Final Publishable JRP Summary for IND53 LUMINAR
Large Volume Metrology in Industry

Overview

The project has successfully tackled the most critical needs expressed by a range of users of Large Volume Metrology (LVM) by developing a range of new dimensional measuring instruments, new ways of compensating for thermal and refractive index distortions, new measurement facilities and updated modelling software, all designed for *in situ* operation in large volumes. The new (prototype) instruments have been developed, inter-compared and successfully tested and demonstrated in both laboratory and industrial locations. The instruments are based on a range of different principles, targeting different application areas. Outputs from the project include instruments, techniques and new knowledge as well as many technical publications and presentations and five patents (two of which are already granted). Selections of stakeholders have already expressed a desire to use or further develop several project outputs and opportunities for commercial and scientific exploitation (*i.e.* as commercial instruments or collaboratively developed facilities) are already under discussion with a range of organisations. Some of the new facilities, such as the improved 50 m tunnel are already available.

Need for the project

In many high value industries and science & healthcare facilities, large objects, assemblies, equipment and facilities are manufactured or used, often at high cost. In order for these to operate correctly, control of position, dimensions and/or shape of key components at the tens of micrometres level has to be performed within large volumes (hundreds of m^3), often in non-ideal environments. Better measurement generates significant advantages such as: better accuracy of aircraft wing and fuselage manufacturing reduces the amount of excess material required (‘shim’) saving weight and fuel-burn, and enables more aerodynamic designs to be achieved (*e.g.* natural laminar flow for better fuel efficiency); better traceability to the SI ensures compatible component dimensions (*e.g*. airframe sections) when sourced from multiple countries (*e.g.* Airbus operational model); particle accelerators (e.g. CERN’s Large Hadron Collider) and advanced energy experiments/facilities (ITER, ESRF) as well as beam-based therapy systems in healthcare require alignment of components over hundreds of metres to hair-width tolerances in order to function. In all these scenarios, the measurement is not performed at a laboratory, but on the shop floor, *in situ*, in non-controlled environments, making it difficult. To achieve these requirements, users of so-called Large Volume Metrology (LVM) systems require these systems to: measure structures which are at uncontrolled temperatures and compensate for thermal expansion; cope with large measurement datasets with low uncertainties and ideally at high speed and low cost; compensate for errors introduced by airborne refraction; provide dimensional traceability to the SI metre; be portable; and ideally assist the operator in calculating the total achieved measurement uncertainty. LVM makes use of a number of optical techniques (laser tracking, photogrammetry, interferometry, *etc*.) to determine position and dimensions of large objects but existing commercial LVM tools cannot achieve all or even some of these requirements, across all ranges and technologies. A consortium of end users identified and collated their key issues with LVM and the top four issues became objectives for this research project. (Other issues were left for future work).

Scientific and technical objectives

The project had four objectives designed to address the most critical issues common to a wide range of end users of LVM. These objectives were:

1. To develop several new measuring tools and techniques that bridge the gap between photogrammetry and laser trackers and are capable of operation in typical industrial LVM environments, based on several different operating principles, to maximise the range of applications where they can be used, over volumes of 10 m × 10 m × 5 m with a target accuracy of 50 µm.

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2. To develop new traceable absolute distance meters to operate over ranges of at least 20 metres, specifically a user friendly portable device and a system that will be built into a laser tracker.
3. To develop both line-of-sight refractive index measuring systems (one standalone and one that will be built into a laser tracker) as well as a novel network based system that can measure refractive index effects over a 3D volume. These systems will enable on-line compensation of refractive index effects in industrial environments over volumes up to of 10 m × 10 m × 5 m with a target accuracy of 1 part in 10^7.
4. To undertake the necessary modelling to understand and predict how large multi-component structures (such as aircraft wing segments) behave in non-ideal measurement environments. This will be supplemented by in situ dimensional and thermal measurement data at critical points.
5. To verify and demonstrate the capabilities of the developed new technologies, instruments and approaches – mixing measurements at project-Partners, with those in real-world industrial environments, and demonstration of how traceable large volume metrology in industrial environments can be achieved practically.

