Publishable Summary for 17IND03 LaVA
Large Volume Metrology Applications

Overview

This project targets improved, accurate, traceable measuring systems for operation as Large Volume Metrology (LVM) tools and integration of these tools into a factory coordinate metrology network. The network and tools will be suitable for operation in typical factory environments or for permanent inclusion inside manufacturing systems such as large machine tools, industrial robots, *etc*., in accordance with ISO Geometrical Product Specification (GPS) standards. The new tools and technologies will offer better accuracy than existing systems, enhanced uncertainty calculation and budgeting, improved compensation methods for air refractive index, and the ability to interface with production and assembly process control, resulting in traceability, efficiency and cost improvements in industries & science facilities relying on LVM.

Need

LVM is often hidden from consumers but is vital for the manufacture and alignment of many items upon which modern life and leading-edge science depend. LVM is necessary because the item or items to be measured or aligned are too large to fit within conventional measuring machines or too bulky to transport to a calibration laboratory – they must be measured *in situ*, often in non-cooperative environments. Aviation, the biggest sector user of LVM, needs to deliver new, lighter aircraft but the metrology tools to achieve the smaller tolerances on large parts do not exist. Existing industrial factories *e.g.* automotive, inspect only ~1 % of items and do this offline as inline tools are slow and not traceable, leading to inefficiency. Industry 4.0 and Digital Factories pre-suppose that Automatic Guided Vehicles (AGVs) and robotics in factories can achieve necessary positioning and alignment accuracies with real-time control but this is far from being available. The *Institute For Robotics* and *IEEE Robotics and Automation Society* state that real-time feedback is a fundamental requirement for *e.g.* robotic drilling machines where accurate metrology over large volumes is needed, but this is not yet delivered (typical robot: 0.5 mm accuracy, typical required tolerances: 0.1 mm). Current large volume factory metrology networks are not sufficiently accurate and local solutions based on laser trackers are too expensive or too slow and there is no integration between localised metrology and factory-wide metrology, impeding the in-process transition between different metrology devices. Existing LVM tools (*e.g*. laser trackers, laser radar) use single point refractive index compensation, therefore fail to deliver claimed accuracies in real-world factories where temperature gradients exist or change quickly. Large machine tools must be error mapped (‘calibrated’) to achieve specification but this is expensive, time-consuming and undertaken only occasionally, leading to accuracy or downtime issues. There are demands for additional novel LVM tools based on novel and/or cheap sensors and techniques for the ever-expanding range of end user scenarios *e.g.* higher accuracy (cheap) photogrammetry, and absolute distance 3D coordinates at long ranges, useable in harsh environments. Additionally, there is a need for novel systems to bridge the gap between expensive but accurate laser trackers and cheaper but less accurate photogrammetry.

Objectives

The project aims to deliver a range of improved and/or novel LVM systems, capable of *in situ* operation in factory environments, and to network several of these systems together to provide the metrology infrastructure for a digitally-enabled Future Factory demonstrator. To achieve this the specific objectives are:

1. To improve the metrology capability of Frequency Scanning Interferometry (FSI)-based techniques beyond the state-of-the-art by removing the current accuracy limitation of the necessary gas cell frequency standard through improved spectroscopy.

2. To develop novel and validated LVM methods for simultaneous metrology of multiple items at different scales and accuracies including: (i) close range precision tracking of robotic systems, (ii) medium

accuracy 3D positioning within whole factory volumes and adjustable accuracy tracking for Autonomously Guided Vehicles carrying workpieces.

3. To develop and demonstrate techniques for *in situ* high accuracy (~10^{-7}) air refractive index determination with factory-sized volumes.
4. To develop models to simulate self-organising production and assembly based on digital information from process-integrated measurement systems and to apply these methods to other project outputs to produce an industrial scenario demonstrator.
5. To produce equipment and validated methods for evaluating the performance and compensating for the errors of large machine tools (> 50 m^3); the cost and operability must be adequate to leave the equipment on board or on the shop floor.
6. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations *e.g.* ISO/TC 213, and end users *e.g.* the automotive and aerospace industry, through operation of one or more demonstration activities, in addition to publications, training, and stakeholder interaction.

