Publishable Summary for 17IND03 LaVA
Large Volume Metrology Applications

Overview

This project targeted 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 were designed and built to 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 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* have stated 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 commercially (typical robot: 0.5 mm accuracy, typical required tolerances: 0.1 mm). 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. Up to now, existing LVM tools (*e.g*. laser trackers, laser radar) have used 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 have been 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 has been a need for novel systems to bridge the gap between expensive but accurate laser trackers and cheaper but less accurate photogrammetry.

Objectives

The project aimed 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 were:

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 m³); 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 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 has now taken these systems and improved them, *e.g.* the FSI system which provided state of the art coordinate metrology of multiple targets simultaneously has been updated with latest HCN spectroscopy data from this project to deliver better length measurement accuracy and hence better coordinate uncertainty; the *InPlanT* system has been developed through several prototypes 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 have been developed into newer systems capable of operating over shorter path lengths and being operated in a multilateration network, together with new along-the-beam temperature sensing.

Additionally, new research in this project has improved on state of the art in other areas, *e.g.* large refractive index measurement has been transformed from a single point measurement at low rate, to large range higher accuracy, higher speed with additional capability to measure air temperature gradients which can cause errors through beam bending due to refraction; novel instruments as well as several classes of existing LVM tools now benefit from provision of a unified interface allowing integration into a cooperative metrology network; a multi-scale variable uncertainty photogrammetry system has been produced to deliver locally precise coordinates (*e.g.* for robots, AGVs); a novel traceability route for photogrammetry systems has been demonstrated; and a smaller scale multi-platform scanning system has been produced that has the ability to deliver higher-density scans of aerospace components.

Results

Improving the metrology capability of FSI-based techniques (Objective 1).

FSI-based techniques scan a laser across a range of frequencies (wavelengths) at high speed and derive their traceability through the use of absorption features in reference gases (in fibres or cells), which are illuminated by the laser light. Modern frequency scanning lasers in the 1.5 µm waveband now cover wavelength ranges far wider than the previously well-documented features in the acetylene molecule, and instead, users are transitioning to the wider set of features offered by hydrogen cyanide (HCN). Up to now, only one inaccurate set of historic (2005) spectroscopy data has existed for HCN and the international committee which approves reference frequencies would not accept this single set of data without further evidence. This has now been superseded by data from the LaVA project where both linear and saturated absorption spectroscopy measurements have been completed by ISI and RISE, with an initial set of data already published and other data entering the publication process (three papers are already published and three more are expected shortly). The new data is several orders of magnitude better accuracy than the previous published work and for some features (measured using saturated absorption spectroscopy) the accuracies are estimated to be at the 10^{-10} to 10^{-11} level - this data currently represents the state of the art in HCN spectroscopy; the newly-achieved accuracy is better than needed by the existing FSI systems and will have additional uses in the telecommunications area. Additionally, better accuracy measurements of the pressure and sensitivity coefficients have been made, allowing for a wider range of gas cell pressures and temperatures to be used. The measurement of the HCN absorption frequencies has been made using several techniques in order to identify/remove any method-based bias, together with a careful analysis of the uncertainties in the measurement. The new data suggests that a correlated uncertainty (*i.e.* an error) exists in the previous reference data (around 300 kHz shift is likely) and this confirms a suspicion of a problem as identified by recent work by NPL and the University of Oxford using HCN in a separate UKRI-funded project *AMULET*: (https://gtr.ukri.org/projects?ref=ST%2FI000526%2F1 , http://dx.doi.org/10.1364/OE.22.024869). The international committee has been informed of the new data and as soon as all the publications are available, they will be tabled for the committee to consider for inclusion in the list of reference frequencies (*i.e.* international ratification). Even before the committee meets, NPL is already using the new frequencies in its FSI system. Now that the new reference data is available, it has satisfied the objective by removing this accuracy limitation from FSI-based systems.

Novel/validated LVM methods for simultaneous metrology at different scales and accuracies (Objective 2).

