Publishable Summary for 14IND09 MetHPM
Metrology for highly-parallel manufacturing

Overview

MetHPM has delivered metrology capabilities enabling order-of-magnitude improvements, in terms of simultaneous speed and accuracy, in state-of-the-art highly-parallel manufacturing (HPM) techniques such as roll-to-roll (R2R) embossing and injection moulding. HPM methods are increasingly being exploited in the production of large-area devices such as printed electronics, flexible photovoltaics and smart packaging, which have sub-micrometre scale features and/or structured surfaces that are critical to bulk sensing, optical, mechanical and/or aesthetic function. Project results include targeted inline metrology tools for defect detection and critical dimension measurement (objective 1); metrology enabling much higher accuracy substrate tracking and lamination overlay (objective 2); good practice for efficient optimisation of manufacturing processes, including parameter-based process feedback (objective 3); and the measurement traceability infrastructure and standards (objective 4) required to underpin these metrology tools.

Need

HPM use is growing rapidly. At the start of the project, expanding markets already needed more efficient and more traceable manufacturing processes. Existing markets demanded advanced HPM-based products in new areas and with much higher manufacturing accuracy than previously sought. The ongoing growth in HPM has created an urgent need for improved quality control, as current inspection metrology could not solve the conflicts between metre scale substrate size, high throughput, and sub micrometre scale 3D feature dimensions. Crucially, metrology was poorly matched to SME innovator capital budgets and metrology skills.

HPM encompasses multiple key independent technologies with common metrology needs. Printed electronics has been predicted to have a lasting impact on the EU economy, if underpinned by investment (2027 market estimate €262bn [2013 Organic and Printed Electronics Association roadmap]). R2R embossed or injection-moulded micro-structures add light management, antimicrobial, and security functionality to macroscopic surfaces. Similar growth was anticipated in e.g. smart packaging and in organic large area electronics fabrication. As HPM enters these markets for new advanced devices, the accuracy demands will increase because the devices require smaller feature sizes and higher yields.

The breadth of users, industrial processes, and measurement challenges required MetHPM to develop widely-applicable metrology solutions. Very high speed 3D feature inspection is needed for in-process geometrical tolerancing. Substrate metrology enabling sub-10 µm overlay accuracy is essential for R2R multilayer lamination in lighting and sensors. Process-speed inline metrology is needed to control the quality of functional nanostructured surfaces on low-reflectivity surfaces.

Objectives

MetHPM led to the development of smarter inspection metrology for HPM by tackling key gaps in metrology capabilities. The specific technical objectives of the project were to:

- **Develop more accurate measurement techniques for 2D/3D surface structure** – targeting 1 µm lateral and 0.1 µm height resolution, using a three-stage hybrid approach involving: 2D vision/novel imaging (*defect detection*); faster topography sensors (*defect measurement*) and utilising *a priori* knowledge (*bandwidth mitigation*). This included inline metrology support for large-area, often transparent or non-reflective, substrates up to 1.5 m in width.
- **Improve metrology for handling large-area substrates** – targeting 1 µm overlay accuracy measurement for sheet-to-sheet (S2S) and R2R applications through a mixture of: modelling of deformations; developing a high-resolution camera-based system; and preparing and testing novel inline registration methods.
- **Define and characterise surface measurement parameters** – to achieve correlation between surface parameters and functional behaviour of the manufactured item, to apply to real-time process control.
- **Demonstrate potential process improvements available through the application of new data** – by running a series of test cases through all the technical work of the project, involving traceable, industry-accessible, transferable methods that are readily exploitable.
- **Provide the missing traceability infrastructure** – by providing transfer artefacts, reference level instrumentation and new measurement methods that are self-referencing.

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Progress beyond the state of the art

14IND09 MetHPM was expected to advance the state of the art in four areas:

Sensor systems. At the start of the project, available inline surface inspection methods could not achieve the required resolution performance whilst simultaneously supporting HPM's large substrates and fast production throughputs. MetHPM has delivered: process-speed inline inspection of micro/nano-structured surfaces on challenging substrates; true high dynamic range proofs of concept for inline 3D topography; and by delivering a number of sensors, concepts and metrology tools for high-speed hybrid vision/topography inspection, emphasising non-proprietary optimisation, benchmarking and traceability.

