OPTIMUM accuracy trials and volume simulation

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Bilbao,
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TOMORROW.
DONE BETTER.

Outline

- Introduction to NPL
- What is OPTIMUM
  - Concept
  - Current development status
- Initial testing at AMRC Cymru
  - Setup
  - Results
- OPTIMUM volume simulation
- Next steps

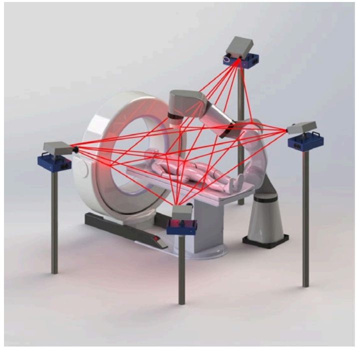
About NPL

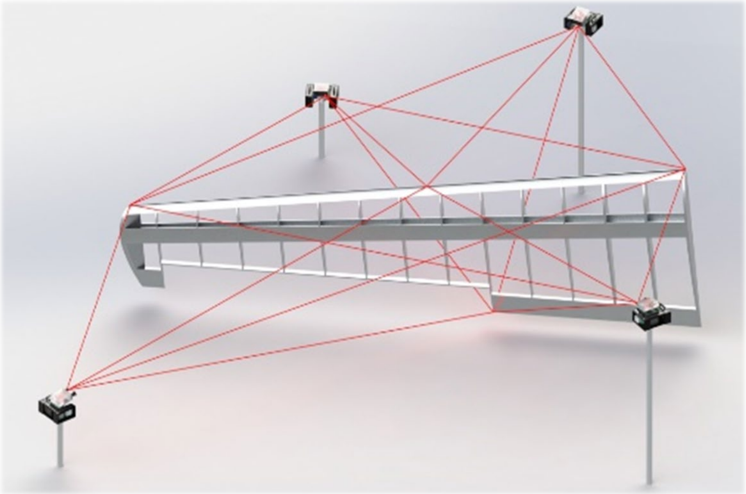
- UK’s National Metrology Institute founded in 1900
- A public corporation owned by the Department for Science, Innovation and Technology (DSIT)
- Based in Teddington (London) with locations in Strathclyde, Surrey, Cambridge, Huddersfield and Solihull
- Strategic partners DSIT, the University of Surrey and The University of Strathclyde
- 1000 scientists and engineers with a breadth and depth of metrology expertise.

OPTIMUM – high accuracy coordinate metrology using frequency scanning interferometry (FSI) and multilateration

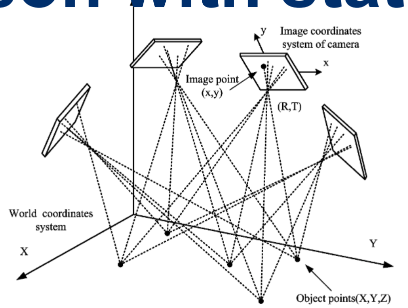
Analogy - The Global Positioning System (GPS)

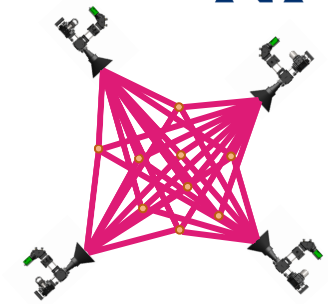
1. Is accurate
2. Measures multiple points simultaneously
3. Self-calibrating - built-in compensation for systematic errors
4. Has built-in traceability to SI
5. Gives on-line uncertainty estimation





Comparison with state-of-the-art





	Photogrammetry	GPS	OPTIMUM
Basic principle	Triangulation - angles	Multilateration, absolute distance, time-of-flight	Multilateration, absolute distance, FSI
Volume	<1 m^3 to > 10^6 m^3	10^{21} m^3	<1 m^3 or > 500 m^3
Precision	1:10^5 to 1:10^4	0.3:10^6 (~4 m)	~1:10^6 (potentially)
Uncertainty	>1:10^4	~1:10^6	~1-5:10^6 (potentially with good geometry)
Traceability	Scale bar	On-board atomic clock	Gas absorption cell built-in
Self-calibration	Camera pose, optical distortion	Receiver clock, real-time	Sensor pose, optical distortion, scale factor, real-time

Current development status

- Sensor hardware operational
  - Some crucial range-noise reduction hardware not yet commissioned
- Bare-bones software functionality in place for testing purposes
- User software in development
  - Already interfaces with SpatialAnalyser
- On-going collaboration with AMRC Cymru on development and testing

Initial accuracy tests at AMRC Cymru

Objective:

To compare accuracy of OPTIMUM in its current configuration with a Laser tracker

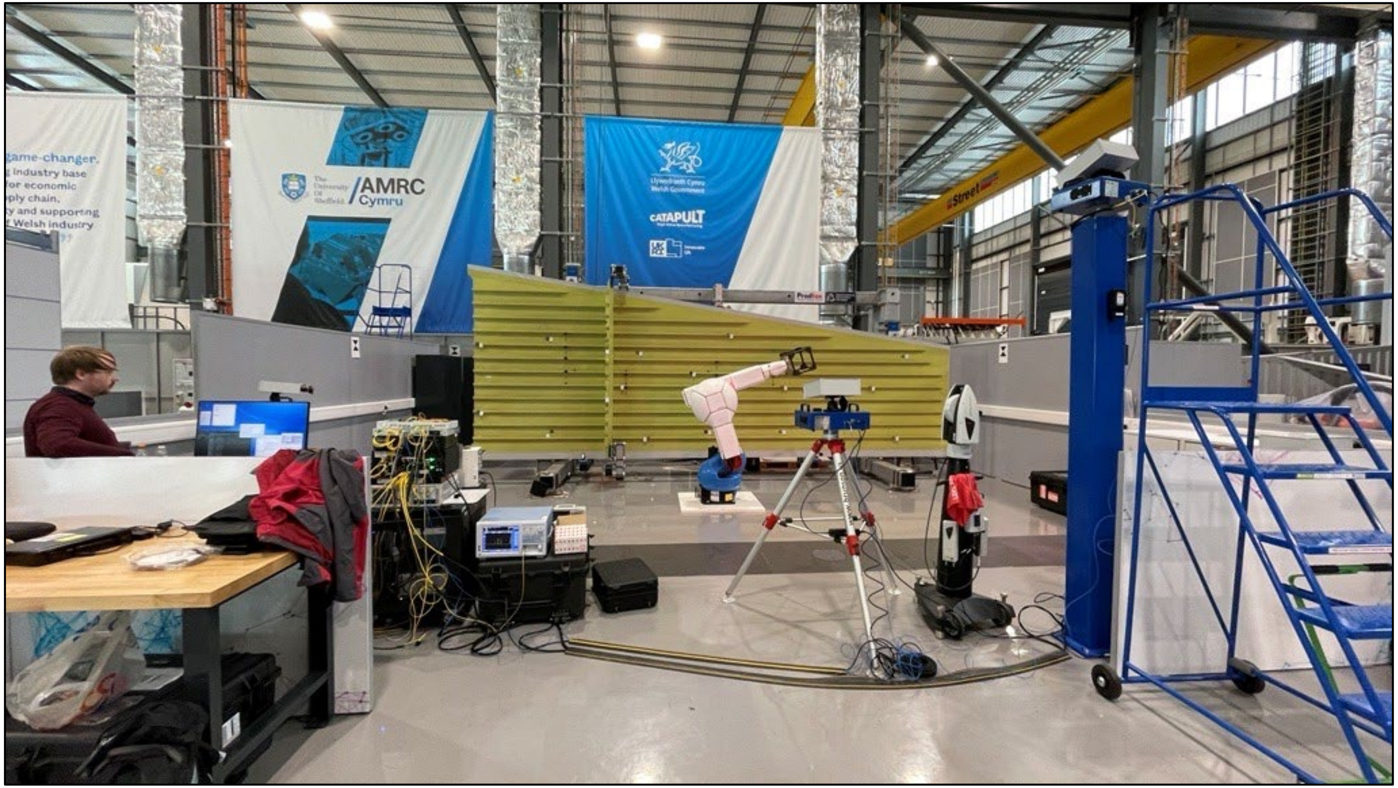
Setup:

