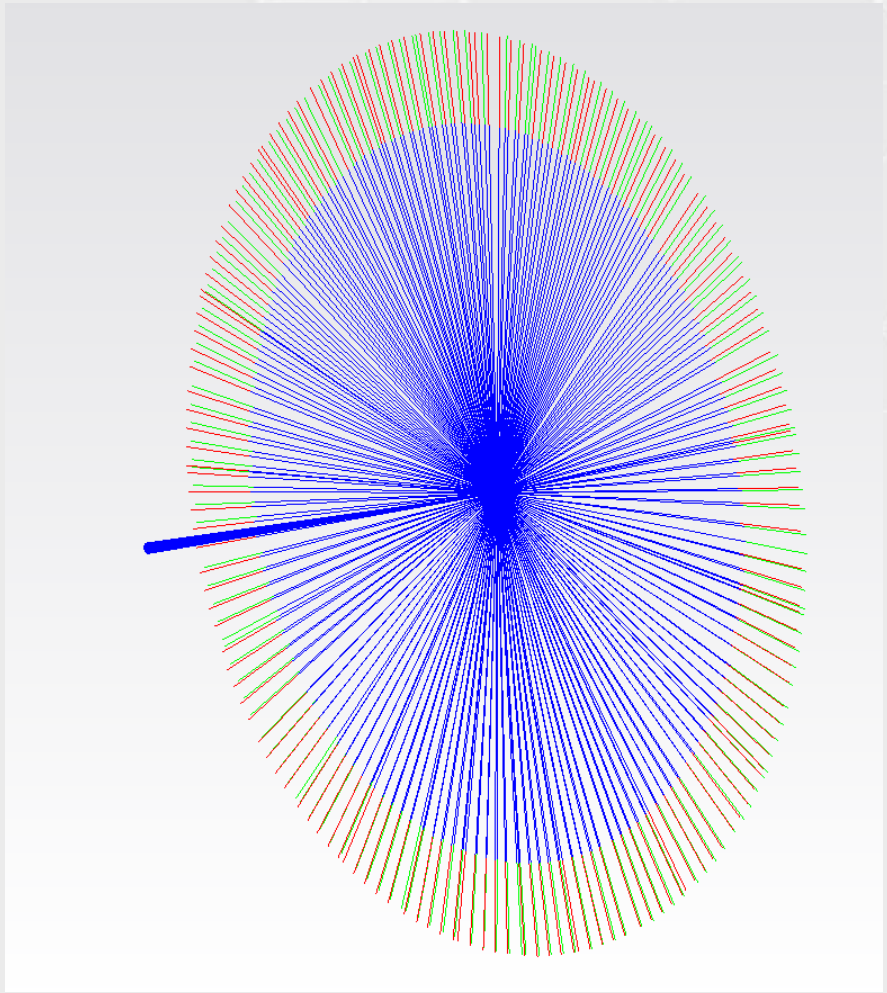
Dynamic Measurement

- VMS Capture is used for real time 6 Degree-of-Freedom (6DoF) tracking of target objects.
- Live feed of data sent to Spatial Analyzer for analysis.
- Centre of rotation of machine joints found and sensible reference frames defined.
- Tool ring or boom arm may be used to define a reference frame.
- Live data viewable in both VMS Capture and Spatial Analyzer