Metrology for substrate handling. This project has produced novel sub-1 µm accuracy lateral substrate position metrology required to enable industry to overlay to better than 10 µm. Complementary methods to monitor alignment and overlay accuracy of (lower-cost, higher-volume) metre scale substrates have been created, including camera-based registration control and direct substrate embossing of alignment fiducials; these are supported by pre-normative concepts for the verification of overlay accuracy, and user-friendly flexible substrate models. Together these have already enabled true alignment accuracy to ± 20 µm.

Surface parameters for intelligent inline quality control. The consortium set out to tackle deficiencies in current methodologies by: defining pre-normative HPM-matched feature parameters; demonstrating a new universal, traceable substrate sample fixture; and by developing good practice on the correlation of surface topography to performance. These outputs have been shown to increase the efficiency of surface-function correlation at HPM pilot lines. Proposals for direct exploitation of correlation data for real-time automated process feedback have also been demonstrated.

Traceability and standardisation. Standardisation for HPM applications was still in its infancy (e.g. IEC TC119 for printed electronics initiated in 2012). This project expects to improve traceability and standardisation using newly-developed: HPM-compatible inline transfer artefacts and calibration procedures; pre-normative proposals for substrate overlay metrology and surface-function correlation; and stakeholder-matched training. Test cases have been presented to promote the uptake of standardisation and of the cost-saving metrology tools developed in the project, and related good practice guidance is to be published shortly.

Results

The MetHPM consortium has advanced the instrumentation state of the art for each of the key dimensional metrology challenges identified in the work plan. The results delivered include truly novel techniques as well as methods adapted and introduced to HPM markets.

Objective 1: Sensor systems.

The MetHPM consortium has gone beyond the state of the art by delivering: process-speed inline inspection of micro/nano-structured surfaces on challenging substrates; true high dynamic range proofs of concept for inline 3D topography; and by delivering a number of sensors, concepts and metrology tools for high-speed hybrid vision/topography inspection, emphasising non-proprietary optimisation, benchmarking and traceability.

For example, a portable spectroscopic scatterometer for the characterisation of nanostructured surfaces was constructed and tested at an injection moulding production line at DTU Danchip (DK) using a nanostructured shim fabricated by industrial consortium partner NILT. The scatterometer enabled real time feedback on the moulding quality of injection moulded polymer structures. This can potentially increase the speed and efficiency of injection moulding production by providing inline optimisation of the moulding parameters and reducing scrap rates. The portable scatterometer was complemented by a reduced cost, very high speed departure detection sensor that simultaneously measured the critical dimension, orientation and displacement of a 1D diffraction grating, such as those used for security markings.

In another example, a hybrid 2D/3D inspection platform has been developed to: demonstrate new, faster metrology approaches in HPM; provide a controlled recreation of inline metrology scenarios for hosted development of new sensors and techniques; and with the addition of appropriate sensors, enable rapid functional characterisation of samples to feed correlation models behind smarter inline process control. This hybrid instrument and hierarchical measurement strategy was capable of the high dynamic range, high resolution (2.5 µm lateral, 100 nm axial) measurement of sparsely located 2D and 3D surface structures and defects on large area substrates (180 mm width as configured; scalable beyond 1.5 m in principle).

The consortium has also enabled faster localised topography for feature dimensions of up to 1 m/s in hybrid systems. NPL and VTT developed methods and artefacts to traceably characterise inline optical topography line sensors, and to help manufacturers understand the effect of challenging surfaces on their sensors.

Two independent systems have been designed to realise high dynamic range 3D measurement by selective reconstruction of large volumes of cheaply-acquired image data from specialised imaging arrangements. For example, a ptychographic sensor has been designed, built and used to test developed image reconstruction algorithms in the visible wavelength range. This is enabling the optimisation of algorithms for the traceable measurement of high-resolution surface structures.

Separately, a general concept for the all-optical difference engine sensor has been developed based on novel filtering optics in the first ever attempt to apply such a system for quality control in HPM processes and this addresses the practical issues of online inspection. In delivering this portfolio of activities, the consortium achieved all aspects of objective 1 of MetHPM.

Objective 2: Metrology for substrate handling.

It is far better to prevent defects than to measure and correct them later. Since the circuitry of printed electronic devices is formed by laminating multiple printed, flexible sheets, more accurate measurements of substrate alignment and overlay enables major sources of defects to be controlled. Multiple techniques have been developed to provide the substrate positioning feedback that is needed for precision overlay and reprocessing in production R2R systems. The consortium demonstrated not only more accurate overlay measurement but also improved overlay control, exploiting the new measurement capability. New vision-based registration technology resulted in sub 5 µm accuracy in substrate position measurement in a running R2R gravure printing platform. New substrate handling mechanisms and tuning of control parameters of the registration metrology system resulted in a fivefold improvement in registration, with ± 20 µm level registration accuracy demonstrated at VTT's Oulu pilot printing facilities. The system design, verification strategy and target accuracy were based on a survey of stakeholder needs and the resulting performance meets those requirements, as validated through stakeholder interaction. Guidance on substrate positioning uncertainties has been developed for line operators and customers, and pre-normative concepts have been prepared relating to the verification of overlay accuracy in printed electronics.