Results

Development of innovative measuring systems which bridge the gap between photogrammetry and laser trackers, working over volumes of 10 m × 10 m × 5 m, to a target accuracy of 50 µm.

The first objective has been achieved *via* the four systems that were developed. These systems all demonstrate novel metrology concepts and two have attracted interest from potential commercial manufacturers/adopters.

(1) A prototype system based on intersecting planes (*InPLanT*) which uses linear axes separated from the harsh environment. This delivered repeatability of 45 µm in an industrial on-site test campaign using short versions of two measuring axes simulating a 10 m × 10 m area.
(2) A prototype system similar to videogrammetry but using spherical targets and through-the-lens laser illumination. This was tested in a lab environment and achieved 100 µm accuracy over 3 m ranges.
(3) A system based on frequency scanning divergent beam interferometry which demonstrated an accuracy of 50 µm over small (1 m^3) volumes. This system was then developed further into:
(4) A longer range system, again using frequency scanning interferometry (FSI), which was demonstrated at 10 m ranges in laboratory and industrial environments. Hardware failure during final testing limited the accuracy to 100 µm but earlier tests indicated that 50 µm or better will be possible.

Development of novel absolute distance meters which are intrinsically traceable to the SI and which operate over tens of metres range.

The second objective has been achieved *via* the two new systems that were developed together with an improved test facility.

(5) A portable telemeter based around cheap off-the shelf components operating at 1550 nm wavelength which could measure over ranges of 50 m with a resolution and accuracy around 2 µm, tolerant of beam break, and easy to operate.
(6) A tracking interferometer with absolute distance determination based on multiple wavelength interferometry, achieving absolute distance measurement with 60 µm standard deviations over a 40 m path length (in IFM mode the device operates at around 1 µm + 0.1 µm/m uncertainty).
(7) The 50 m tape bench facility at GUM was upgraded with additional temperature, pressure and humidity sensors together with heating circuits, to simulate an industrial environment, to allow for testing of outputs (6) to (8) against a compensated laser interferometer.

Outputs (5) and (6) were then further enhanced under objective 3 as outputs (8) and (9).

Development of a method to provide on-line compensation for refractive index effects in ambient air in industrial environments, targeting 10^{-7} accuracy over a volume of approximately 10 m × 10 m × 5 m.

The third objective has been achieved *via* three approaches that were successfully developed.

(8) The portable telemeter was fitted with a second wavelength at 785 nm which enabled it to achieve 500 µm accuracy in refractive index compensated distance measurement at 50 m range.
(9) The tracking interferometer had an additional set of wavelengths added and, despite some optical problems, demonstrated agreement with conventional refractive index measurement to within 5×10^{-7}.

(10) A range of photogrammetry tools (multi-spectral imaging, digital axicon camera, *MathCad* refraction analysis, volumetric refractive bundle adjustment software) were developed and combined into a system which can perform photogrammetric analysis of images with refraction modelling and signal environmental instability across large volume manufacturing spaces.

Modelling, understanding and predicting the behaviour of multi-component assemblies (up to 5 m dimension) in non-ideal environments (5 °C temperature deviation). LVM has to work *in situ* in factory environments where the temperature is uncontrolled and not at the standard value of 20 °C

The fourth objective has been achieved *via* two key outputs

(11) A hybrid thermal compensation scheme was developed and implemented. In this scheme data from a sub-set of dimensional measurements is fed back into a finite element model analysis together with temperature data, to iteratively improve the accuracy of the FEA simulation. The model can then be used to perform thermal compensation of the entire assembly/structure.

(12) A test component/assembly, typical to aerospace manufacturing, was designed instrumented and used as a first stage test of the hybrid technique in a laboratory environment. The technique achieved an accuracy better than linear expansion theory and better than single probe-compensated laser tracker measurements.

Verification and demonstration of the capabilities of the developed new technologies, instruments and approaches – mixing measurements at project-Partners, with those in real-world industrial environments, and demonstration of how traceable large volume metrology in industrial environments can be achieved practically

The fifth objective has been achieved *via* three measurement campaigns.