- Five OPTIMUM sensors placed arbitrarily

- Hexagon AT960-mr
- Hexagon super cat's eye retroreflector

- 1 m Brunson scale bar
- 28 Fixed nests placed arbitrarily in the cell

OPTIMUM setup at AMRC Cymru



Data processing pipeline

1. Acquire 50 ranges (d_{ijk}) from each sensor (S_i) to each visible target (T_j).

2. Compute mean ($\boldsymbol{d\_mean_{ij}}$) and standard deviation (σ_{ij}), after removing outli

3. Use σ_{ij} to weight a fit of $\boldsymbol{d\_mean_{ij}}$ to the multilateration model:

$$|\boldsymbol{S_i} - \boldsymbol{T_j}| = \boldsymbol{d\_mean_{ij}} + e_i$$

to solve for Sensor and Target coordinates $\boldsymbol{S_i}$ & $\boldsymbol{T_j}$ and uncertainties $u(\boldsymbol{T_j})$.

4. Remove correlated uncertainty contributions from $u(\boldsymbol{T_j})$ leaving just the relevant un-correlated uncertainties $u^*(\boldsymbol{T_j})$.

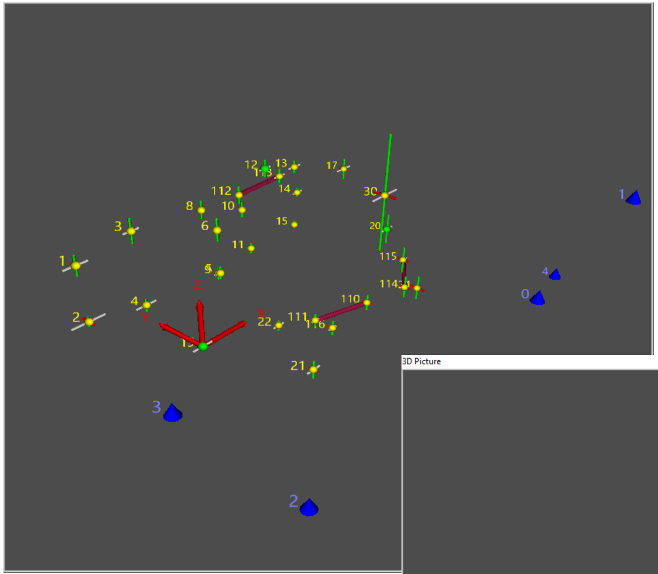
5. Use $u^*(\boldsymbol{T_j})$ to weight a fit of $\boldsymbol{T_j}$ to reference target coordinates, $\boldsymbol{R_j}$ measured using the laser tracker.
$\boldsymbol{T_j} \rightarrow \boldsymbol{T^*_j}$

6. Compute $\boldsymbol{E_j} = \boldsymbol{R_j} - \boldsymbol{T^*_j}$ and $U(\boldsymbol{T_j}) = U(\boldsymbol{T^*_j}) = 2\,u^*(\boldsymbol{T_j})$ and plot.

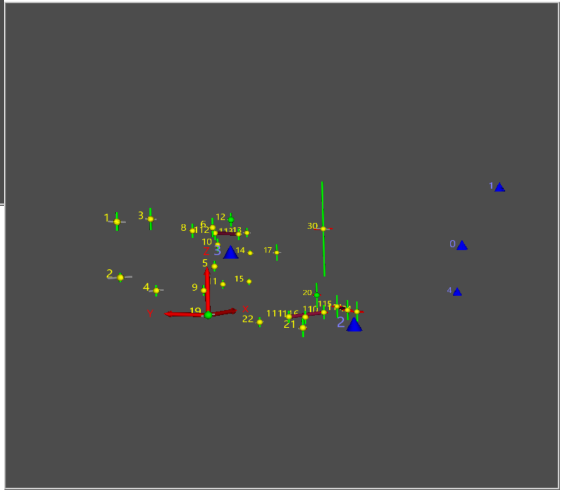
$\boldsymbol{d\_mean_{ij}}$ is the mean of the range measurements between the i^{th} sensor and j^{th} target.
$\boldsymbol{S_i} = (x_i\ y_i\ z_i)$ *is the coordinates of the* i^{th} sensor.
$\boldsymbol{T_j} = (x_j\ y_j\ z_j)$ *is the coordinates of the* j^{th} target.
e_i is a range offset associated with the i^{th} sensor.
$u(\boldsymbol{T_j})$ *is the estimated uncertainty associated with* $\boldsymbol{T_j}$.
$u^*(\boldsymbol{T_j})$ *is the un-correlated uncertainty associated with* $\boldsymbol{T_j}$.
$U(\boldsymbol{T_j})$ *is the expanded* (k = 2) *un-correlated uncertainty associated with* $\boldsymbol{T_j}(\boldsymbol{T^*_j})$.
$\boldsymbol{R_j}$ are the reference coordinates of the j^{th} target from the laser tracker.
$\boldsymbol{T^*_j}$ *are the coordinates of the* j^{th} target after best fit to $\boldsymbol{R_j}$.
$\boldsymbol{E_j}$ *are the "errors" in the measured coordinates of the* j^{th} target.

Test results

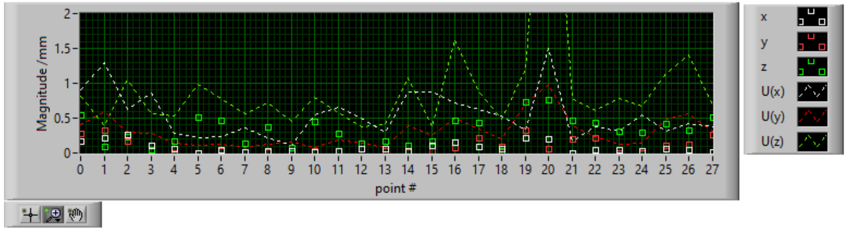
3D Picture



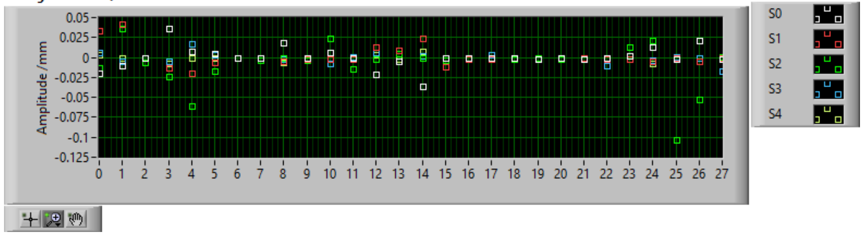
3D Picture



Target cordinate errors (OPTIMUM - Laser Tracker) and expanded uncertainties (2σ) /mm