CNAM's telemeter-based multilateration system is now complete and operational. The system comprises four optical heads which share a common absolute distance meter (ADM) via a 4-way fibre split. The ADM uses affordable components from the telecommunications world. Four gimballed heads use both micro-stepped stepper motors (450 µrad resolution) and a PZT-driven mirror with 1 µrad resolution to point at optical targets. The optical system can use both conventional corner-cube retroreflectors (up to 140 m, which is longer than commercial laser trackers) and spherical (n = 2) reflectors (up to 20 m). A gimballed mount for the corner-cube reflector allows motorised re-orientation to point at any measurement head (compared with commercial versions which require manual adjustment). The measurement heads contribute only 1.3 µm error in distance measurement and the overall distance measurement uncertainty is 4.3 µm (sphere target) to 4.7 µm (retro target). The length dependent part of the uncertainty is very small due to both in-beam refractive index determination and a highly-stable modulator frequency. During a validation test up to 35 m range, the difference between the CNAM ADM and a reference interferometer showed a standard deviation of 2.2 µm when using a cube corner retro reflector. This is much better that commercial laser trackers which typically can achieve 15 µm using their ADM. The performance with a spherical retro shows standard deviation of 3.3 µm up to 22 m range. The multilateration operation has been demonstrated by comparison with a laser tracker in a working volume which had no air conditioning, with distances up to 11.5 m. 94 % of the compared coordinates showed agreement between the two systems within their combine uncertainties. For the photogrammetry systems, three approaches have been completed. Firstly, the LNE self-contained dual-camera measurement system has been produced and tested in a series of measurement scenarios. The system is designed for close-range scanning of medium to large parts and has been mounted on a 6-axis Kawasaki industrial robot arm and later with the robot arm mounted on a linear stage. The range of the system can be extended by exterior position/pose monitoring, as demonstrated using the CNAM multilateration system to track the LNE sensor head. Algorithms for self-calibration have been produced based on machine-learning/particle swarms and automatic stitching of images has been achieved. The scanning system has been demonstrated using an aerospace manufacturing-compatible reference artefact. Measurements of the artefact by CMM and the scanner showed RMS errors of 66 µm for the CMM and 166 µm for the scanner system. However the CMM took much longer to sample only 5000 points compared with the 3,000,000 points sampled by the scanner. Secondly, a long-range multi-camera system has been implemented for coverage of factory shopfloor-sized volumes, using low-cost cameras, for the tracking of moving objects. Indoor photogrammetric tracking in factory environments can often be problematic due to multiple shiny surface causing errant bright spots in camera images. TEKNIKER have solved this using wireless active infrared targets operating at 850 nm, and camera lens to leave much clearer images of the photogrammetric targets. The Bluetooth-controlled targets have a typical 8 hr battery and Bluetooth communication allows the system to light individual active targets, or simultaneously all of them. In each target module, all three LEDs can be activated in a close/medium range, or a single LED can be used for larger volume applications where the three LEDs from each target module could not be resolved in the image. Because this system is software-driven and uses off-the-shelf camera and computer components, it is easy and affordable to install, operate and repair. In addition, real-time position of the moving parts is measured automatically, without human intervention. The system has been demonstrated in a 10 m × 10 m × 5 m shop floor environment. Finally, work by VTT (in cooperation with MAPVISION) has developed a new traceability route for existing commercial cameras used in industrial applications using high accuracy optically calibratable targets and carbon fibre linear target clusters. Taken as a whole, the project has delivered novel methods, operating at different scales which have been validated, satisfying this objective of the project.

In situ high accuracy (~10^{-7}) air refractive index determination with factory-sized volumes (Objective 3).

Air refractive index is a function mainly of the temperature and pressure; within enclosed factory volumes with industrial heating, pressure variation is mainly meteorological-based and can be measured using one or two cheap pressure meters (as built into laser trackers), however temperature fluctuates much more and large gradients can develop which erroneously bend optical beams (e.g. from laser trackers) or cause length measurement errors. 3D air temperature sensing via networks of many sensors is not practical, instead, three novel air thermometer systems have been successfully developed and tested, with all three systems measuring along an optical beam-line. The three systems are: VTT's spectroscopic thermometer (based on spectral absorption peaks in O_2 molecules); and two acoustic thermometers utilising speed of sound (the INRIM system using phase advance measurement, the CNAM system using time of flight vs. an optical signal. The systems perform measurement along an optical beam to a target/reflector, mimicking the dimensional measurement approach of many LVM devices. As such, they sample the true along-the-beam refractive index which is needed to compensate deliver 0.1 °C to 0.2 °C along-the-beam accuracy and the INRIM system has demonstrated 0.1 °C vertical gradient measurement accuracy. With the refractive index temperature sensitivity $\partial n/\partial T$ being 9.2×10^{-7} °C^{-1}, these systems deliver the objectives target accuracy of ~10^{-7}.