In complementary work, NPL and CU delivered a prototype encoder system to enable precision steering control on a 1.4 m width R2R production research platform. The encoders work with gratings embossed directly onto transparent flexible webs, and currently support web speeds of up to 15 m min^{-1}. A measurement repeatability of 20.6 nm was achieved in benchtop tests, well beyond the sub 1 µm target of the project. In summary, the consortium has fully satisfied, and in places exceeded, objective 2 of the MetHPM project.

Objective 3: Surface parameters for intelligent inline quality control.

The ultimate test of the strength and relevance of the MetHPM project has been to demonstrate increased efficiency of surface-function correlation at HPM pilot lines as well as direct exploitation of correlation data for real-time automated process feedback. Through a set of key HPM test cases, partners have delivered new practical tools, techniques and good practice to enable HPM users to efficiently quantify correlations between a functional surface's performance (such as photovoltaic efficiency) and its 3D topography (in particular, defect class and population), and to exploit this correlation data for smarter in-process measurement and ultimately real-time process feedback. The work applies new quantitative analysis and parameter definitions, and introduces new user-oriented physical tools including universal substrate fixturing for efficient workflows.

Test cases were grouped into two thematic families: PLC, for printed linear conductors and conceptually equivalent features such as injection-moulded microfluidic channels; and SS, for highly micro- and nano-structured surfaces such as nano-imprinted optical gratings. The primary PLC test case, supported by Applied Materials Italia SRL, looked at the screen-printed metallisation of solar cells. New parameters were developed to describe the cross section of the printed conductors, they were then correlated with electronic properties to enable online property prediction as part of a proposed hierarchical feedback loop. The primary SS test case considered the use of precision injection moulding to imprint diffractive nanostructures onto rigid polymer discs. This reduced-cost technique may be used, for example, to create colour effects on plastic products. A method was developed to record the emitted colour, which was then correlated with values for grating height and width indicated by a new portable scatterometer. The new parameter-based fast inspection capability made it much more efficient to optimise the injection moulding process, and enabled real-time process control during stable mass production. Specific good practice guidance has been developed, and will be made available shortly. These outputs, which increase the efficiency of surface-function correlation at HPM pilot lines and demonstrate exploitation of correlation data for real-time automated process feedback, achieved all aspects of objective 3 of MetHPM.

Objective 4: Traceability and standardisation.

Traceable calibration, independent benchmarking, and unified standards are important prerequisites for the widespread use of new inspection metrology in quality control and have been a focus of MetHPM. New HPM-compatible inline transfer artefacts and calibration have been developed, with support for high-speed in-process 3D instruments. Existing and newly developed calibration techniques have been applied to new classes of instrument for independent offline benchmarking of the metrological characteristics. Partners have explored how 3D confocal inline sensors respond to difficult surface optical properties – typical for printed functional structures. New stakeholder-matched training, guidance and relevant test cases have been prepared to promote uptake of standardisation and the cost-saving metrology tools developed in the project. Pre-normative proposals relating to substrate overlay metrology and surface-function correlation have been prepared for input into standards committees. Transfer of standardisation and skills, such as uncertainty budgeting, has been encouraged between the industrial partners to promote good practice to industry by example. Project outputs have been presented at high-profile workshops and trade shows for wider industry awareness and learning. The project also indirectly supported the development of several doctoral students and early-career scientists. In this way, the project has developed and strengthened the skills of the European metrology community, both for HPM and for wider applications, and achieved objective 4 of MetHPM.