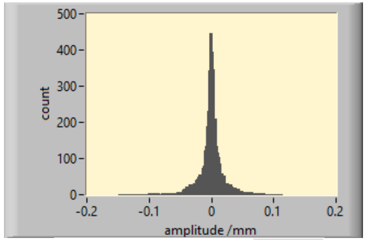


Range residuals /mm



Scale bar length /mm OPTIMUM	OPTIMUM - AT960-mr /mm	Scale bar length /mm AT960-mr
999.9249	-0.047	999.8775
999.9195	0.018	999.9374
999.9507	-0.019	999.9319

Range Histogram

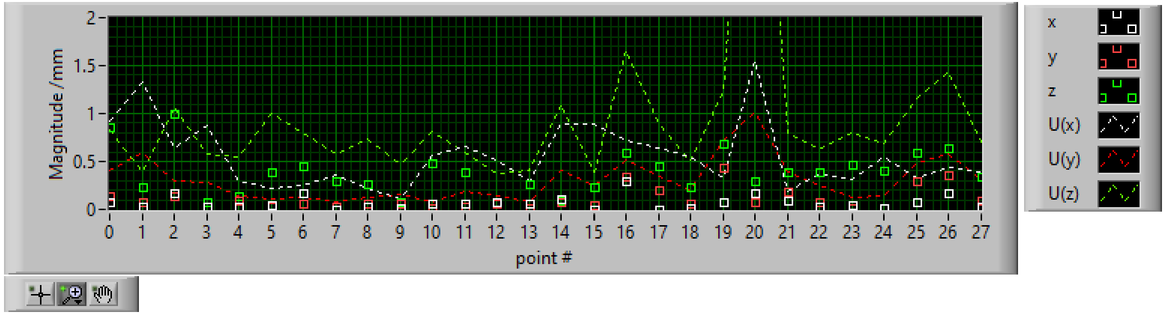


standard deviation /mm 0.02

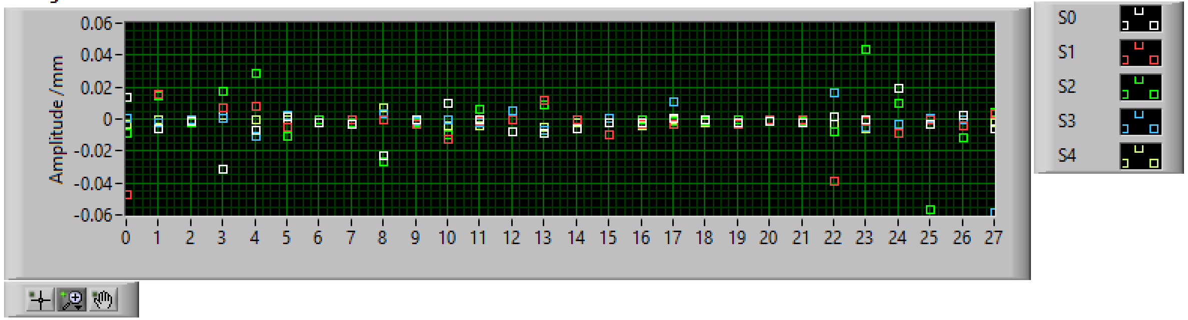
USMN uncertainties 20 - 40 μm (k = 2)

Simulation with range uncertainty of 20μm

Target corrdinate errors (OPTIMUM - Laser Tracker) and expanded uncertainties (2σ) /mm

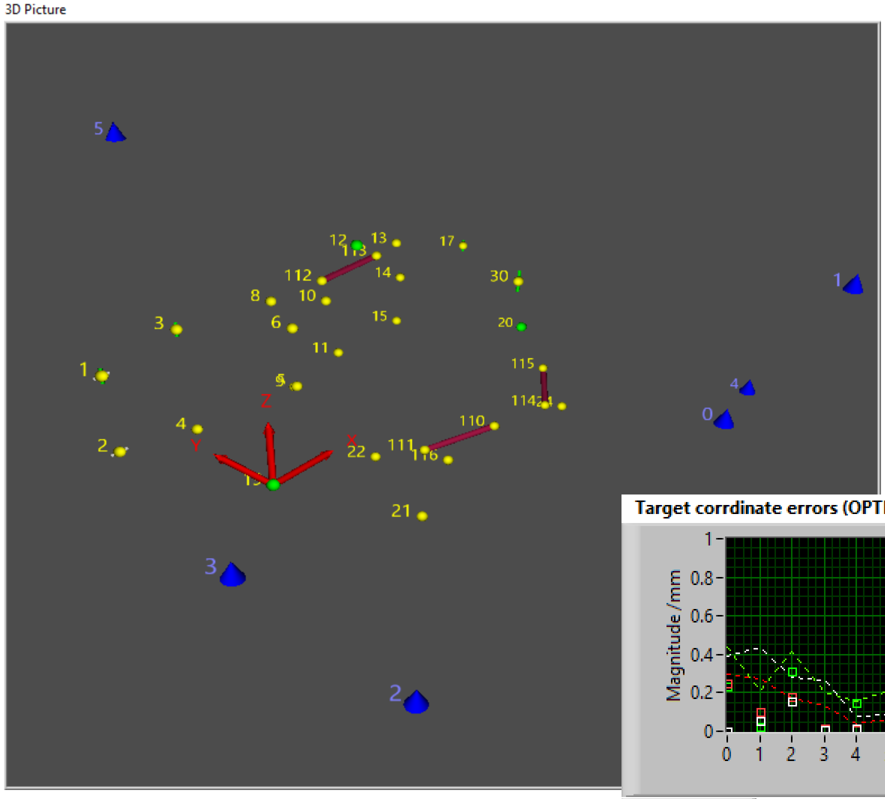


Range residuals /mm



Scale bar length /mm OPTIMUM	OPTIMUM - AT960-mr /mm	Scale bar length /mm AT960-mr
999.7884	0.089	999.8775
999.9054	0.032	999.9374
999.8871	0.045	999.9319

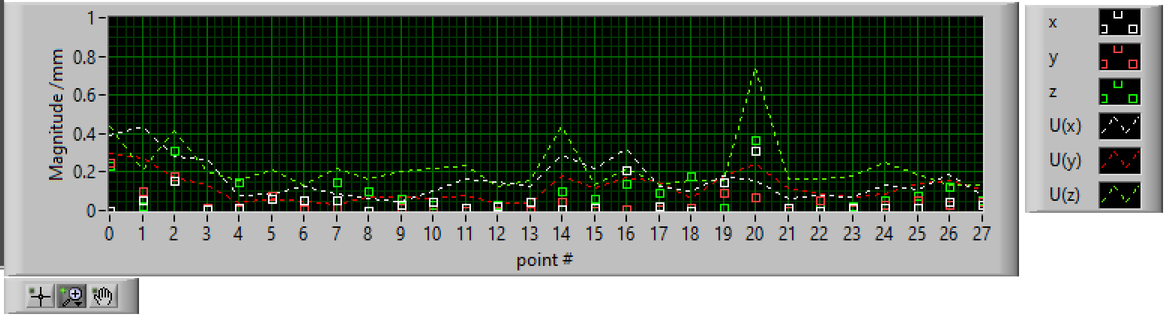
Simulated additional Sensor



- Additional sensor
- Uncertainty reduced by ~3-5x
- Optimisation of geometry could improve further