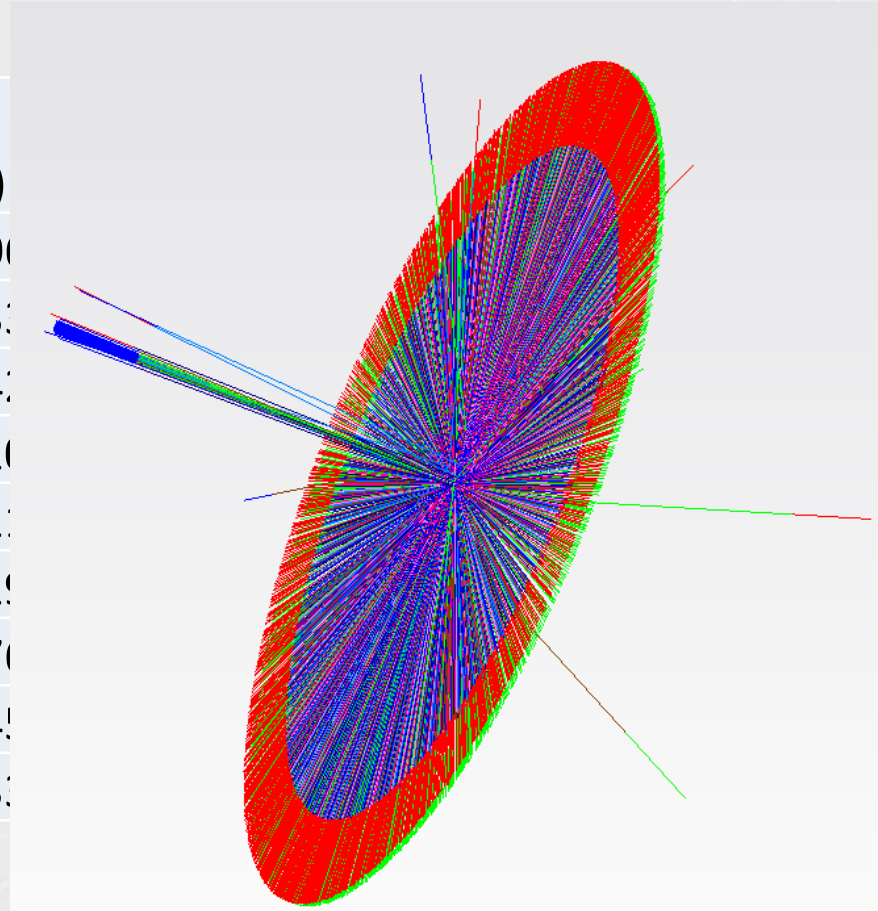
Dynamic Measurement – Results

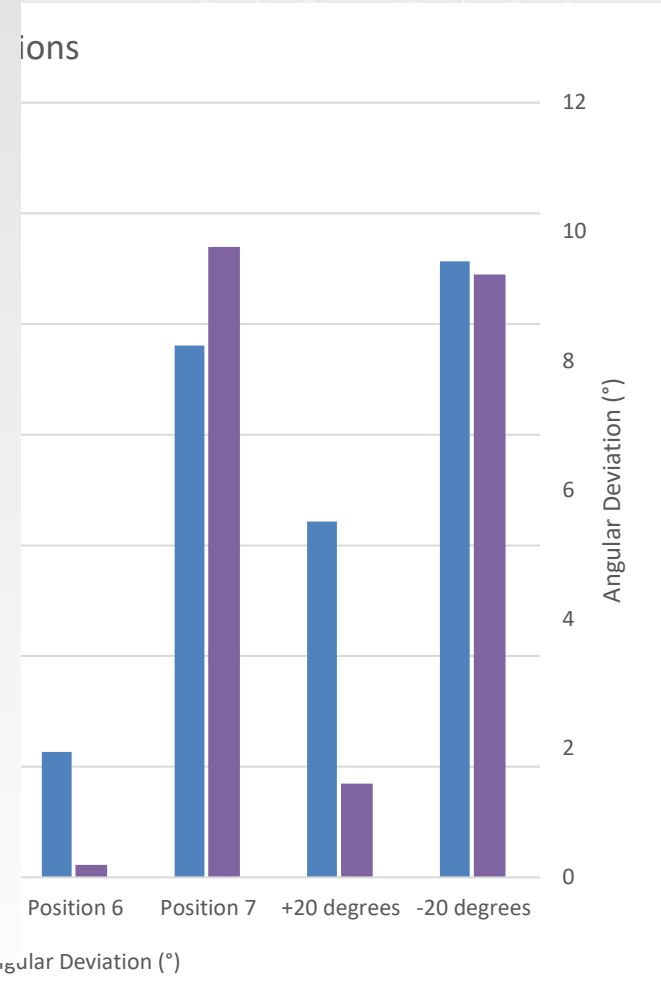
- When the machine is running the cutting tool should rotate around a consistent axis relative to the target ring around the tool.
- Given an accurate characterisation of the tool axis from the reference 6DoF measurement, deviations observed in the estimated tool 6DoF can be used to assess noise in the measurement system and give a measurement of its precision.
- Spatial Deviation: 22.7 µm
- Angular Deviation: 0.061 °
- This test is then repeated across the observed volume to assess the variation present.



Dynamic Measurement – Initial 6DoF stability results

	Spatial Deviation (µm)	Angular Deviation (°)
Central	22.7	0.0
+250mm in X	390.0	0.3
-250mm in X	653.1	3.4
+250mm in Y	54.0	0.1
-250mm in Y	44.7	0.1
+250mm in Z	113.5	0.1
-250mm in Z	480.7	9.7
+20 degrees	321.6	1.4
-20 degrees	556.7	9.3

