Publishable Summary for 20IND02 DynaMITE

Dynamic applications of large volume Metrology in Industry of Tomorrow Environments

Overview

Large Volume Metrology (LVM) is a critical requirement in many high value industries where the EU is globally competitive. The overall aim of the project is to provide fundamental metrology that will enable the Digitisation of European advanced manufacturing, especially in the aerospace and automotive industries. This project will deliver improved, dynamic-capable and traceable measuring systems for operational use, as LVM tools & technologies allowing integration of these tools into reconfigurable factory coordinate metrology networks, that can function in typical & harsh factory environments. The project results will offer industrial-level speed capability, with the ability to interface with production and assembly process control with reduced latency synchronisation which will lead to efficiency and cost improvements in industries reliant on LVM; this will enable automation beyond the current state of the art, which is mostly automation by simple repetition.

Need

Key European industries (such as aerospace, automotive, civil engineering, energy, and power generation) are moving to advanced manufacturing approaches, *e.g.* 'Factory 4.0/Industry 4.0' and cyber-physical systems. Underlying all these, is metrology, delivering accurate, traceable measurements in non-ideal environments at the required speed. Previous EMRP and EMPIR projects focusing on "Large Volume Applications (LaVA)" and "Large Volume Metrology (LUMINAR)" produced traceable solutions for static/slow speed situations, but dynamic situations, ideally using novel, cheap sensors and techniques must be handled now.

The 'holy grail' for many LVM end-users is an indoor equivalent of a Global Navigation Satellite System (GNSS) – an 'indoor global positioning system'. A system with similar capabilities (with scaled down range (10s of m) and uncertainty (10s of µm)), would revolutionise indoor coordinate metrology. This can be delivered using a combination of systems coming from outputs of DynaMITE. Outputs from LUMINAR and LaVA deliver accuracy and traceability, but not the speed needed to allow for in-process swap-over between different metrology devices within large volume factory metrology networks. Furthermore, robotic control demands minimisation of latency of metrology data as well as delivery of data at a rate suitable for control system integration. These needs are addressed by work towards the first two objectives of the research: faster speed for Frequency Scanning Interferometry approaches; and much higher speed (and frame rates) for photogrammetry.

Autonomous remote-monitored Advanced Manufacturing underpinned by metrology can continue to operate during pandemics, unlike other processes relying on close human interaction. Integrated, heterogeneous LVM systems, delivered *via* LaVA, empowers the control system to manage the complete production or assembly process (*e.g*. allowing the robot mounts to be movable as well as the part) based on measured data. But uncertainty of dynamic measurements is missing, so position and velocity inputs to motion control/estimation algorithms may be unsuitable for delivering required accuracy or integrity. Furthermore, time synchronisation of metrology systems is often missing due to data latency from varying hardware dependent computation cycles - this is particularly acute in different & distributed hardware typical to Industry 4.0 (such as Metrology System, Edge, Cloud, HMI). Devices may claim simultaneity but the data arriving at the computing system may be out of time sequence, with unknown delay between physical measurement and result. This is a real problem when swapping between available measuring systems when tracking a tool/robot during dynamic line of sight blockages. This diverse set of requirements is being addressed under the third objective of the project which is centred around modelling and the low-latency communication requirements for operation of metrology tools in typical advanced manufacturing workflows.

The demand for better volumetric performance in machining large parts balances the difficulty of accurately determining the error map of a large machine tool (to enable necessary geometrical error compensation), and the re-verification of the machine performance when used for production. Highest accuracy volumetric error mapping of such tools currently requires multiple sequential measurements using *e.g.* LaserTracers, but this takes time as only static points (whilst machine is paused) can be captured. Considerable speed increase and measurement of currently un-measured dynamic error sources may be obtained if accurate on-the-fly measurements can be made using a dynamic-capable multiple laser Tracer system. These needs are addressed by the fourth objective of the project which seeks 20 % reduction in time required to error compensate large machine tools using dynamic approaches rather than current static methods.