Impact

MetHPM is designed to directly address the most challenging metrology barriers to creating product value in HPM today. The project, therefore, benefitted users through several direct pathways:

1 *Wider community:* significant reductions in the economic and environmental cost of living in a range of targeted areas (solar energy, medical tests, stock control) through increased production efficiency in key HPM product applications.
2 *Industry:* immediate gains in quality control capabilities, and competitive advantage, for HPM stakeholders through smarter, traceable defect/function correlation, metrology specification and application, and understanding of the behaviour of substrates in process. Progress will also be made towards large-area inspection techniques which hold the promise of creating step-changes in substrate inspection.
3 *Industry:* new and disruptive production processes in HPM enabled by better inline monitoring of substrate, defects and features, including feedback control.
4 *Metrology community*: dramatically increased collaboration and knowledge transfer across previously isolated metrology communities and rationalisation/upskilling of key actors; supply of artefacts and guidance, improved NMI visibility and traceability uptake; improved stakeholder engagement across the technology- or manufacturing level range, in order to focus and sponsor academic innovation.
5 *Standardisation*: identification of opportunities to strengthen existing specification standards and to merge existing roadmaps according to stakeholder needs.

These technical outputs will be enhanced by contributions to international specification standards and dissemination of research outputs to end-users, including demonstrations of new measurement techniques.

Dissemination of results

Partners raised awareness of the MetHPM objectives and results throughout the project at key industry events such as the annual PrintoCent Industry Cluster meetings (Oulu, Jun), A&T 2018 (Turin, Apr 2018), and international conferences such as euspen (UK, May 2016; IT, Jun 2018), InnoLAE (UK, Feb 2016, Feb 2018), Macroscale (FI, Oct 2017), EOSAM (DE, Sep 2016) and Photon16 (UK, Sep 2016). By targeting both academic- and industry-oriented conferences, interaction with potential users has increased.

A test case involving prior correlation modelling and portable in-process scatterometry of injection-moulded nanostructures was showcased at the International Metrology Congress (Paris, September 2017) with a presentation and live demonstration, along with new calibration artefacts. Partners designed and held the 'Metrology of functional surfaces' workshop at industry event A&T 2018 (Turin) to showcase MetHPM outputs and to provide informal training, in particular relating to inspection of printed conductors. Project stakeholders including Applied Materials Italia SRL presented innovations at the workshop.

More generally, at least 16 open access papers have been published in international journals (listed in the next section), with a number of others under preparation. Results have also been publicised via trade journals.

Impact on industrial and other user communities

The consortium set out to equip stakeholders with new metrology tools to significantly reduce costs and wastage and ultimately to increase product value. Examples of these tools follow.

Bringing together outputs for several objectives, NPL developed a hybrid 2D/3D inspection platform intended to demonstrate the hybrid measurement approach, provide a controlled recreation of inline metrology scenarios for the hosted development of new sensors and techniques, and – with the addition of appropriate sensors – enable rapid functional characterisation and data registration to understand how surface features and functional performance correlate. The concept demonstrator is a lasting laboratory capability in its own right, and this is already in use to demonstrate other new defect and substrate metrology, as well as the artefacts and procedures used to calibrate inline 2D and 3D sensors for traceable dimensional measurement. The system has helped NPL measure customers' heavy steel parts, laser-etched hoses, and XCT standards, and, as part of a secondment from INRIM, has helped explore correlations with other electrical parameters.

New hybrid feature detection and local topography measurement using available sensors will enable the previously impractical inline assessment of defects, and new pathways for process feedback. The MetHPM consortium used industrial test cases to show how the novel use of new and existing sensors, combined with efficient, feature-parameter-based surface/function correlation determination can enable inline process control and, ultimately, commercial gains.

For example, DFM's new portable scatterometer was combined with a model of how grating dimensions influence clarity and shade of colour; the new parameter-based capability for fast inspection made it much more efficient to optimise a live precision injection moulding task, and it enabled real-time process control of the system during stable mass production. This lasting capability gives NILT the confidence to propose more sophisticated nanoimprint shims to customers who can realise new product features. This and related work at NPL should stimulate more formal specifications for structured surfaces in everyday products – a quantitative means for EU suppliers to highlight the exceptional value of 'premium' products and to maintain that 'local is reliable' silent unique selling point.

The consortium has delivered a standardised sample holder to enable efficient multi-instrument inspection, with data pre-registered for correlation analysis. MetHPM's correlation work will dramatically reduce the labour cost required to bring a new or modified product to full production by shortening offline 'trial and improvement' work, enabling automation and, in time, enabling process improvement insight from the continuous stream of 'free' quality control data. Key stakeholder partners will act as 'evangelists' for the wider community and this will drive further change.

In a test case supported by Applied Materials Italia SRL, INRIM and NPL applied the new standardised sample holder for industrial users and measurement good practice to co-register critical dimension and electronic performance maps of printed conductors. The resultant topography/resistance correlation model enabled slow resistance tests to be replaced with fast indirect estimates, as part of a proposed hierarchical control loop that will reduce waste in a very high-throughput photovoltaic wafer process. The parameter-based analysis has been adapted to printed electronics on flexible polymer at VTT, and the routine use of the universal sample fixture is being demonstrated at NPL and INRIM.