Progress beyond the state of the art

A preceding project ('LUMINAR') delivered several outputs such as prototype instruments and new approaches which re-defined the state of the art at the time, and this project will take further action *e.g.* the FSI system which provides state of the art coordinate metrology of multiple targets simultaneously will be updated with latest data from this project to deliver better length measurement accuracy and hence better coordinate uncertainty; the *InPlanT* system will be developed into a novel low cost system for use on large machine tools (lower cost than existing commercial systems enabling it to be embedded and remain in a machine for its lifetime); the absolute distance telemeters which delivered absolute position with refractive index compensation but required long paths for accurate operation will be developed into newer systems capable of operating over shorter path lengths and being operated in a multilateration network.

Additionally, new research in this project will improve on state of the art in other areas, *e.g.* refractive index measurement will be transformed from a single point, low rate, to large range higher accuracy, higher speed; novel instruments will benefit from provision of a unified interface and integration into a cooperative metrology network demonstrator; a multi-scale variable uncertainty photogrammetry network will deliver locally precise coordinates (*e.g.* for robots, AGVs) within a much larger medium accuracy factory coordinate metrology network.

A new, model-based approach will be developed to obtain a protocol-agnostic interface description, in which an LVM instrument is viewed as an abstract object-oriented system consisting of one or more base units and mobile entities. The model's object-oriented structure will allow a realization of the interface in arbitrary structured communication protocols by adhering to fixed data transformation schemes. Moreover, the transformation between different protocols decouples software requirements of measurement instruments and actors, generally allowing an efficient integration into manufacturing production systems than can be achieved today where the end user has to grapple with a multitude of proprietary interfaces and software. At the moment, integration of a new LVM device into an existing system requires significant effort; by structuring the device interface using a generalized functional model within the utilized *Internet of Things* protocols, this limitation can be overcome and factories owning multiple expensive LVM instruments can link them together to make a higher density, larger reference coordinate framework, making more efficient use of metrology resources.

Outside of the project, we note that other research groups have been developing optical frequency comb approaches for absolute distance metrology, with some degree of success. However, such systems are currently very expensive due to expensive bought-in components and they have not solved the issues associated with tracking multiple targets at the same time with high accuracy.

Results

<u>To improve the metrology capability of Frequency Scanning Interferometry (FSI)-based techniques beyond the state-of-the-art by removing the current accuracy limitation of the necessary gas cell frequency standard through improved spectroscopy.</u>

Several LVM instruments derive scale and traceability to the International System of units (SI) by scanning a channel of their laser measuring systems through absorption features in spectroscopically pure gas at low pressure. FSI systems which are designed to operate in the ‘C-band’ (1530 nm to 1565 nm) to make use of cheap telecoms lasers, find only one gas species with absorptions across the entire C-band – hydrogen cyanide (HCN). Only one set of historic spectroscopy data exists for HCN and this is not internationally recognised or of high enough accuracy, so LaVA seeks to make multiple, independent, higher accuracy HCN spectroscopy measurements in this wavelength range. Measurements of pressure dependence are also required due to pressure-dependence of absorption features.

HCN gas cell frequency standards at three low pressures have been purchased from a commercial supplier and used in initial tests. However, the available pressure accuracy was found to be insufficient and we now have concerns that the pressure in the cells may not be maintained over the duration of the project so ISI and NPL are having to build their own vacuum systems for controlled filling of HCN gas cells, with lower pressure uncertainty. The components for a dual-comb HCN spectroscopy system at NPL have been identified and orders have been placed for delivery by end April 2020. ISI have designed and constructed their optical setup for linear spectroscopy and have already obtained a linear spectrum from a HCN gas cell. They have also started investigating pressure shift/broadening aspects using a temperature-controlled oven. ISI’s more accurate Doppler-free spectroscopy system has so far showed only a weak absorption signal with low power laser input – tests with a much higher power laser show a better signal. Work continues on sourcing new lasers for the project and improving the Doppler-free signal. RISE are planning their approach to their set of HCN measurements, which will use a tuneable external cavity laser, by making initial tests using acetylene gas cells (which cover only part of the C-band) in anticipation of using the ISI/NPL HCN cells at a later date.