Objectives

The overall aim of the project is to deliver novel LVM systems that are, capable of operating in **dynamic applications**, closed loops associated with Industry 4.0/Future Factory environments, without compromising on the traceability and accuracy requirements from end users in all disciplines. The specific objectives of the project are:

1. To develop Frequency Scanning Interferometry (FSI)-based techniques with high-performance data analysis capable of: (i) tracking **at least 3 targets** at speeds of up to **150 mm/s** with quantified position uncertainty; (ii) updating data at a rate of **100 Hz** to enable input to closed-loop 6DoF robotic controls for trajectory correction; (iii) reducing latency of the processing electronics / algorithms to a minimum.
2. To develop low-cost photogrammetry-based metrology systems for very large volumes with elevated dynamic capability (up to **10 m/s**) and high frame rate (> **100 Hz**) capable of: (i) tracking large numbers of mobile entities (*e.g.* AGVs, drones and mobile robots) across the entire factory; (ii) allowing adaptive real time synchronization of virtualised and real factories for cloud-based coordination of complex automation systems.
3. To design and produce (a) an IoT-based architecture to integrate cooperative LVM systems with reconfigurable, self-automating processes in the FoF. The architecture should: (i) integrate methods for tracking **data integrity** in addition to conventional traceability; (ii) include **uncertainty models** for dynamic coordinate measurements for automated assignment of metrology resources to dynamic automation platforms (*e.g.* robots); (iii) provide a framework for deducing **communication requirements** (latency, bandwidth) from metrology based cyber physical manufacturing systems; and (b) automated, dynamic reconfiguration of distributed LVM systems capable of reacting to the visibility and uncertainty constraints of factory environments.
4. To develop equipment, models and associated strategies for **dynamic performance evaluation/error compensation of medium to large machine tools** (5 m^3 - 50 m^3) capable of reducing measurement times by 20 % without the need for stationary measurement locations and to allow in-process machine behaviour to be investigated.
5. To **facilitate the take up of technology & measurement infrastructure** developed, by the measurement supply chain (NMIs & DIs), standards organisations (ISO) and end users (aerospace, automotive and energy industries). The tools developed in the project will be targeted at industrial applications and knowledge should be appropriately transferred to the relevant end users.

Progress beyond the state of the art

Whilst some laser trackers and laser radar can deliver high speed scanning, this is for a single target, and there is traceability only in range data (if fitted with an interferometer) – the angular data is not traceable. The National Physical Laboratory's **OPTIMUM FSI system** has the traceability and simultaneous multi-target capability, but only demonstrated so far on static or pseudo-static targets (*e.g.* in LUMINAR, the system took 4 days to align ready for measurements on static targets). Within DynaMITE, NPL is updating the existing FSI system so that it is capable of achieving better accuracy than current SOA systems, with direct SI traceability, with faster operation (100 Hz target update, fixed/known/minimised latency) on multiple targets simultaneously, with ability to track targets moving at 150 mm/s, thus, delivering the final missing piece for this innovative and much anticipated novel large volume coordinate metrology system.

It is not cost-efficient to deploy commercial photogrammetric camera units (>€20k >€80k per sensor in the numbers needed to create large volume photogrammetric networks). Conversely, low-cost multi-camera solutions for on-line metrology are mature at small to medium volumes and can operate at higher frame rates but are stretched for large volume applications where angular measurement uncertainty is dominated by a combination of target image quality and environmental factors. DynaMITE will go beyond the Service Oriented Architecture (SOA), by developing one or more **photogrammetry systems** that can handle acquisition at rates up to **100 Hz** and simultaneously track many targets with some moving at up to **10 m/s** target velocity, in a **10 m × 8 m × 2 m** volume.

Consistent handling of dynamic coordinate measurements is not covered by the SOA. This gap directly extends to communication in metrology networks, which currently nearly always involves multiple software layers and does not foresee any real-time requirements (apart for very few instruments developing their own solution, *i.e.* the EtherCAT interface to the Leica AT960™ laser tracker). The project will establish a **communication architecture, protocols, models** building on advances in distributed computing and information technology allowing the (re)-configuration of LVM devices in a network with spatio-temporal **synchronisation**, coping with line-of-sight dynamics, and providing a formalised way to account for **uncertainty**, **traceability**, **integrity and latency of dynamic coordinate measurements.**

Current laser tracer-based approaches and the *InPlanT* system are pseudo-static in their operation – require the machine tool to restrict the range of motion or to pause at each point whilst data is captured. They do not experience, and cannot measure, multi-axis dynamic errors. This means that some dynamic errors may be missed and the overall time for error mapping is still extended beyond the ideal. The project will deliver a system, based on updated *LaserTracer*-like technology, targeted at **large machine tool error mapping** with measurements performed using interferometers, tracking and **measuring moving targets**, with no need to pause for each position.