(13) An inter-comparison of outputs (5, 6, 8, 9) was performed at project-Partner GUM using their new facility (7). This allowed verification of the ultimate accuracy of these new instruments.

(14) Output (4) was taken to project-Partner PTB and tested in their Reference Wall facility, allowing a test of the technique's ultimate accuracy in a good environment.

(15) Industrial testing/demonstration of outputs (1, 4, 5, 6, 8, 9, 10 & 11) took place at Airbus, Filton, UK in a live factory environment. This included measurements on a 45 m long diagonal path across the side of the building (maximum range available indoors) and on the 12 m high wing test rig. All 7 project outputs which were taken to Airbus were able to make satisfactory measurements in this location where there were temperature gradients, vibration and acoustic noise present.

Additional Results

A project researcher from the Karlsruhe Institute of Technology was able to tackle an additional objective by significantly advancing knowledge in the field of dynamic measurements in LVM. Outputs include: real-time uncertainty calculation for dynamic measurements (including a laser tracker uncertainty model for dynamic measurements), detection of and techniques to avoid poor solutions in multilateration networks, and detection of dynamic path deviations of robots, in real-time.

Actual and potential impact

The project has already demonstrated impact and interest from end users across a selection of fields and this has been growing in momentum. However, the greatest impact will occur when the project outputs have been developed into commercial instruments and when discussions on future collaborations have culminated in new collaboratively developed facilities such as that being discussed with CERN.

Dissemination

Ten publications have been submitted to peer-reviewed journals (five already published) and we have made twelve inputs to standardisation and metrology committees (EURAMET, ISO, VDI/VDE, UNI) with one standard already citing work from the consortium partners. The project work and outputs have been presented at 32 conferences and project staff have given eight training sessions (six of which were for external audiences of end users). Three trade journal articles have been used to publicise the work in industry and we have conducted a two week long successful onsite measurement and demonstration campaign at Airbus, Filton as well as two successful inter-partner measurement campaigns.

Early impacts

Five patents have been submitted based on the work of the project and two have already been granted: DE 10 2010 032 407 B3 and DE 10 2015 203 697. These patents have been the basis of two project partners entering into partnership discussions with two commercial organisations, to exploit the developed technology; a partnership agreement is close to signature. An existing €0.5M collaboration with the University of South Wales changed direction as a result of the project (*i.e.* the project outputs showed a better route for the research direction). The variable temperature environment tape bench with improved sensor systems is already operational at GUM and has been used by two project partners.

The UK national project 'The Light Controlled Factory' (€6.93M funding value) is taking several outputs form the LUMINAR project (the work of University College London and the University of Bath) and developing them further into a full technology demonstrator. Demonstration of the FSI system to CERN has resulted in a request from them to collaborate to develop the FSI system for their use in periodic realignment of the Large Hadron Collider and in future alignment of its successor; CERN have already purchased target spheres for the FSI system for use in alignment tasks. The *InPLanT* system has been demonstrated to a machine tool company and this has led to a request to explore further development of the technology. There has been a strong and potentially highly valuable request from a commercial organisation to enter into collaboration to develop and exploit the FSI system. There has also been an early discussion with a commercial organisation to exploit the tracking interferometer. The Capabilities and Potential report (IP Exploitation Plan) for the project outputs lists 23 items for potential commercialisation or exploitation ranging from cheap environmental loggers based on the Raspberry Pi computer, to exploitation of a developed laser tracker uncertainty mode for dynamic measurements which can be used to improve the accuracy of hand-carried laser tracker targets.

<u>Longevity</u>
A new collaboration between University College London and Airbus in structures testing will be using work from the project. The National Physical Laboratory has received a request from a national (UK) funding body to submit proposal for further development of the FSI system into a facility for use by aerospace companies. A plan to set up a calibration service for large coordinate measuring machines using the tracking interferometer is already underway at PTB and NPL is already continuing to improve the FSI prototype system using national funding.