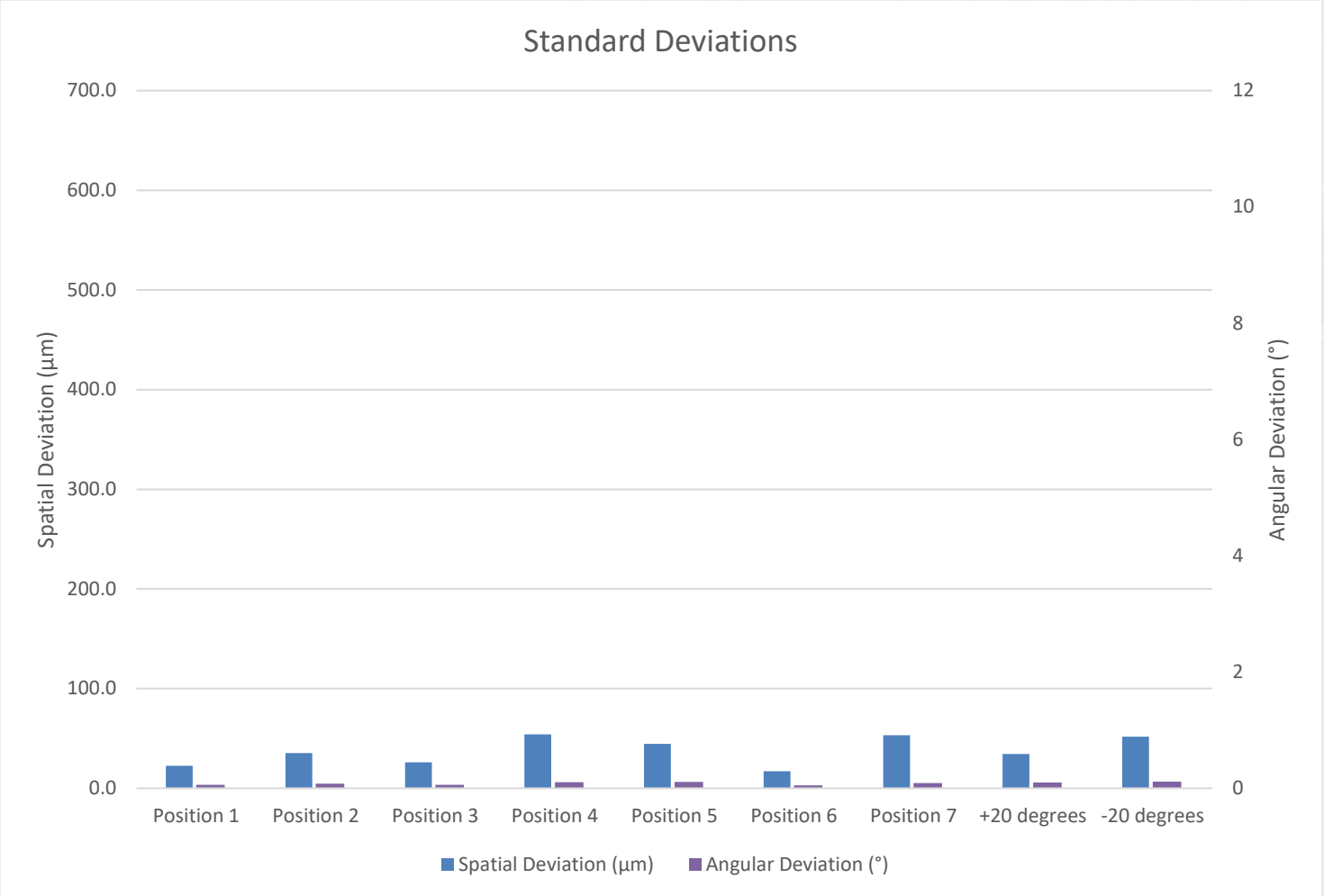




Dynamic Measurement – 6DoF stability Results [gross outliers removed]

	Spatial Deviation (µm)	Angular Deviation (°)
Central	22.7	0.061
+250mm in X	35.3	0.079
-250mm in X	26.0	0.061
+250mm in Y	54.0	0.105
-250mm in Y	44.7	0.112
+250mm in Z	17.2	0.053
-250mm in Z	53.2	0.092
+20 degrees	34.5	0.101
-20 degrees	51.8	0.113

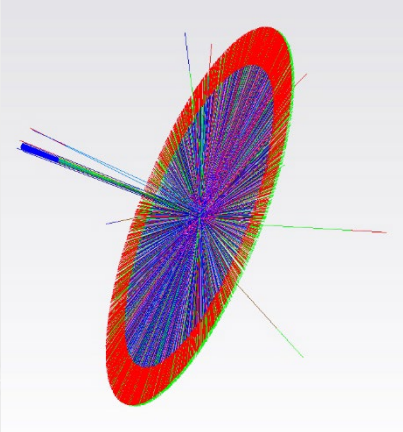
*15 of 1712 Frames removed



Summary following initial Demonstrator

- IDEKO's VSET system was easily able to be used with the VMS system, demonstrating the benefits of information sharing across metrology systems in order to find the most optimal solutions.
- A low-cost photogrammetric approach can be used to capture usable images of targets travelling at high speeds.
- Data captured with this approach can be used to for resilient, real time 6DoF tracking.
- Measurements made can be used for real-time operator or machine feedback.
- Tracking cameras auto-reference into common coordinate frame allowing the system to adapt as required to machine tool movements, making the system resilient to occlusions and camera movement.