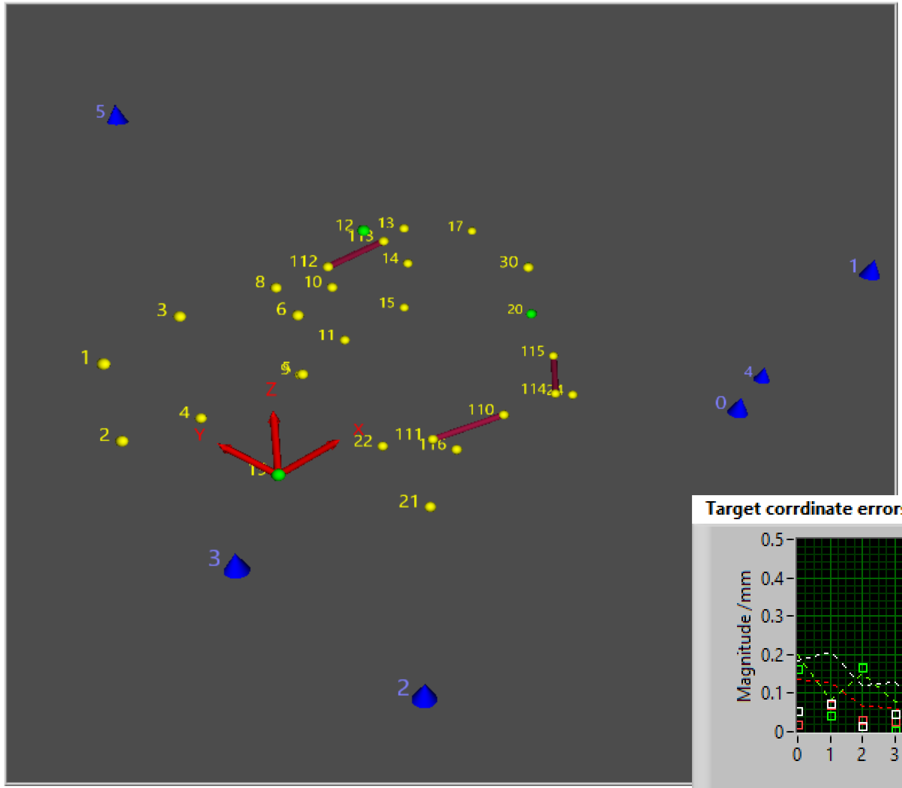
Scale bar length /mm OPTIMUM	OPTIMUM - AT960-mr /mm	Scale bar length /mm AT960-mr
999.9084	-0.031	999.8775
999.9099	0.027	999.9374
999.9215	0.01	999.9319

Target corrdinate errors (OPTIMUM - Laser Tracker) and expanded uncertainties (2σ) /mm



Simulated with reduced range noise

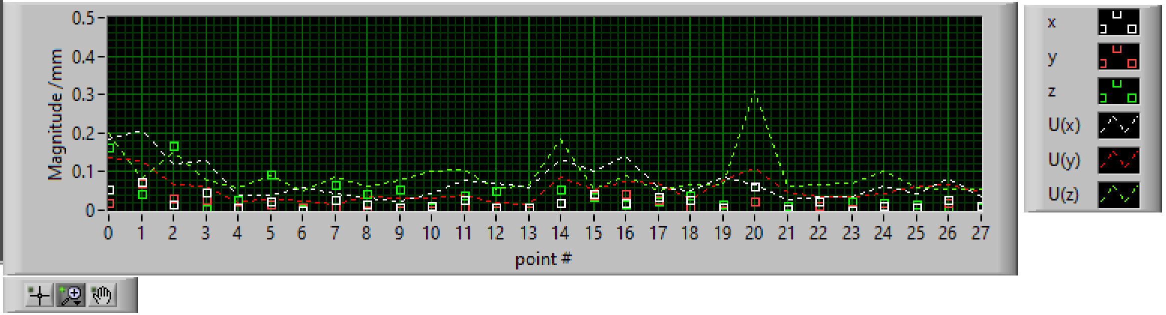
3D Picture



- Reduce range uncertainty to 10 µm, in-line with expected improvements with additional hardware
- Uncertainties reduce to < 100 µm

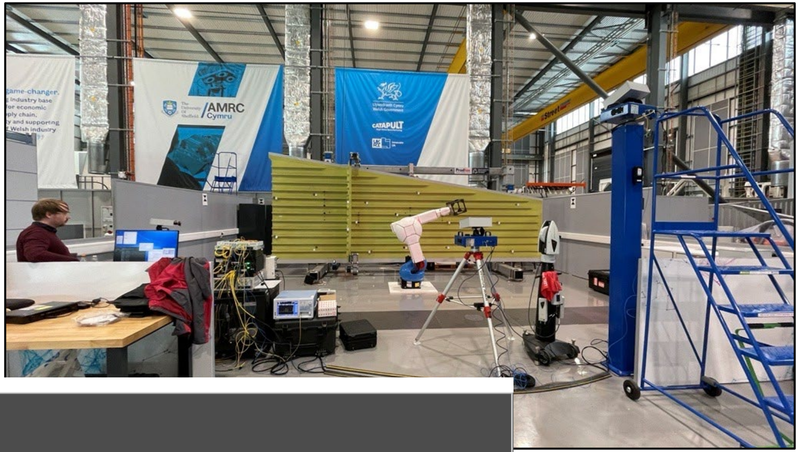
Scale bar length /mm OPTIMUM	OPTIMUM - AT960-mr /mm	Scale bar length /mm AT960-mr
999.8987	-0.021	999.8775
999.9479	-0.011	999.9374
999.9224	0.0094	999.9319

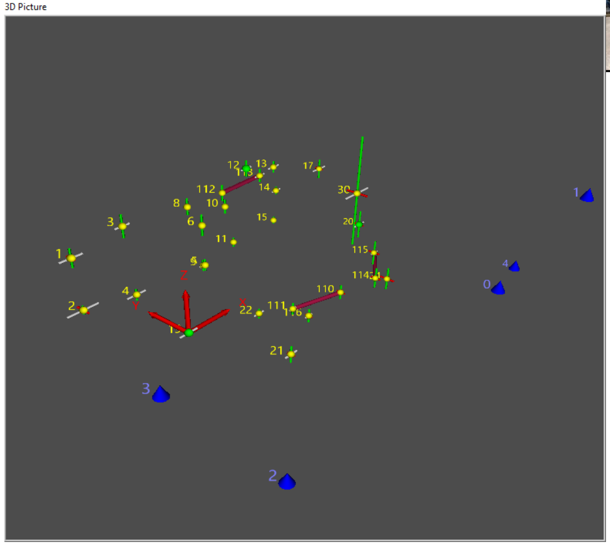
Target corrdinate errors (OPTIMUM - Laser Tracker) and expanded uncertainties (2σ) /mm



Conclusions from initial test results

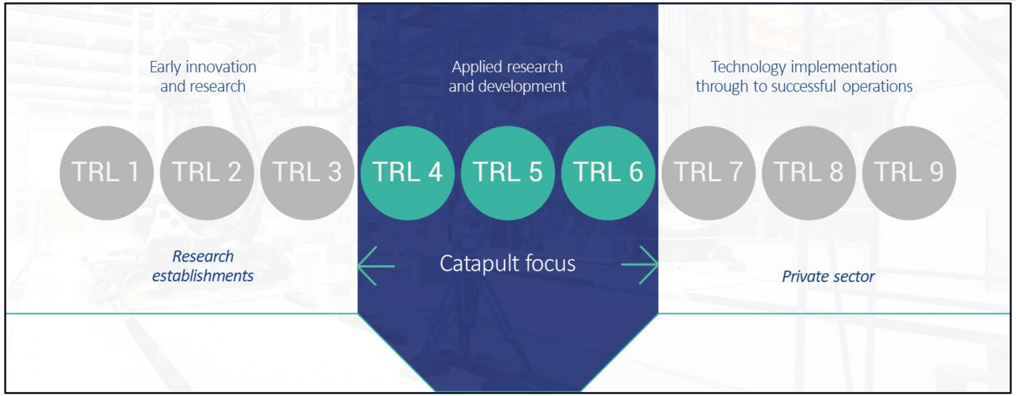
- Range residuals show a standard deviation of 20 μm.
  - Range noise suppression hardware should improve this in the near future
- Simulated measurement results for 5 sensor setup consistent with observations
  - suggesting the model is a good representation of reality
  - No obvious un-modelled systematic behaviour (within current noise limits)
- Uncertainty achieved depends on the number of sensors deployed and the geometry of the setup.
  - More sensors better
  - More targets better
  - Better to have sensors all round the measurement volume
- Achieving <100 μm (k = 2) volumetric uncertainty believed to be achievable soon.
- The system tells us what the uncertainty is with confidence
  - See target ID 30 in 3D plot

