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 (e.g., 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 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 (**Objective 2**).

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 (tens of m) and uncertainty (tens 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 (**Objective 1**).

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 **Objective 3** 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 **Objective 4** of the project which seeks 20 % reduction in time required to error compensate large machine tools using dynamic approaches rather than current static methods.

The uptake (**Objective 5**) of new technologies and processes enabled by or delivered through the work in DynaMITE will enable European manufacturing to transition more quickly to the Industry 4.0 ideals.

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** ($5\ \text{m}^3$ - $50\ \text{m}^3$) 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 a previous project IND53 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 (target updates at tens of Hertz, fixed/known/minimised latency) on multiple targets simultaneously, with ability to track targets moving at speeds encountered during robotic manufacturing operations, thus delivering the final missing piece for this innovative and much anticipated novel large volume coordinate metrology system (**Objective 1**).

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^{-1}** target velocity, in a **10 m × 8 m × 2 m** volume (**Objective 2**).

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** (**Objective 3**).

Current laser tracer-based approaches and the *InPlanT* system developed in previous projects IND53 LUMINAR and 17IND03 LaVA, 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 (**Objective 4**).

Results

Development of Dynamic FSI for robotic control

The focus at the start of the project was on surveying the effect of different data latency values on robotic feedback control, resulting in an **internal report and discussion**. A valuable conclusion from the work was that the positioning accuracy does not degrade as quickly as expected with reducing data rate, meaning that it may not be necessary to achieve 100 Hz data rate from e.g., the FSI system, to be able to obtain significant positioning accuracy improvements when used to provide position feedback to robots.

Work by the University of Bath started with setting up their dynamic model of the NPL OPTIMUM system and testing ways in which it can be integrated into their own KUKA robot system model. A pose-dependent model has been generated and tests have been performed using inertial sensors and voice coil actuators. These tests have shown that dynamic properties of the chosen KUKA robot change with pose. Using a laser tracker and single target on the robot, an implementing a H-infinity control, UBATH managed to effectively reduce vibration during robotic machining on a moderately-sized workpiece. Their work has confirmed that significant improvement in robot-based machining operations can be obtained by tracking targets on the robot at speeds of only a few mm/s.

In order to increase the data rate available from the FSI system, work is progressing on developing a laser that scans much faster. Two approaches have been examined: a MEMS-tuned VCSEL laser and a multi-diode laser array. The MEMS-based laser work has shown that it would not deliver the required linearity; instead a design for a system based on stitching together a number of sub-scans from diode lasers has been found in the literature with each sub-scan being linearised in frequency using an optical phased-lock loop approach. A suitable **diode laser array** and a prototype controller were previously procured, which allows production of two overlapping sub-scans covering 5 nm - 6 nm. After designing several versions of a custom laser controller PCB, a single scan width of **almost 3 nm** has been achieved using a single diode laser of the array. Recent work has achieved a faster scan rate covering multiple diodes.

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 fibres**. The custom-designed system has been delivered and is being evaluated.

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, studying the photogrammetric aspects of the design). New faster GPUs have been delivered and integrated into the measuring heads to deliver faster data update rate – target location computations can now deliver data at rates up to 30 Hz. 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**. As part of the planned commercialisation of the OPTIMUM system, it has recently achieved UKCA (*c.f.* CE) marking status and has been awarded UK Government funding for initial market surveys and updated prototyping.

Development of low-cost and dynamic photogrammetry

Work by UCL and IDEKO has achieved the **100 Hz** and **10 m s^{-1}** targets of objective 2. Speed limitations caused by computation time needed to robustly detect, identify and measure 2D target image locations have been overcome by offloading image processing from the CPU to GPU whilst maintaining the same threaded pipeline and further parallelisation of the 2D processing pipeline so that the output frequency can match the input frame rate. The net outcome is that it is now possible to operate a photogrammetry network consisting of **18 cameras**, simultaneously tracking **51 objects with live 6-degee-of-freedom (6DoF) data** available for each object. Within the network, which consisted of **over 800 targets**, were targets on objects travelling at speeds in **excess of 10 ms^{-1}**, which were being tracked at 25 Hz, as well as large bundles of hundreds of targets which were being handled at 1 Hz. This demonstrates the capability to handle dynamic factory networks, tracking: a **large number of items** (in **6DoF**), tracking items moving faster than **10 m s^{-1}** and providing updated data for parts of the network at up to **130 Hz**. Thus the increased speed targets of Objective 2 have been delivered.