<u>To develop novel and validated LVM methods for simultaneous metrology of multiple items at different scales and accuracies including: (i) close range precision tracking of robotic systems, (ii) medium accuracy 3D positioning within whole factory volumes and adjustable accuracy tracking for Autonomously Guided Vehicles carrying workpieces.</u>

Outdoors, many examples show the ubiquity of GNSS/GPS/GLONASS global positioning systems. However, the equivalent metrology systems, working inside factories, such as iGPS, have some limitations in terms of line of sight and accuracy – they cannot yet achieve the small uncertainty required for precision manufacturing, alignment and assembly tasks within Industry 4.0 facilities. Robots with typical 0.5 mm local accuracy cannot be tracked and repositioned to new locations within factories without re-aligning ad re-calibration after movement. Locally accurate laser scanner systems are not located in a global factory reference frame to sufficient accuracy, and almost all factory-wide LVM systems cannot demonstrate traceability. LaVA’s solution is to deliver a range of ways of delivering simultaneous metrology of multiple items at different scales and accuracies.

Several different systems are being developed including photogrammetry-based approaches and optical tracking systems based on telemeter heads on gimbal mounts coupled using multilateration. The telemeter system is now highly developed. A new piezo-drivel gimbal mount (microradian resolution) has been added for fine angle positioning, completing the engineering of the four measuring heads. The measurement heads are now assessed as contributing only 1.3 µm error in distance measurement. The overall distance measurement uncertainty is 4.5 µm and a new test campaign is having to be devised due to the uncertainty being smaller than the reference system previously planned to use in the test. A first step experimental multilateration measurement (at around 1 m scale), gave standard deviations (on 3D coordinates) below 5 µm. Comparison with a traceable standard shows 16 µm error and 8 µm standard deviation. Latest experiments are working on improving signal from retroreflecting spheres.

For the photogrammetry systems, three approaches are being followed: a long range multi-camera system for covering factory volumes with low cost cameras – here a project partner has filed a patent and has developed LED-based optical targets; a short range traceable camera system for precision tracking of robots with scanner heads – a self-calibration system based on checkerboard imaging has been developed and is being tested; and a traceability route for existing commercial cameras used in industrial applications – a series of high accuracy optically calibratable targets and carbon fibre linear target clusters is in development

To develop and demonstrate techniques for in situ high accuracy (~10^{-7}) air refractive index determination with factory-sized volumes.

All high-accuracy (*e.g.* laser tracker) LVM instruments operating in air are subject to errors caused by air refractive index. Compensation for refractive index is usually performed through measurements of air temperature, pressure and, to a lesser extent, humidity. However, with instrument ranges going from 10 m up to 50 m it is not possible to obtain a true *beam-average* air temperature using single point probes (or even multiple probes) overs such long ranges. This leads to uncorrected errors in laser-based distance measurements. LaVA seeks to perform along-the-beam temperature measurement simultaneous with laser distance metrology, to obtain a more representative air temperature for compensation corrections.