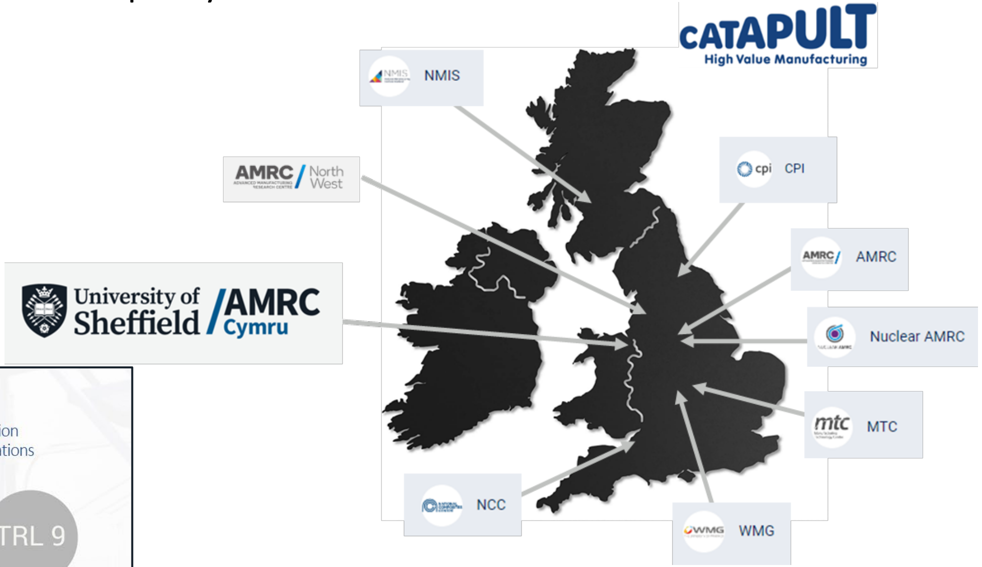




AMRC Cymru

Introduced to support the region's manufacturing community access advanced technologies to drive improvements in productivity, performance and quality.