Results

Development of Dynamic FSI

The focus at the start of the project has been on surveying the effect of different data latency values on robotic feedback control, resulting in an **internal report and discussion**. In order to increase the data rate available from the FSI system, work has started on developing a laser that scans much faster. A design for a system based on stitching together a number of sub-scans from diode lasers has been found in the literature. Each sub-scan is linearised in frequency using an optical phased-lock loop approach. A suitable **diode laser array** and a prototype controller have been procured, which will allow project partners to produce two overlapping sub-scans covering 5 nm - 6 nm. Manufacturing of the laser system is underway, and some initial scans of the laser are being evaluated. At the moment the sequential scan rate is not as high as necessary, and work continues on improving this. So far, a single scan width of **almost 3 nm** has been achieved using a single diode laser of the array.

In order to reduce the effect of Doppler shifts when measuring moving targets, a four wave mixing approach is being developed to allow generation of the reverse direction laser scan, using **photonic waveguides**. This will be able to produce a lower-cost solution to driving two lasers in opposite scan directions by using a single laser. This is part of a collaboration between NPL and the University of South Wales.

The hardware of the FSI system has been updated into a more robust physical platform with improved initial target location using photogrammetry (an NPL staff member is now registered at UCL as a PhD candidate). A version of the updated hardware (without the forthcoming new dynamic capability) has been delivered to the UK's **Advanced Manufacturing Research Centre (AMRC)** and this is now being evaluated and demonstrated in an **aerospace manufacturing research environment**; this system will be updated to dynamic operation after the research is completed within DynaMITE. A second OPTIMUM system, which will have dynamic capability built in from the start, is being constructed for the UK's **Advanced Manufacturing and Productivity Institute**.

Development of low-cost and dynamic photogrammetry

Work has already delivered a system that can obtain data from targets moving at **13 m/s** using calibrated cameras which are delivering **0.17 mm coordinate precision**. The objective is to compute the 6DoF data for every incoming set of images at 100 Hz. Currently the system is limited by the 20 ms computation time needed to robustly detect, identify and measure 2D target image locations across all four images and to display and update the user interface. Subsequent 3D processing, including 3D display, takes 6 ms. This combination currently gives an output data frequency of **35 Hz**. Offloading image processing from the CPU to GPU maintaining the same threaded pipeline has allowed **60 Hz** output. Work is ongoing to further parallelise the 2D processing pipeline so that the output frequency can match the input frame rate. Work has also started into proposing and examining various designs of 6-degee-of-freedom (6DoF) qualification objects. Project partner UCL has delivered **two photogrammetry systems** to manufacturing organisations - the UK National Composites Centre, and Airbus. Photogrammetry partner IDEKO have worked with other partners to produce an initial design for a **multi-system target cluster** which can be tracked by all these partner's metrology systems. The target cluster can be evaluated in 6D, *i.e.* 3D position plus 3 orientation angles. This will allow it to be used for comparisons of different systems by tying together their separate coordinate networks into a common network. A version of the target is being designed for use on a machine tool spindle. IDEKO have undertaken a measurement campaign at UCL's *Here East* facility and visited other project partners as part of the joint target system development.

IoT architecture for reconfigurable LVM systems and dynamic applications

A complete **framework for uncertainty-driven reconfiguration** has been implemented based on modelling the process in discrete time steps which lead to expected measurement locations. These are passed on to an engine which checks the line-of-sight/physical constraints of the LVM system (*e.g.* angle, distance…) and estimates the expected measurement uncertainty. Both results enter an objective function which is then used in a particle swarm optimization function to evaluate the optimum set of values. A *Pozxy* system is being set up for use with further modelling and work on implementing a version of the **Universal Interface** (developed in the previous LaVA project) is underway for a laser tracker implementation.

Dynamic large machine tool compensation

Work undertaken so far has resulted in a new design for a **fast self-tracking interferometer** with multiple-wavelength **coaxial beams**, and the interferometer is under construction. Work on the **high-speed phase meter** is also underway. PTB have benefited from collaboration with Hexagon Manufacturing Intelligence and SIOS Messtechnik. The interferometer system will be used initially for large CMM compensation as a proxy for large machine tools. Extending the range to much larger tools, collaboration on metrology for a hangar-sized cable-crane driven robot has started, with a visit from the metrology system developers to the **large cable robot at Montpellier**. This has been accompanied by **updates to the multilateration system** at CNAM.