<u>Wider potential impact – meeting high-level societal needs</u>
Assuming exploitation routes already started are successfully concluded (new LVM services at GUM, PTB, NPL are used by customers; development of INRIM, PTB, NPL outputs taken up by commercial companies; CERN takes delivery of an FSI system; UCL & UBATH outputs developed further in the Light Controlled Factory demonstrator produce eventual update), the project will have several direct impacts on many sectors:

- Instrumentation: a range of instruments will become available, giving accuracy approaching that of laser trackers but with SI traceability and ability to measure more targets simultaneously and compensate for refractive index effects. At around €100k minimum each unit, commercial instrument sales could lead to significant new EU turnover at the commercial technology partners.
- Science: the Large Hadron Collider's successor will be aligned using technology based on the project research – without accurate alignment, the largest machine ever built will not work - $7.8 billion direct costs plus 13,000 person years of contributed effort would be wasted.
- Transport: aerospace manufacturing will be using measuring systems coming from project outputs to perform *in situ* testing of new wings without the need to pause tests to wait for measurements to be made statically; live monitoring of wing assembly jigs will lead to the accuracy improvement (400 µm down to 100 µm) required for next generation aero-structures, saving at least 100 kg in weight on each aircraft built and 122 tonnes of fuel/aircraft *p.a.*, leading to a reduction of 38.5 tonnes of CO_2 /aircraft *p.a.* and reduced overall operating costs of around €5.5k per aircraft p.a.
- Advanced manufacturing / Industry 4.0: factory-wide metrology system will be based at least partly on combinations of technologies from the project, enabling automated robotic assembly and manufacture at necessary accuracy level. A recent report concluded that an industrial-scale version of the Internet of Things, i.e. Industry 4.0, could add $14.2 trillion to the world economy over the next 15 years. Advanced large scale manufacturing will require the advanced metrology from this project.

This project has produced a range of new techniques, instruments and knowledge that will enable LVM users to deliver their own advanced products, facilities, and measurement services which will all make contributions to society either by being more efficient, or generating higher impact/ new science, using fewer manufacturing resources & creating less scrap/waste, *etc*.

"We Shape Our Tools, and Thereafter Our Tools Shape Us"

List of publications

Journal papers

- Warden M S, Precision of frequency scanning interferometry distance measurements in the presence of noise,*Applied Optics*, **53** 580-558 (2014)
- Ulrich T, Uncertainty modelling of real-time observation of a moving object: photogrammetric measurements,*Metrologia*, **52** (2) 201-213 (2015)
- Martinez J J, Campbell M, Warden M S, Hughes E B, Copner N, Lewis A, Dual-sweep frequency scanning interferometry using four wave mixing, *IEEE Photonics Technology Letters*, **27** (7) 733-736 (2015)
- Ulrich T, Uncertainty Estimation for Kinematic Laser Tracker Measurements, *IEEE Explore*
- Lewis A, Campbell M, Stavroulakis P, Performance evaluation of a cheap, open source, digital environmental monitor based on the Raspberry Pi, *Measurement*, **87** 228-235 (2016)
- Robson S, MacDonald L, Kyle S, Shortis M R, Close range calibration of long focal length lenses in a changing environment, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci*. **XLI-B5** 115-122 (2016)
- Ross-Pinnock D, Yang B, Muelaner J, Mullineux G, Temperature interpolation in a hybrid approach to dimensional metrology, submitted to *Measurement*
- Meiners-Hagen K, Meyer T, Prellinger G, Pöschel W, Dontsov D, Pollinger F, Overcoming the refractivity limit in manufacturing environment, submitted to *Optica*
- Ulrich T, Analysing Multilateration Measurements to Generate a Ground Truth for Kinematic Laser Tracker Measurements (submitted to *Journal of Geomathematics*)
- Yang B, Ross-Pinnock D, Muelaner J, Mullineux G, Thermal compensation for large volume metrology and structures (submitted to *International Journal of Metrology and Quality Engineering*)

The project also informed end users *via* several trade magazine articles in *Quality Digest*, *Journal of the CMSC*, and *QMT*. In addition we published a Good practice guide on Coping with Thermal Expansion in Large Volume Metrology and gave 32 conference presentations including many at the two premiere conferences in this area, *Coordinate Measurement Systems Conference* (USA) and *Large Volume Metrology Conference* (UK). Full details are in the Final Publishable Report or on the project website (see above).

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