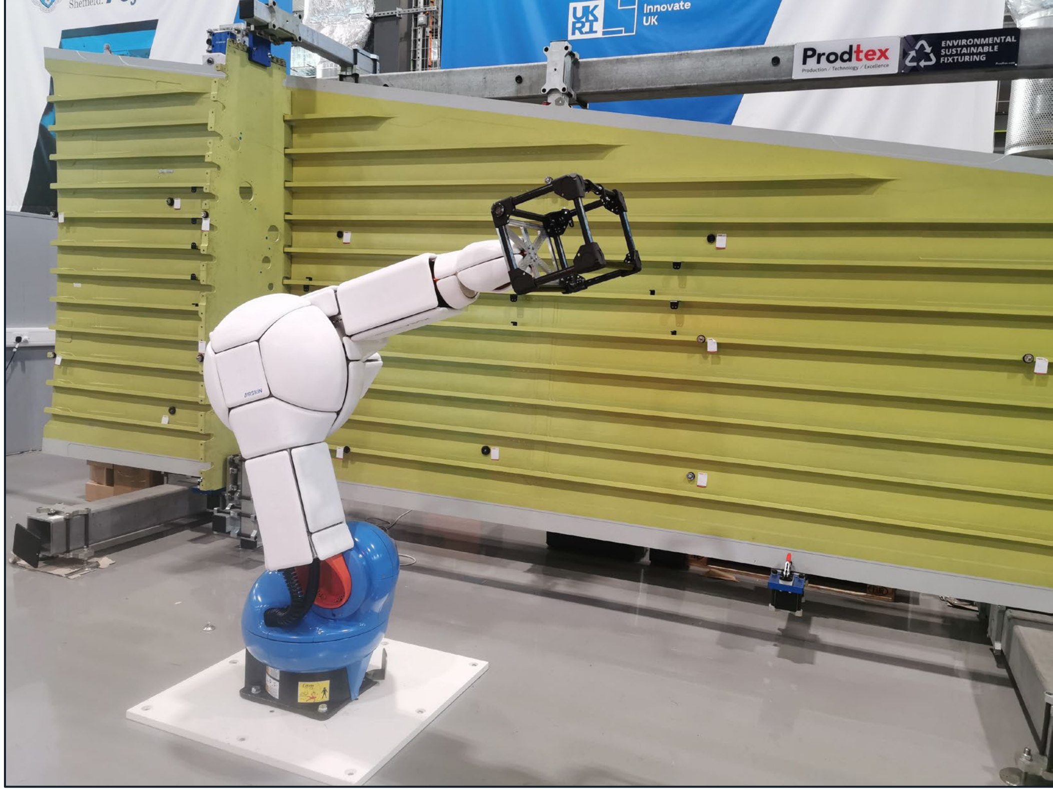


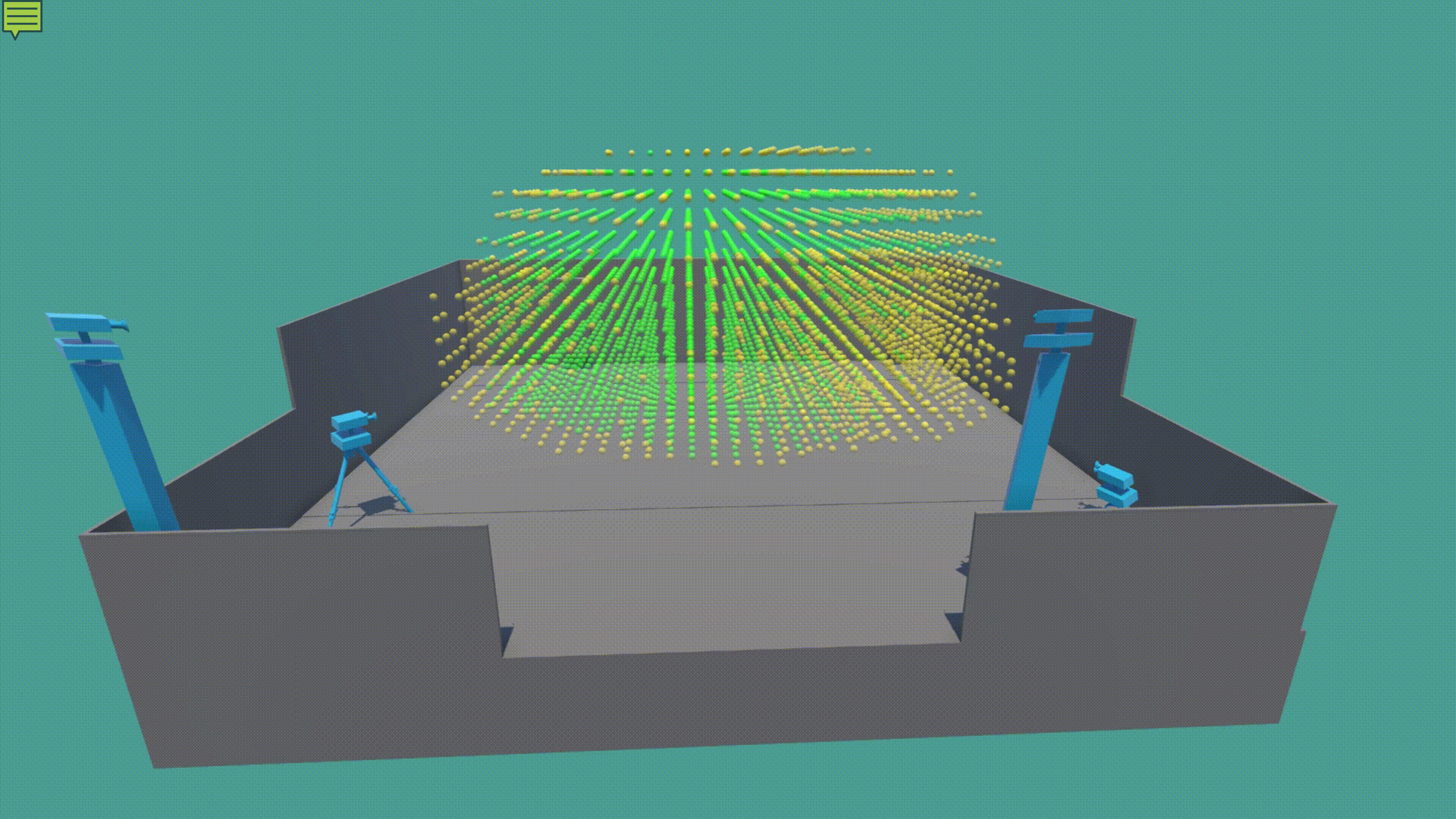
Key themes:

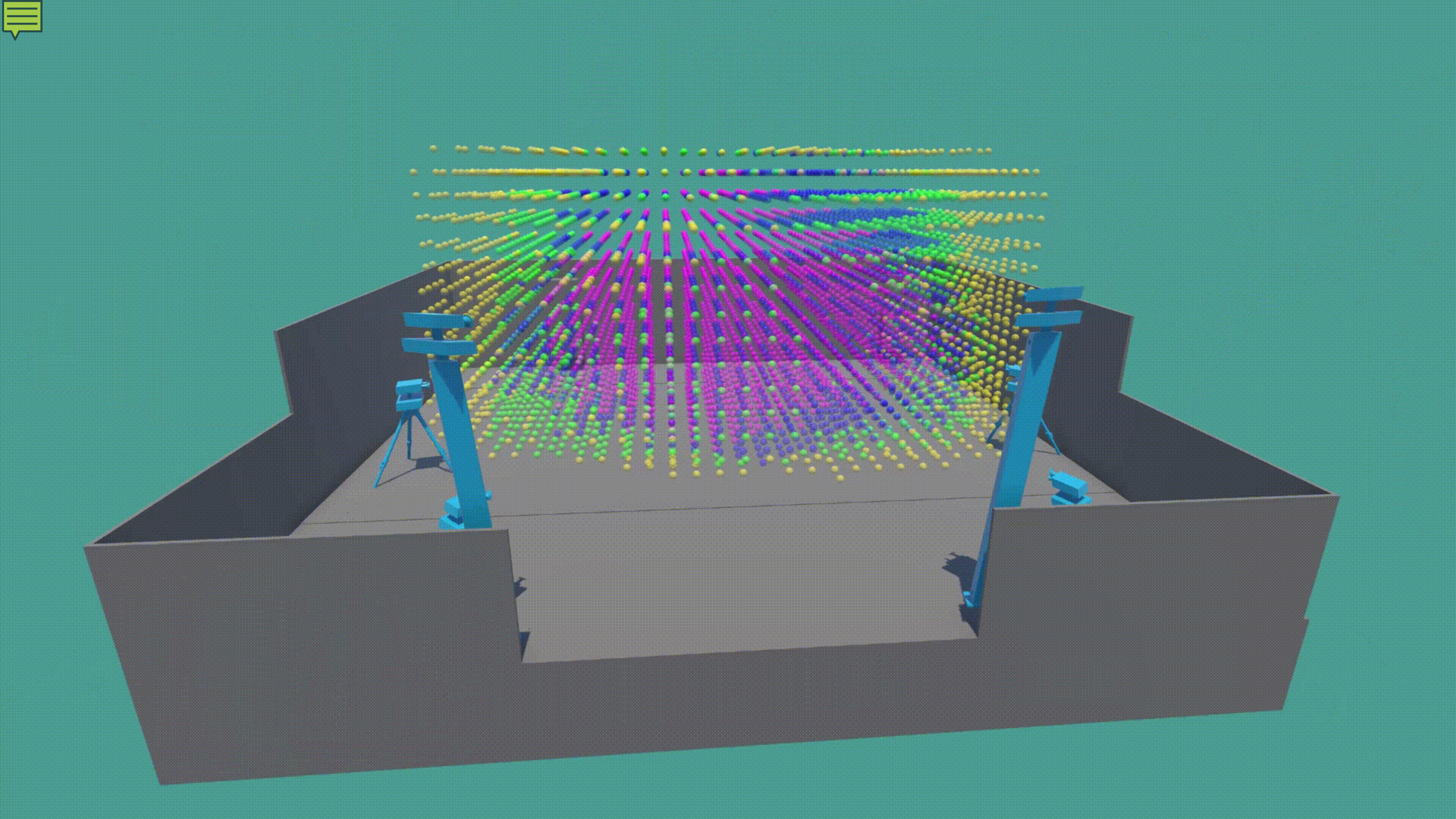
- Design
- Automation
- Manufacturing Intelligence