Three approaches are being investigated: a spectroscopic thermometer (based on spectral absorption peaks in oxygen molecules); and two acoustic thermometers utilising speed of sound to sense air temperature. For the spectroscopic thermometer a fully functioning prototype has now been constructed using a laser sweeping at 150 Hz rate. Traceability (to SI second) comes from known absorption peaks documented in an international database (HITRAN), so the system requires no calibration. Using a microcontroller to filter the data and perform all calculation has resulted in correct detection of weak spectral peaks and direct output of beam average temperature. Standard deviations in test results are currently at around 0.2 °C level and in agreement with 3 reference temperature sensors (Pt100) to within 0.2 °C along a 25 m path. The advantage is that the spectroscopic system measures along the beam (*e.g.* of a laser interferometer) whereas the Pt100 sensors are only single point local sensing. Further work is underway to improve the accuracy and prepare for comparison with the acoustic thermometers.

One of the acoustic thermometers is now at prototype stage with new pulse generation and detection – it can currently track changes in air temperature but not yet obtain absolute values. Work continues on this device to increase the signal to noise ration to obtain longer range operation. So far test results suggest < 0.1 °C standard deviation in results and absolute errors ranging from -0.19 °C to +0.02 °C over the temperature range 18 °C to 24 °C at distance up to 16 m. A second prototype system is performing similarly well (0.1 °C resolution, 0.2 °C accuracy) at ranges so far up to 10 m. This device uses a self-calibration technique to calibrate the effective distance from the transmitter to the received. A bi-direction transmitter-receiver pair is being used to compensate for non-static air (*i.e*. variation in air speed not due to temperature).

To develop models to simulate self-organising production and assembly based on digital information from process-integrated measurement systems and to apply these methods to other JRP outputs to produce an industrial scenario demonstrator.

A first approach for a model based on the functional view of a Large-Scale Metrology system has been elaborated and implemented for a Laser Tracker, iGPS and Ultra-wideband systems and was presented at a conference in June 2019 to obtain broader feedback. The process model refers to characteristics of 'mobile entities' which are the main metrology components of LVM systems, *e.g.* laser tracker, photogrammetry targets. The key characteristics necessary for consideration are now elaborated in prescriptive detail. A digital representation containing some samples is being prepared as a prototype. A thorough review of established Internet of Things protocols for digital information sharing has been carried out resulting in a list of key required properties for LVM systems such as messaging pattern, data serialization, authentication and authorisation. Further study has been performed into protocol-agnostic communication patterns to show that they can be condensed into 8 exemplar Actions. Taking these results into account, a modelling scheme based on a set of resource classes has been defined resulting in a proposed overall structure for the instrument model. Consideration of the need for traceability has identified possible interactions with the *SmartCOM* project, for example in the aspect of inclusion of digital calibration certificates into the unified device mode.

A collaborative software repository is being set up for use of project partners that need to interface their systems to the end of project demonstrator. Initial planning for the demonstrator (to take place within the period 28 June – 2 July, at RWTH, Aachen, Germany) is underway. A new laboratory, intended to be the demonstrator location, is being constructed and should feature a 7 m × 14 m clean floor robotic space.

To produce equipment and validated methods for evaluating the performance and compensating for the errors of large machine tools (> 50 m³); the cost and operability must be adequate to leave the equipment on board or on the shop floor.

Geometrical errors (axis misalignments, bending) in machine tools require corrections to be applied in order for the machine to be able to machine workpieces accurately. Several techniques exist for such error mapping, but they are all slow and/or expensive making users reluctant to undertake these activities unless absolutely necessary. The problem is exacerbated for large machine tools as these are more difficult to error map. More frequent checking or error mapping would give more accurate machine more of the time. This could be accomplished by using *in situ* cheap optical components which are left in the tool permanently.

A low-cost optical target design (based on the *InPlanT* system developed in the LUMINAR project) has been selected and early tests with it resulted in a design change – the sensor design is no longer based on vision algorithms, rather on mechanical modulation/electronic demodulation of analogue signals. Modulation using a rotating slit together with cross-correlation detection has been successful at ranges up to around 3 m (distance to glass retro-reflecting target), achieving resolutions as small as 7 µm. A generic data format suggested by partner RWTH is being used for data interchange between the optical system and the machine tool controller. A suitable test machine tool is being identified for further work – likely to be a 4.5 m linear axis, 5.5 m diagonal span tool. Modelling of the machine tool errors has been undertaken together with a sensitivity analysis of the model parameters.