Modelling to simulate self-organising production/assembly using digital information from process-integrated measurement systems; applying these to produce an industrial scenario demonstrator (Objective 4).

Following completion of initial modelling of simulated measuring systems, a Unified Device Interface (UDI) has been produced, documented, and made open access (https://git-ce.rwth-aachen.de/wzl-mq-public/soil), including Python and C++ libraries which can be used by LVM equipment manufacturers and researchers. Specific versions of the reference model implementation (API Radian tracker, Nikon iGPS system, *Pozyx* UWB system) have been created. The COVID-19 lockdown periods across Europe required the project to switch to multiple smaller demonstrators, and several of these have taken place. Generally these were in situ demonstrations of the new systems' accuracies (CNAM multilateration system, TEKNIKER photogrammetry system, LNE photogrammetry system, the 3 novel air thermometers, combined CNAM and LNE systems, NPL's FSI-based OPTIMUM system measuring head). A unifying demonstration was organised by RWTH who provided a data collection and dashboard facility which accepted live data uploaded by other partners; data was uploaded by NPL, GUM, TEKNIKER and RWTH. The UDI software repository also contains the necessary documentation, and further details are available from a submitted PhD thesis which is available: https://doi.org/10.18154/RWTH-2021-10238.Thus the requirements of this objective have been delivered.

To produce equipment and validated methods for evaluating the performance and compensating for the errors of large machine tools (> 50 m³) (Objective 5).

Large machine tools are traditionally error-mapped using expensive systems *e.g.* laser trackers; periodic re-mapping is similarly expensive. To address this issue, INRIM have developed a system for evaluating critical parts of machine tool geometry based on optical assessment of straightness of motion, using a cheap technology that could remain embedded. After producing two prototypes, a final version of INRIM's *InPlanT* system has been developed. The device has a 300 mm × 300 mm × 175 volume and uses commercially-available optics to reduce cost. A software model for the system in use on a machine tool was developed and has been extended through a simplification which enables it to be used on a wider range of devices. The device has been tested on an available machine tool at FIDIA to assess the practicality of use and a speculative cost/benefit analysis of using the device has been produced. Thus the needs of this objective have been addressed.

Impact

Direct project outputs

Twelve articles have been published as open access peer-reviewed papers and three others are in preparation for submission after the end of the project. Project partners have presented papers or posters to scientific or mixed audiences at seventeen national or international conferences and workshops and given face-to-face six 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, another member at RWTH has submitted a PhD thesis on unified interfacing and process modelling, and a third person (from LNE) is about to submit a PhD thesis on work in photogrammetric scanning. The University of Oxford is working on FSI with NPL and the University of South Wales is working with NPL on photonics for the FSI system (both collaborations outside of the LaVA project). 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 has undertaken several demonstrator activities and these will be reported in future conference publications.

The Unified Device Interface is already made publicly available (https://git-ce.rwth-aachen.de/wzl-mq-public/soil) including example implementations for three commercial instruments. Discussions are underway with a metrology company which is interested in implementing the Interface for LVM tools. NPL has received requests from both the AMRC and AMPI organisations to supply them with commercial copies of the FSI-based OPTIMUM system which will use work from the LaVA project (HCN data) and from previous project LUMINAR. The OPTIMUM system will additionally be developed further in the DynaMITE project (http://empir.npl.co.uk/dynamite/) to update it to be able to handle faster-moving targets. There is ongoing interest in OPTIMUM expressed by the aerospace community at the annual 3DMC and CMSC events. The CNAM multilateration system is already being used in the DynaMITE project to provide metrology for a large cable-crane robot in Montpelier, owned by a research organisation. Other outputs such as the robotic photogrammetric scanner from LNE, and the IR-targeted photogrammetry system from TEKNIKER are designed with aerospace manufacturing in mind.