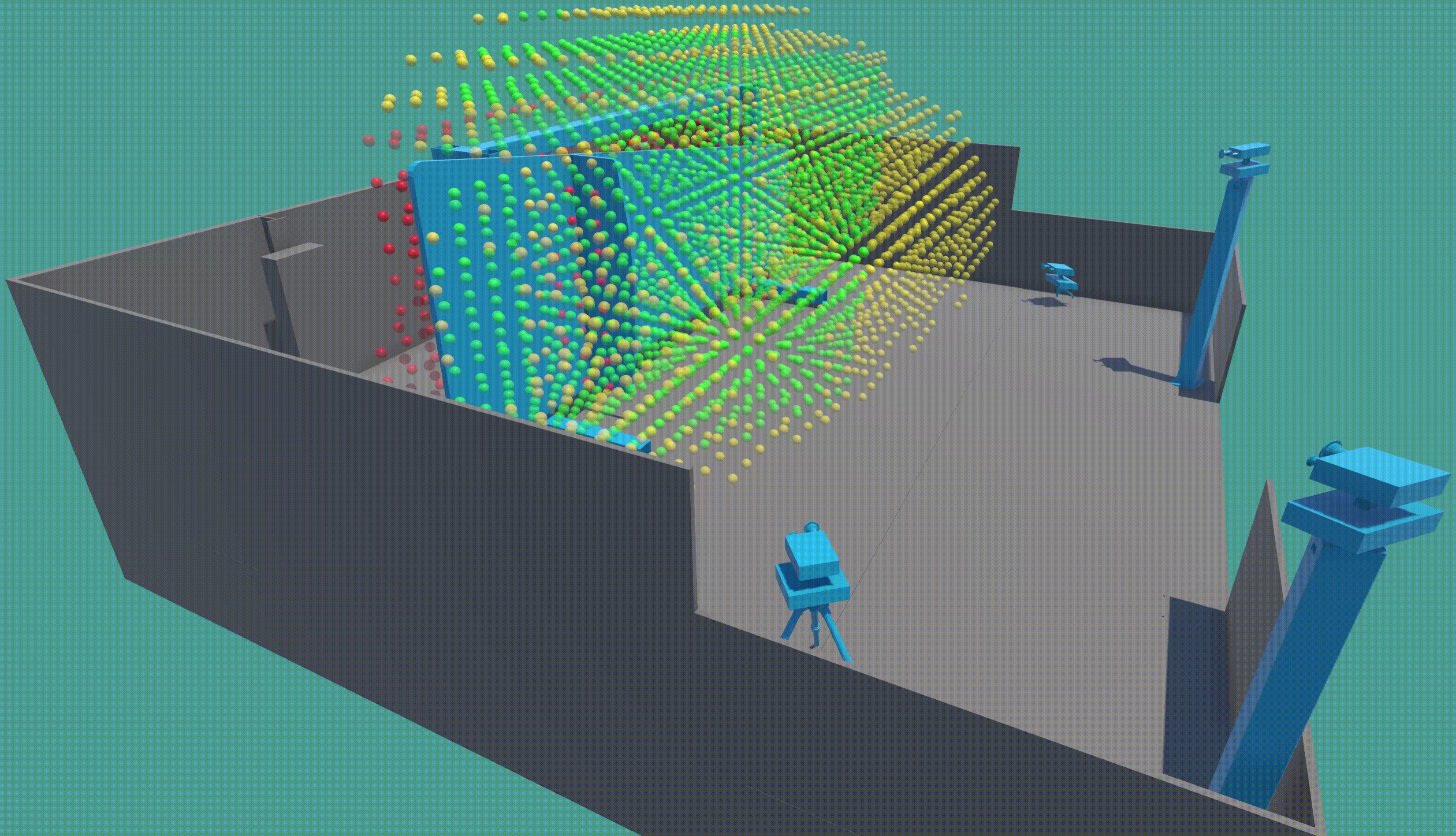
Application:

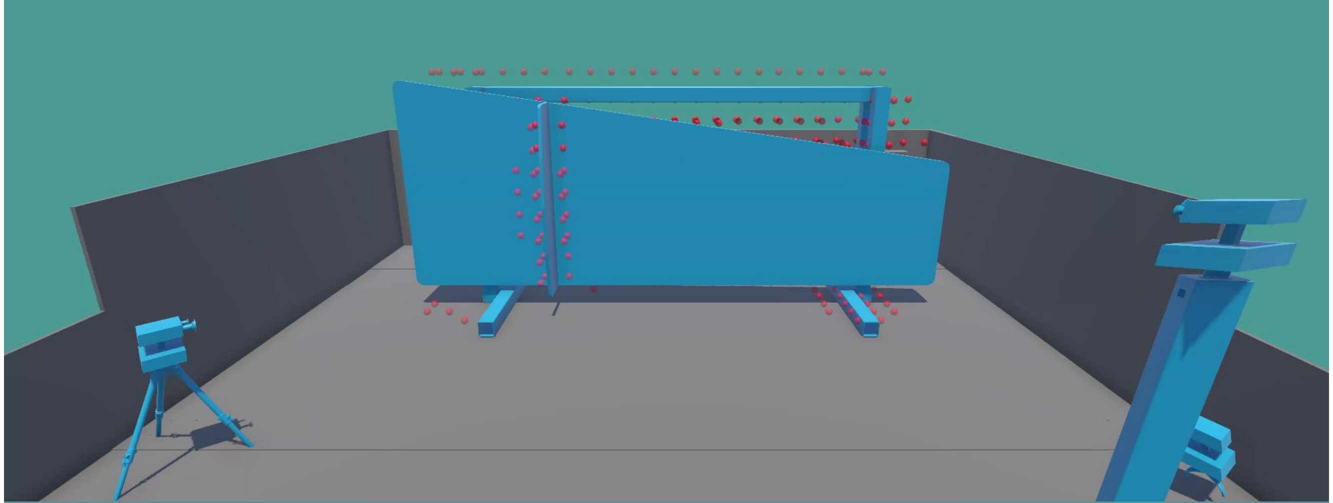
- Automation
    - Serial arm / gantry robots
    - Large machine tools
- Jigs / fixture
    - Certification
    - Monitoring
    - Re-configuration
- Process monitoring
    - Continuous monitoring of process
    - Alignment of large assemblies
    - Dynamic metrology assisted machining, assembly and automation.