Impact

The LaVA project website has been set up (empir.npl.co.uk/lava/) and is being populated with news and information from the project, and a stakeholder committee has been formed consisting of eleven members representing end users from aerospace, automotive, metrology and academia. In terms of publications, four articles have been published as open access peer-reviewed papers. We have made three inputs to the ISO TC213 technical committe on the subject of laser tracker verification testing. Project partners have presented papers or posters to scientific or mixed audiences at 14 national or international conferences and workshops and given 5 training sessions (internal training for project partners and training sessions at the two major LVM conferences - Coordinate Metrology Society Conference (CMSC) in the USA and 3D Metrology Conference (3DMC) in the EU). Project partners are co-organisers of 3DMC. One member of staff at partner VTT has submitted his MSc thesis on the spectroscopic thermometry system and another member at RWTH is preparing a PhD thesis. We count as unofficial collaborators the University of Oxford (work on FSI with NPL) and the University of South Wales (working with NPL on photonics for the FSI system). One patent has been applied for by participant IK4-TEKNIKER in the subject of spatial tracking of objects.

Impact on industrial and other user communities

Impact on these communities will happen through the use of the project's outputs as metrology enablers for digitisation of European industries manufacturing large items (*e.g*. aerospace, automotive, civil nuclear build). Many organisations are building robotic manufacturing and inspection cells but what is *missing* is the data *traceability*, especially for larger measurands – the robots measure a feature and give a result, but without any estimate of the measurement uncertainty. The Digitally Enabled Supply Chain (DESC) is reliant at its core on valid data and without meta data such as *uncertainty* and *SI traceability routes*, the outputs of these expensive systems are 'images', 'pictures', and estimates – they are not measurements. To facilitate the take-up of the project outputs, the project will produce a demonstrator integrating many of the developed systems into a factory metrology network. Uniquely, in this network, the measuring systems will exhibit a unified network interface and will be outputting traceable dimensional data. Initial planning for the demonstrator activity at RWTH at the end of the project is already underway and partners have reserved dates in calendars.

Other deliverables such as the *InPlanT*-based large machine tool metrology system will be demonstrated *in situ* in an operating machine tool, and others such as the FSI-based approach and the multi-camera technology already have commercially interested parties looking at exploitation routes. For example, partner NPL has received direct requests from several interested parties to purchase commercial versions of the FSI system and has been asked to demonstrate it at several end user locations as soon as it is ready.

Due to the intensive equipment build of the project, most of the impact will take place once the equipment is ready for demonstration. However, there have been requests for early access to technology being developed in the project by end users, e.g. NPL has received a request from the aerospace community to demonstrate the improved FSI system in a factory environment. Several requests for stakeholder membership have been received so far; some of these were stakeholders in the previous LUMINAR project and wish to keep involved, others are new. They are predominantly in the aerospace sector – a key target audience for the project outputs. The stakeholders will start to receive updates on project progress and be invited to the end of project demonstrator. Some project partners‘ are mebers of the International Academy for Production Engineering (CIRP) and will ensure that this community will be able to access the research, its open data and new facilities and measurement/consultancy services available.

Impact on the metrology and scientific communities

Some project partners‘ are members of the EURAMET Technical Committee for Length (TC-Length) and Consultative Committee for Length (CCL) at BIPM. The project will develop metrology capability at the smaller NMIs – for example GUM is setting up a LVM laboratory and participates in many aspects of the project, gaining experience of research and knowledge of current LVM tools and techniques. The inclusion of several external partners strengthens the interaction between the metrology and non-NMI communities, *e.g.* between NPL and ISI, VTT and MAPVISION, and INRIM and FID. Several outputs are targeted at the wider metrology community – the improved HCN spectrum data will be useable by any NMI looking for frequency standards in the infra-red optical regime and the frequency comb being built by NPL for dimensional use will have other applications in length metrology.