Impact

At this early stage of the research, the achieved impact is relatively modest, as the project targets end-user use of project outputs that will not be available for some time (generally not until the end of the project at the earliest). Nevertheless, the stakeholder committee has been set up and has 14 members so far. The stakeholder committee members will receive updates from the project, be invited to selected demonstrator activities and be asked to comment on relevant outputs before they are published to ensure they address relevant needs. In addition, early research has already been published (two papers published, one of which is multi-partner multi-national) and three conference presentations have been delivered at a key Large Volume Metrology Conference in July 2022 (which was attended by many of the stakeholder community). A training event was also delivered at the same conference. So far, staff members from the project partners have participated in 14 meetings of standardisation bodies which consider standards which are relevant to this project such as ISO TC172, DIN NA 005-03-04, VDI/VDE FA 4.31-4.32 and DIN NA 152-03-02-12. Two project outputs (one a development from the previous project LaVA) have been or are in the process of being delivered to stakeholders. Perhaps the largest impact route underway is the supply of two measuring systems based on Frequency Scanning Interferometry to UK-based manufacturing organisations. One system has been delivered to the AMRC in Wales and this is being demonstrated to end users as well as entering a research evaluation stage to assess how to integrate the system into aerospace manufacturing. Feedback from the trials is being used by NPL to update the system and is feeding into the design of a second system being built for the Advanced Machining and Productivity Institute.

Impact on industrial and other user communities

The project outputs will serve as metrology enablers for digitisation of European industry; for production/maintenance/repair/overhaul of large items (*e.g.* in aerospace, automotive, civil nuclear, wind energy, robotic factories); especially those moving to flexible or line-less mobile assembly. It is foreseen commercial versions of the project outputs within a few years and are negotiating with potential manufacturers & customers. Many organisations are building robotic manufacturing and inspection cells but what is missing is the data traceability, especially for larger measurands and especially for those performed whilst moving. DESC is totally reliant at its core on valid data and without parameters such as uncertainty, traceability & timing, the outputs of these expensive systems are 'images', 'pictures', and estimates – they are not measurements of dynamic processes. To facilitate the take-up of the results, the project will organise several demonstrator activities to show the capabilities of the new developments in typical scenarios. Additionally, project outputs such as the dynamic machine tool error mapping will be demonstrated *in situ*, and others such as the dynamic FSI system already have commercial interest in exploitation by multiple end-users in their own organisations. The consortium has already been asked to build two copies of the FSI system for delivery to advanced manufacturing research centres. The first system, which was delivered autumn 2022, was installed at theAMRC Wales, which is part of the University of Sheffield Advanced Manufacturing Research Centre (https://www.amrc.co.uk/facilities/amrc-cymru-wales). A second system is to be constructed for use by the Advanced Machinery and Productivity Institute - AMPI (https://www.ampi.org.uk/) - which is itself currently being constructed. AMPI is an initiative that will drive innovation for the UK's advanced machinery manufacturers to meet the challenges of developing new technology and entering emerging markets. The Institute is being led by an industrial consortium and will be based in Rochdale, UK. Additionally photogrammetric-based measuring systems have been delivered to end users - one to the UK National Composites Centre (where photogrammetric tracking is used in robotic composite pre-forming) and one to an aerospace manufacturing organisation.

Impact on the metrological and scientific communities

Project outputs will be presented to over 200 participants at the world's major LVM conferences: CMSC (Coordinate Metrology Society Conference), USA – where NPL helps deliver training services; and 3DMC (Europe's 3D Metrology Conference) – which is currently co-organised by project partners. Already **one training session has been delivered** at CMSC as well as one presentation and presentations have been made at **EUSPEN** and during **World Metrology Day** events in Germany. Relevant project outputs will also be presented at ISPRS Congress (International Society for Photogrammetry and Remote Sensing). Further routes to impact will be through memberships in: CIRP; EURAMET TC-Length – which hosts the regular MacroScale conference (project partners are members of the TC); CCL at BIPM; the DynaMITE project web portal, the *DynaMITE* ResearchGate portal, webinars and a range of high level journal articles. Communities will be able to access the research, its open data and new facilities and measurement/consultancy services available from the NMIs (*e.g.* FSI work in previous projects LUMINAR & LaVA has been used by the consortium to develop novel, systems for thermal vacuum testing of ion thrusters). Additional metrology spin-outs are anticipated from the DynaMITE work at partners and in other members of the metrology community.