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 has helped develop metrology capability at the smaller NMIs – for example GUM has set up and equipped a LVM laboratory and participated in many aspects of the project, gaining experience of research and knowledge of current LVM tools and techniques including submitting data to the end of project data aggregator at RWTH. The inclusion of several external partners has strengthened the interaction between the metrology and non-NMI communities, *e.g.* between NPL and ISI, VTT and MAPVISION, and INRIM and FID. The HCN spectroscopy data is already being used by NPL in its FSI system and other NMIs have stated that they wish to see the data ratified by the CCL and enter the List of *Recommended Values of Standard Frequencies* for realising the metre, published by the BIPM(https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies), and publications on the HCN data by ISI have identified possible uses in metrology for telecommunications. NPL is working with the BIPM and CCL to make entries in the *Recommended Values of Standard Frequencies* list available for download in machine-readable format for automatic inclusion in FSI-based systems.

Impact on relevant standards

LaVA partners made three inputs to the ISO TC213 technical committee on the subject of laser tracker verification testing and work previously performed by NPL has now been cited in the updated issue of standard ISO 10360 Part 10 on laser trackers. The approach developed by NPL was in response to comments from some end users of this standard that regarded the tests as being too cumbersome to perform on a regular basis. The NPL approach is cited as a way of performing interim testing of laser trackers.

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 outputs from the project will be enabling technologies 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).
5. J Guillory, D Truong, and J-P Wallerand, "Assessment of the mechanical errors of a prototype of an optical multilateration system", *Review of Scientific Instruments* **91** 025004 (2020). (DOI: 10.1063/1.5132933).
6. M Peterek and B Montavon, "Prototype for dual digital traceability of metrology data using X.509 and IOTA", *CIRP Annals* **69** (1) 449-452 (2020). (DOI: 10.1016/j.cirp.2020.04.104).
7. J Guillory, D Truong, and J-P Wallerand, "Uncertainty assessment of a prototype of multilateration coordinate measurement system", *Precision Engineering* **66** 496-506 (2020). (DOI: 10.1016/j.precisioneng.2020.08.002).
8. Š Řeřucha, M Holá, M Šarbort, J Hrabina, J Oulehla, O Číp, and J Lazar, "Compact differential plane interferometer with in-axis mirror tilt detection", *Optics and Lasers in Engineering*, **141** 106568. (DOI: 10.1016/j.optlaseng.2021.106568).
9. J Guillory, D Truong, J-P Wallerand, and C Alexandre, "Absolute multilateration-based coordinate measurement system using retroreflecting glass spheres", *Precision Engineering*, **73** 214-227 (2022). (DOI: 10.1016/j.precisioneng.2020.08.002).
10. M Hošek, Š Řeřucha, J Hrabina, M Cizek, and O Číp, " Measurement of the Hydrogen Cyanide Absorption Lines' Centers with the Potential for Mise en Pratique", *Proc. IEEE*, 2021 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS) 1-3 (2021).
(DOI: 10.1109/EFTF/IFCS52194.2021.9604261), zenodo.org/record/6497486
11. J Hrabina, M Hošek, Š Řeřucha, L Pravdová, J Lazar, O Číp, and Z Pilát, " Saturated Spectroscopy of HCN", *Proc. IEEE*, 2021 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), 1-2 (2021).
(DOI: 10.1109/EFTF/IFCS52194.2021.9604272), zenodo.org/record/6497501
12. J Guillory, D Truong, and J-P Wallerand, "Multilateration with self-calibration: uncertainty assessment, experimental measurements and Monte-Carlo simulations", *Metrology* **2**(2) 241-262 (2022). (DOI: 10.3390/metrology2020015)
13. S El Ghazouli, A Vissiere, L-F Lafon, M-L Bouazizi, H Nouira, "Optimised calibration of machine vision system for close range photogrammetry based on machine learning", Accepted Publication *J. King Saud University – Comp. Info. Sci* (2022), (DOI: 10.1016/j.jksuci.2022.06.011)
14. J Hrabina, M Hosek, S Rerucha, M Cizek, Z Pilat, M Zucco, J Lazar, Ondrej Cip, ":Absolute frequencies of H13C14N hydrogen cyanide hyper-fine transitions in 1,5 μm region with saturated spectroscopy and sub-kHz scanning laser, submitted to *Optics Letters*. https://doi.org/10.48550/arXiv.2206.09232

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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 August 2018, 45 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 (withdrawn from 31 January 2020)
13. SAAB, Sweden</td></tr>
<tr><td colspan="3">RMG: -</td></tr>
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