Future of the Project



Work to automatically identify and remove sources of outlier data

Dynamite 6DoF reference object travelling between partners during 2024 for multi-system validation

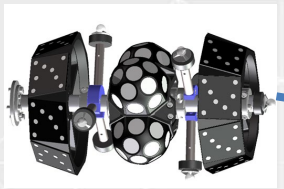
Factory environment led to oil spot contamination of lens surfaces, leading to image distortion. Work is being done to mitigate this.

Large-scale CMM
Laboratory conditions

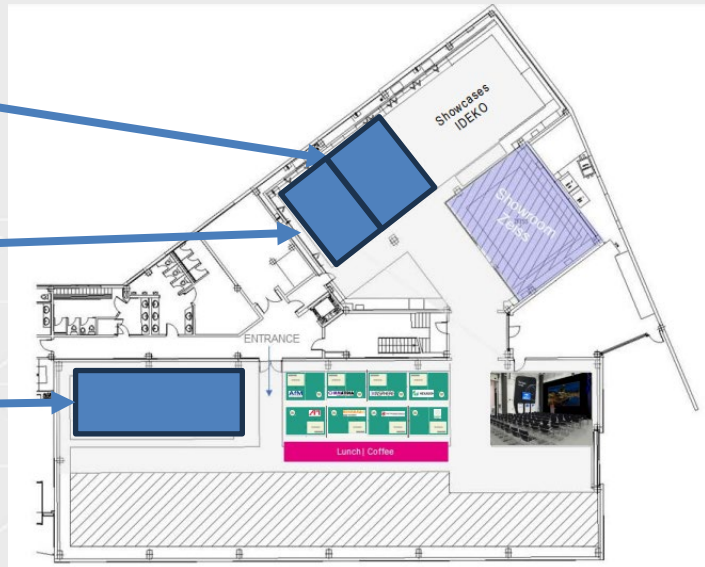
Large cable Robot
Industrial conditions

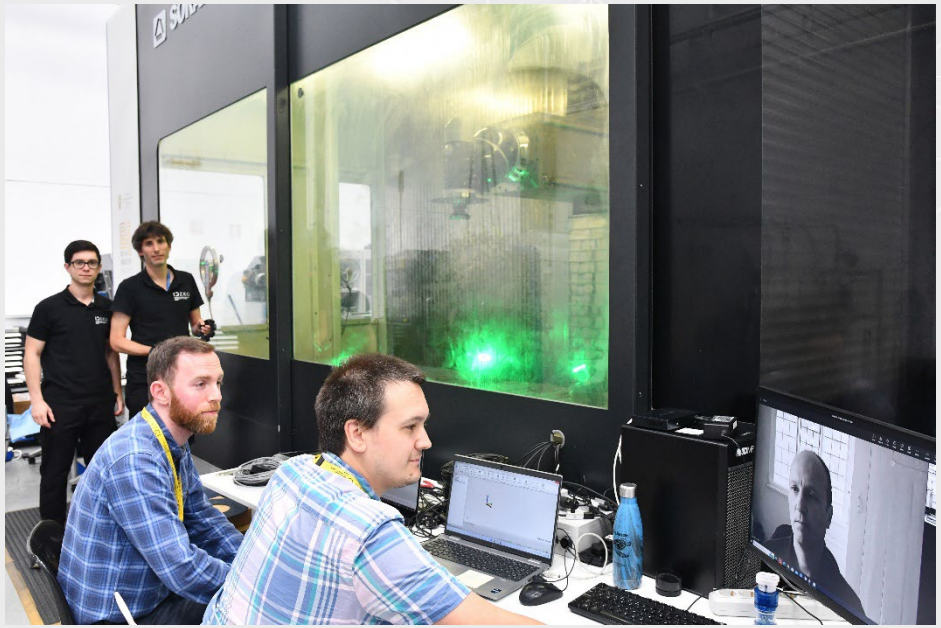
Thank You

Please visit our live demonstration at IDEKO tomorrow to see the system for yourselves!



VSET MEASURING





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