Impact on relevant standards

This encompasses more than just the generic knowledge transfer into *e.g.* ISO/TC 213, which has been asked by end users to re-think the current ISO standard on laser trackers as it is regarded as too cumbersome to be used in a commercial environment. Digitisation of industry relies on data and data interchange and the project outputs will be used as inputs to validating designs of factory metrology networks and future standards for DESC. The end of project demonstrator will be a unique facility embodying the concepts envisaged for DESC/Industry 4.0 and will able to be used to generate much pre-normative data and knowledge needed by the digital standards and ISO Geometrical Product Specifications standardisation activities. A request for inputs to the next draft of the ISO 10360 standard for laser tracker verification has been received and this will be actioned in the next few months.

Longer-term economic, social and environmental impacts

The Global Navigation Satellite System (GNSS) was invented with military applications as its *raison d'être*, however it is now known for much wider applications of the technology, from mapping applications and personal navigation in mobile phones, to aircraft landing guidance systems, autonomous vehicles, structure monitoring, machine guidance, geophysics studies, climate monitoring, cadastral surveying and many more. From conversations with end users, it is envisaged that the project will be an enabling technology for indoor precision navigation/coordinate metrology with a similar broadening of the impact that was experienced by GNSS, and will be joined by the commercialisation of other project outputs feeding into factories etc. Thus the longer-term impacts will come from the products that are manufactured in the Digitised Factories of the Future using Industry 4.0 approaches. These will include: lighter weight aircraft with reduced shimming and laminar flow wings; more efficiently manufactured cars and vehicles with eco-friendly design for re{-manufacture, -cycling, -use}; cost effective engineering and assembly of large, expensive, critical components for nuclear new build; better control of aerofoil geometry in wind turbines; better alignment of next-generation science and beamline-based facilities (proton therapy systems); the ability to control fusion energy plant engineering for future ramp-up post *ignition*; and new metrology systems for use in hostile environments (undersea engineering, reactor monitoring; nuclear facility stability evaluation).

List of publications

1. A Egidi, A Balsamo, and M Pisani, "High-Index Glass Ball Retroreflectors for Measuring Lateral Positions", *Sensors* **19** 1082 (2019). (DOI: 10.3390/s19051082).
2. M Hošek, Š Řeřucha, L Pravdová, M Čížek, J Hrabina, and O Číp, "Investigating the use of the hydrogen cyanide (HCN) as an absorption media for laser spectroscopy", *Proc. SPIE* **10976**, 21st Czech-Polish-Slovak Optical Conference on Wave and Quantum Aspects of Contemporary Optics, 1097605 (2018). (arxiv.org/pdf/1905.07272).

3. T Pfeifer, B Montavon, M Peterek, and B Hughes, "Artifact-free coordinate registration of heterogeneous Large-Scale Metrology systems", *CIRP Annals* **68** (1) (2019). (DOI: 10.1016/j.cirp.2019.04.077).

4. B Montavon and M Peterek, "Model-based interfacing of Large-Scale Metrology instruments", *Proc. SPIE* **11059** Multimodal Sensing: Technologies and Applications, 110590C (2019). (arxiv.org/abs/2001.05897).

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 August 2018, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Andrew Lewis, NPL Tel: +44 20 8946 6074 E-mail: andrew.lewis@npl.co.uk
Project website address: http://empir.npl.co.uk/lava/</td></tr>
<tr><td>Internal Funded Partners:
1. NPL, United Kingdom
2. CNAM, France
3. GUM, Poland
4. INRIM, Italy
5. LNE, France
6. RISE, Sweden
7. VTT, Finland</td><td>External Funded Partners:
8. FID, Italy
9. IK4-TEKNIKER, Spain
10. ISI, Czech Republic
11. RWTH, Germany</td><td>Unfunded Partners:
12. MAPVISION, Finland
13. SAAB, Sweden</td></tr>
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