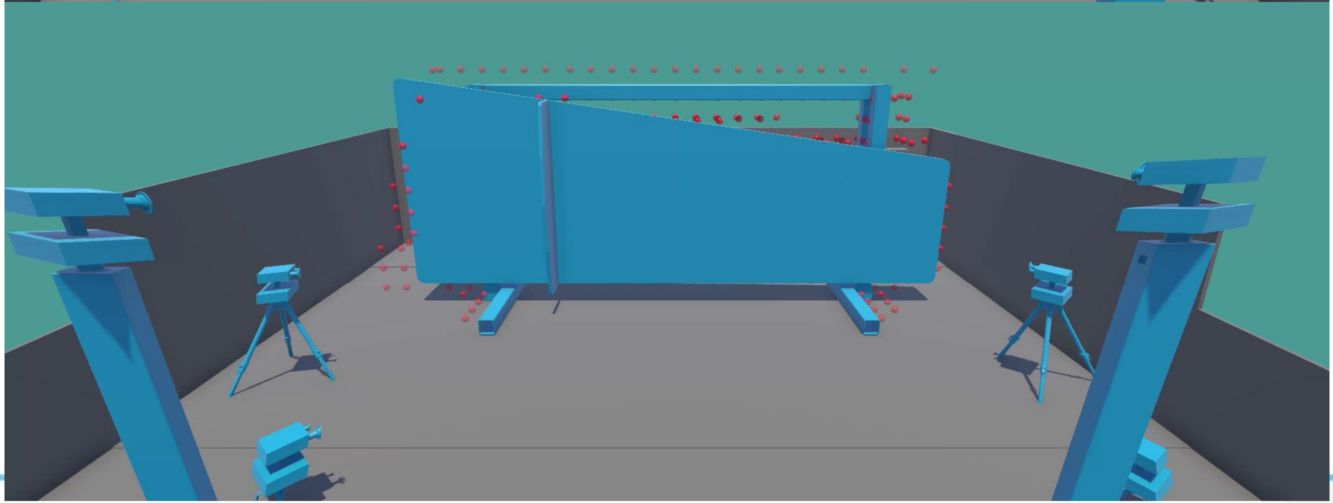




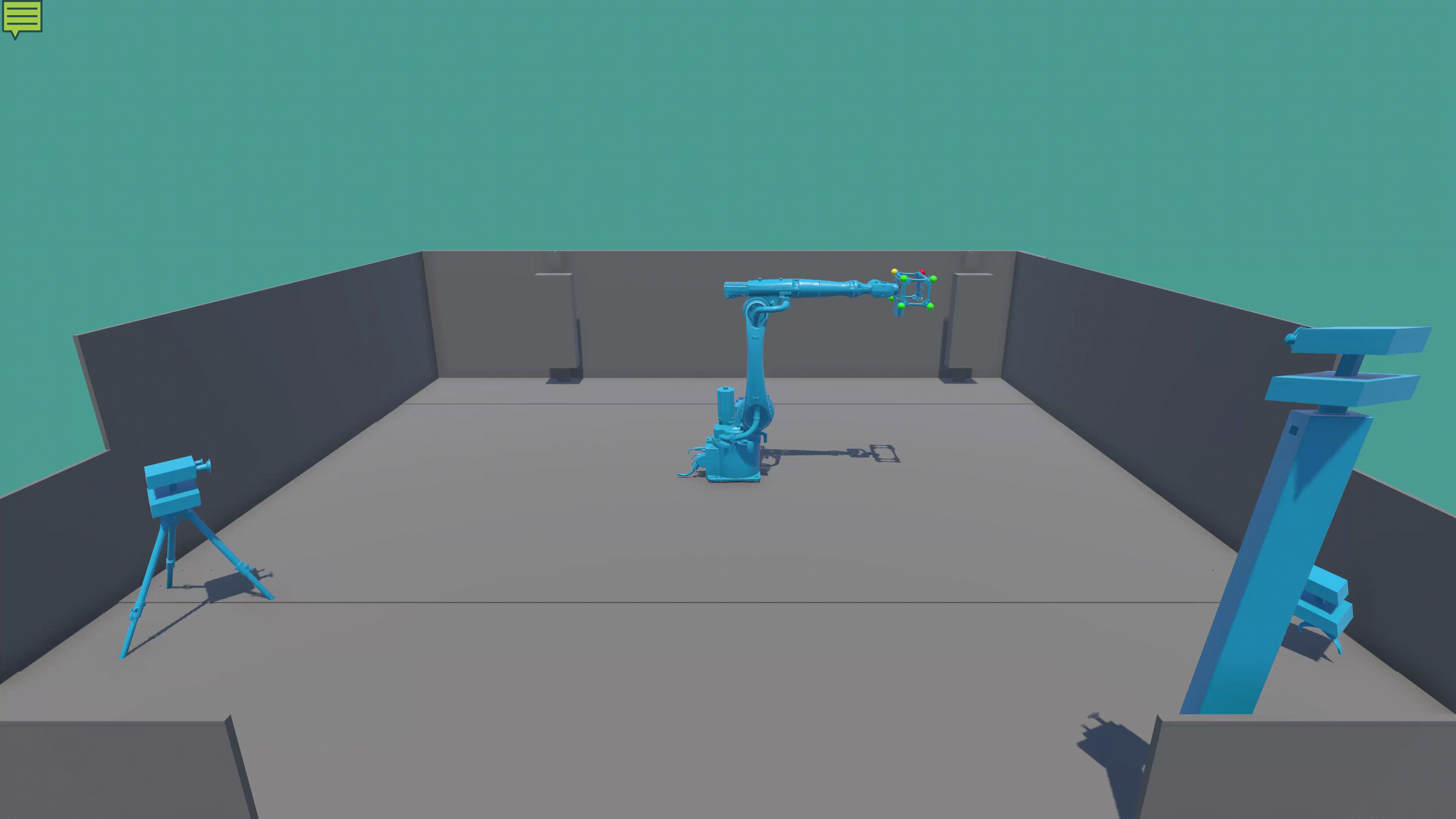


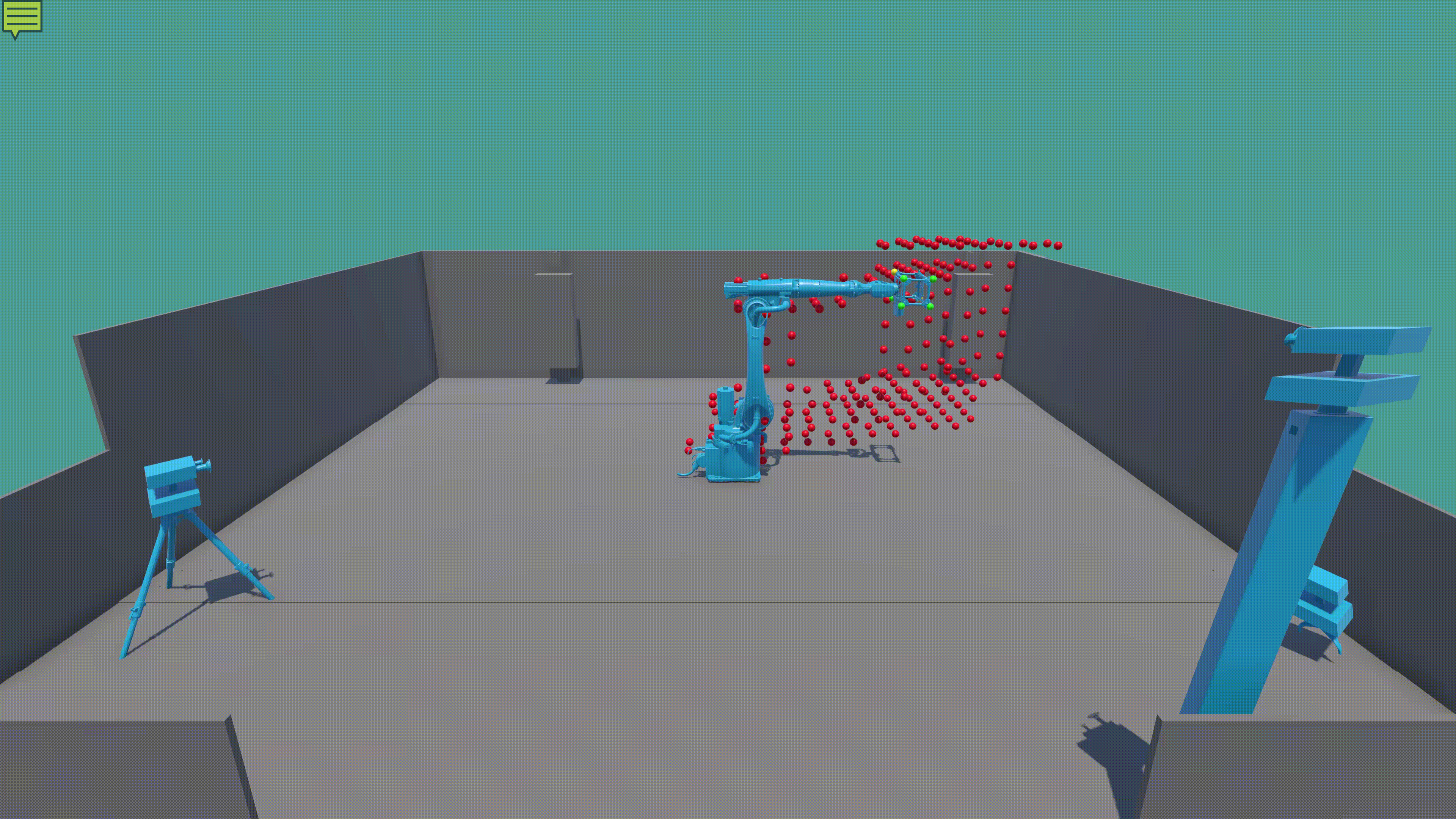
4 sensor network

Line of sight issues



6 sensor network





Next Steps:

- NPL and AMRC Cymru working closely to develop and test the OPTIMUM system
- ‘Optimise’ sensor positions for future experiments and applications
- Develop simulation capability to include uncertainty estimation
- Test 6 DoF accuracy for automation / robotic applications.

Thank you.

For further information please contact or visit:

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