The project directly supports development of metrology capability at the smaller NMIs, for instance GUM has a small but expanding LVM laboratory and participates in many aspects of the project, gaining experience of others' research and knowledge of current LVM tools, techniques, and latest research. The inclusion of several external partners strengthens the interaction between the metrology and non-NMI communities. It provides a foundation for closer working between NPL and the UK Universities, between CNAM and CNRS, and between PTB and RWTH, in addition to the planned activities in which the NMIs benefit from latest research coming from the external partners. The external partners were selected to provide complementary knowledge and facilities to the internal NMI partners, to help counter the low level of NMI LVM metrology R&D in Europe.

The project will deliver high-performance dynamic, traceable tools for LVM which can then be used by the wider metrological and scientific communities to benefit their research, with regard to the need for highly accurate systems in research fields (*e.g.* large astronomic telescopes, synchrotron, medical beamline devices). Additional benefits will come from access to affordable in-network time synchronisation which can be applied to a range of dimensional systems.

Impact on relevant standards

The architecture for communications and data interchange is a potential input into digital standards, in particular, the framework for metrology data interchange, is very timely. Knowledge coming from other physical metrology parts of the project will eventually influence updates to specification standards at their next update (*e.g.* the revision of the laser tracker standard within ISO TC/213, where standards are revised on longer periodicity. Furthermore, perhaps with the longest timescale, use of the tools from the project and future devices based on the project outputs will generate traceable data and knowledge which may lead to further standardisation efforts. The various demonstrators throughout the project will embody updated concepts envisaged for dynamic DESC/Industry 4.0 situations and may offer pre-normative data and knowledge needed by the digital standards and ISO GPS standardisation activities.

Longer-term economic, social and environmental impacts

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, and more. It is anticipated that similar spinout for several technologies from DynaMITE, such as the high data rate photogrammetry cameras could replace some wide field measurement systems such as iGPS or deliver higher data rates for improved dynamic accuracy in gait monitoring; the FSI system has already been used for static measurements inside ion thrusters, and dynamic FSI is so akin to GNSS that a similar range of possibilities are envisaged (*e.g.* indoor navigation, precision robotic surgery, electronics manufacturing lines, modular wind turbine blades, deflection testing/monitoring of large structures, precision drone tracking and cooperative additive manufacturing).

Thus, the longer-term impacts will come from the products that are manufactured in Industry 4.0 using Advanced Manufacturing approaches which will rely on outputs of the project to provide the traceable metrology and connectivity between devices. These new products 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 modular wind turbines; better alignment of next-generation science and beamline-based facilities (LHC, ILC/CLIC, proton therapy systems); the ability to control fusion energy plant engineering for future ramp-up post *ignition*; new metrology systems for use in hostile environments (undersea engineering, reactor monitoring; nuclear facility stability evaluation), and highly novel manufacturing outputs from *e.g.* cooperative additive manufacturing. There is an additional sustainability benefit coming from the enabling of reconfiguration of large, automated assembly machines to extend their use in assembly/manufacturing sites when the product changes, *e.g.,* aerospace manufacturing switching from A380 manufacture/maintenance to newer models – the project will enable tool and facility re-use through reconfiguration rather than current single-product specialisation.

List of publications

- Guillory J, Truong D, Wallerand J-P. "Multilateration with Self-Calibration: Uncertainty Assessment, Experimental Measurements and Monte-Carlo Simulations", *Metrology* (2022) **2**(2):241-262. https://doi.org/10.3390/metrology2020015
- Puerto P, Heißelmann D, Müller S and Mendikute A, "Methodology to evaluate the performance of portable photogrammetry for large volume metrology", *Metrology* (2022) **2**(3):320-334. https://doi.org/10.3390/metrology2030020

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 September 2021, 36 months	
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Internal Funded Partners: 1. NPL, United Kingdom 2. CNAM, France 3. GUM, Poland 4. PTB, Germany 5. RISE, Sweden 6. VTT, Finland	External Funded Partners: 7. IDEKO, Spain 8. RWTH, Germany 9. UBATH, United Kingdom 10. UCL, United Kingdom	Unfunded Partners: 11. CNRS, France