Tests on adaptive synchronisation have been undertaken (though the data analysis is not yet completed or published). Camera images have been cross checked with a flashing light system to check synchronization at 1 Hz base rate. Further work on obtaining 6DoF solutions scalable for volume, complexity, and number of tracked objects allowed the tracking of 50+ 6DoF solutions at different temporal rates and accuracies, including a wing, a reference table, 4 aerospace drills, multiple joints on 2 robots, several scale bars, a large desk fan (which gives 10 m s^{-1} target speeds) and a range of more random objects which UCL moved about the volume. Furthermore, six low-cost cameras have been used for robot tracking at greater than 10 m stand-off covering an 8 m x 8 m x 8 m volume with a better than 0.1 mm photogrammetric coordinate fit to reference locations determined by a laser tracker. Tracking the robot using photogrammetric 6DoF fitting across multiple robot locations achieves 0.2 mm RMS accuracy and circle fits to individual robot joint motions had 0.2 mm RMS errors. Laser tracker monitoring of an SMR location vs a photogrammetric 6DoF estimate of the same location, showed that the RMS error varied within the range 0.1 mm to 1.0 mm depending on spatial location and target visibility. This demonstration scenario with issues such as roof camera placement not optimized for robot motion, 6DoF reference quality issues and uncontrolled environment, snake robot stability, etc. reflects a real working environment. The outputs of this work are being prepared for publication in an open access journal paper in early 2024.

Design and manufacturing work has been completed by CNAM, IDEKO, GUM, PTB, and NPL on a set of **6DoF qualification objects** which can be tracked by not only the photogrammetry systems but by other systems being developed in the project. The project team has achieved a target structure that is lightweight enough to be mountable on a large volume CMM ram, allowing the CMM to move the structure around. The structure has been validated at both UCL and IDEKO. Additionally, a demonstration of the capability of photogrammetric machine tool spindle calibration has been undertaken at IDEKO where a large machine tool was instrumented with photogrammetric targets and cameras. The coordinate reference system was obtained using the IDEKO VSET system. Data was obtained whilst the spindle rotated at 3000 rpm. The machine tool calibration did not use any strobe light, just the camera shutters; careful selection of shutter timings allows for selection of periodic errors to be ‘frozen’ during rotation.

Project partner UCL has delivered **three photogrammetry systems** to manufacturing organisations - the UK National Composites Centre, and two Airbus locations. 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. UCL and IDEKO are working with CNAM to prepare for the use of photogrammetry on a large cable robot at CNRS. Targets for the telemeters will be attached to the cable robot but the telemeters require an initial value for the target location (to around 1 mm accuracy) in order that they can be precisely pointed at the targets before making ranging measurements; the photogrammetry system will provide this initial target location data through a communication interface.

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. Additional fields have been added to the data model from the LaVA project by adding dynamic covariance elements, time-window data and filter type. To allow for error-free synchronisation, persistent unique identifiers are now being used. Additionally, to match the requirements of the FAIR data initiative, the units of measurement are now using open access semantic definitions from qudt.org. Authenticity is checked using a self-describing fingerprint field and the measurements can be related to a defined origin/coordinate system with a defined source entity. An additional semi-regulated annex to the data model allows for both static and dynamic covariances and a defined acquisition time period. Temporal derivatives are now modelled and linked to originating fields. Data stream analysis has been implemented but the hashing (required for data integrity and measurement plausibility checking) is still being implemented.

A *Pozxy* system is being loaned by CNAM to GUM 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.

On the synchronisation front, work has been completed on surveying the possible time synchronisation approaches (PTP, gPTP, and WhiteRabbit), resulting in the development, and testing, of a PC ethernet interface card designed to use Precision Time Protocol (PTP) IEEE 1588-2008, using cheap NUCLEO-F429Z cards. Early results show an in-loop stability of around 36 ns and actual edge to edge time differences of around 22 ns. A guidance document on implementing an i210 ethernet card PTP synchronisation system is being prepared. The consortium has integrated the 5G network with its existing network such that currently, LAN, Wi-Fi and 5G are seamlessly useable as these are all IP-based. Additionally, BLE has now been integrated at RWTH. Two experimental setups have been used for testing of achievable accuracy. The synchronisation accuracy of PTP in back to back connection is around 40 ms; jitter in the transmission link affects synchronisation accuracy. The influence of a network switch between two client boards is soon to be investigated. VTT-MIKES have tested pulse detection using ethernet and WhiteRabbit. They found that the distribution of PTP output (delays) does not vary much with ethernet cable length difference. High end network switches which implement time stamping (TSN) cost between 400 Euros and thousands of Euros but have been found to degrade performance to the 10 microsecond level.

Dynamic large machine tool compensation

Work by PTB has resulted in a new design for a **fast self-tracking interferometer** with multiple-wavelength **coaxial beams**. After initial testing on V1 of the assembly, a new V2 has been produced which is much more rigid and uses a multi-layer optical layout. A commercial gimbal system is being used as a mechanical platform in which the reference sphere is independently mounted. Testing of the interferometer on the PTB geodetic base has been undertaken by comparison against a classical He-Ne interferometer at maximum range with a folded beam geometry. The results were good although there was observed noise on the infrared interferometer signal. This was partially attributed to amplitude to phase noise coupling and has been significantly reduced by replacement of the InGaAs photodetector by a Si-based detector. The implementation of an online-Heydemann correction is no longer required as the heterodyne interferometer scheme now in use is less sensitive to non-linearities than the scheme originally foreseen. A test campaign at GUM was prepared but delayed due to a last-minute issue (eventually traced to a fibre coupler). The PTB system has been further presented at ASPE, 3DMC, ISMT-II, at World Interferometer Day and at the Harbin Institute of Technology.

Multiple copies of the CNAM telemeter measurement head have now been produced. Measurements of received power and signal to crosstalk ratio have been obtained for different reflector types and length measurement capability has been assessed by comparison against a commercial laser interferometer on a 50 m interferometric bench. Testing showed that a Variable Optical Attenuator induces noise when it is open to compensate for the losses due to poor reflection from the glass sphere – the VOA is being replaced. A digital twin for a ray tracing of the optical beam has been developed in order to allow determination of error sources of the geometrical arrangement of each head. The digital twin will also be used for estimating the uncertainty contributions of mechanical errors in the measured distances using Monte-Carlo simulation. The digital twin will also be used for aiming assistance during multilateration measurements.

The design of the demonstrator involving the **CNRS cable robot in Montpelier** has been completed. Currently the cable robot has **centimetric** accuracy - the target is for the platform to position a cylinder into a bore at the **100 micrometre level** to demonstrate significant accuracy improvement. The accuracy improvement will come from the CNAM telemeter system however this system will need millimetric initial targeting from the UCL/IDEKO photogrammetry system. Planning is underway to ensure that all the systems required for this demonstrator are ready in time, are interface compatible with one another and arrive at the cable robot in time.

Take up of technology & measurement infrastructure

As described earlier, 4 systems have already been delivered to external organisations and are in use, and a fourth system is being prepared for another organisation. Project partners have also given training in best practice at an international conference and four research papers have been published in journals (see later). In mid-March 2023 the project partners visited the large volume CMM at PTB, Germany, to discuss a forthcoming measurement campaign based on the CMM which will feature systems from several project partners. The CMM is part of the Wind Energy Competence Centre of PTB, targeted at metrology for wind energy generation. Further details of impact routes targeting the take up of the developed technology may be found in the following section. NPL has won additional funding from the UK government for marketing of the OPTIMUM FSI system.

Impact

At this stage, the achieved impact is relatively modest, as the project targets end-user use of project outputs, some of which 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. In addition, early research has already been published (three papers published, one of which is multi-partner multi-national) and eleven conference presentations/posters have been delivered. Four sets of training events have also been delivered. So far, staff members from the project partners have participated in 23 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. Several 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 three photogrammetry systems and two measuring systems based on Frequency Scanning Interferometry to UK-based manufacturing organisations. One FSI 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. The photogrammetry systems have been delivered to two Airbus locations and the National Composites Centre.

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 the AMRC 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. The UK leader of the opposition Sir Kier Starmer's 2023 New Year speech was held in the UCL *HereEast* large volume lab. Photogrammetric systems under development for DynaMITE were presented during a lab tour (see https://www.ucl.ac.uk/news/2023/jan/sir-keir-starmer-makes-key-national-renewal-speech-ucl).

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; a dedicated DynaMITE session was held in 2023 where several partners presented their work. Already **two training sessions have 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
- Yan, H, Pollinger F, Koechert P, Knigge P, Blohm J, Meyer T, Prellinger G, Stein M, Heißelmann D, “Design of an absolute distance interferometer for the dynamic calibration of large-volume coordinate measurement machines”, *Proc. EUSPEN 23* (2023). https://www.euspen.eu/knowledge-base/ICE23231.pdf
- Köchert P, Meyer T, Yan H, Sauthoff A, Prellinger G and Pollinger F, "The PTB Multiwavelength Interferometer for Distances up to 5000 m", Proc. 2023 ASPE Winter Topical Meeting, https://doi.org/10.7795/810.20240130

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	
Coordinator: Andrew Lewis, NPL	Tel: +44 20 8943 6074	E-mail: andrew.lewis@npl.co.uk
Project website address: http://empir.npl.co.uk/dynamite/		
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
RMG: -		