The consortium developed improved substrate tracking metrology and models that have been offered for use by the stakeholder partners for pilot line activities.

For example, following the NPL development of a very fast and repeatable prototype encoder system for objective 2, CU agreed to finance an early uptake activity in which NPL delivered the first two of six precision substrate tracking encoders to implement the direct tracking of webs on a state of the art 1.4 m wide roll-to-roll web guidance system running at metre-per-minute production speeds.

In another example, VTT and Offcode's new metrology, positioning hardware and alignment verification strategy yielded a five-fold improvement in actual registration accuracy at their Oulu facilities, which provide services for European printed electronics innovators. The new capability easily satisfies documented stakeholder needs.

Improved traceability for inline metrology will provide short-term competitive benefits to stakeholders – followed by wider take-up of calibration artefacts (and measurement services) in new industry sectors. Instinctive use of calibration in production is an impact ideal. To engage industry on traceability, the NMI partners have fabricated new and improved single-chip artefacts that will be rolled out with training and good practice emphasising the role and benefits of traceability in real industrial examples.

For example, VTT worked with the instrument manufacturing partner Focalspec (FSPEC) to develop not only robust, standard and practical methods to establish an in-process sensor's metrological characteristics – to 'calibrate' the sensor – but also ways to check how sensors perform when the surface is sloped or made up of multiple materials with very different properties. By using the new methods, and training provided by VTT, FSPEC was able to quantify current product performance and can confidently map out future product development.

The work also supports artefact manufacturers. By working with LU and NPL to support LU's synthetic aperture imaging (SAI) work, the UK manufacturer of a large, bespoke calibration plate was able to identify a ten-fold improvement to plate manufacturing precision, and can now sell a new product calibrated by NPL.

Impact on the metrological and scientific communities

MetHPM set out to breach cultural barriers between the well-integrated precision engineering metrology community (where the NMIs are established), and other industries contributing to HPM innovation (print, semiconductor fabrication, and others). The consortium includes some of the best candidates to enhance the fledgling traceable, standardised metrology capabilities within R2R today. 'Top-down' advanced manufacturing and precision engineering has established capable, well-integrated, industry-focussed dimensional metrology communities (NMIs, instrument manufacturers, academia).

The substrate tracking metrology successes at CU and VTT are a great example of how the MetHPM consortium has been guiding capability transfer towards R2R production, complementing current materials-science driven 'bottom-up' innovation. Leading by example, the consortium also worked together to apply classical dimensional uncertainty and metrology frame analysis to R2R printed electronics processes to quantify influences of process parameters and substrate selection; to complement this, the partners used the recent Macroscale conference (FI, October 2017, linked to TC-L and CCL meetings) to emphasise the multiscale industrial challenges in HPM to the dimensional metrology community. The NMI partners have helped create important links between industry and academia. For example, VTT provided the process insight and test samples to enable UNOTT to complete a benchtop industrial demonstration of their prototype all-optical difference engine (AODE) sensor, demonstrating the relevance of this lower-TRL work. Tools have also been passed to academic partners to support the training of future metrologists; for example, NPL's low cost reconfigurable illumination system for machine vision was demonstrated both on printed conductors and low-reflectivity nanoimprinted parts, before being repurposed by CU as a training tool.

Impact on relevant standards.

The priority was to collate and rationalise relevant specification standards from the contributing industries (topography, machine vision, print, semiconductor fabrication, application-focussed). The consortium targeted application-specific technical committees such as IEC TC119, in which the first MetHPM-relevant IEC TC119 standardisation activities had already begun. VTT has developed guidance on substrate positioning uncertainties for line operators and customers, and pre-normative concepts have been developed for the verification of overlay accuracy in printed electronics. VTT has also provided committee input relating to registration mark design. A new ISO 25178-linked areal calibration standard, to be supplied with guidance and training, is being rolled out to encourage take-up of existing standardisation. The consortium has developed written recommendations for ISO TC213, including pre-normative proposals relating to substrate overlay metrology and surface-function correlation, as well as a proposal to dramatically simplify the standard behind an important instrument calibration task to accelerate publication and simplify adoption.

Longer-term economic, social and environmental impacts

MetHPM's long-term key societal impact will be to reduce the cost of the EU's high standard of living by enabling innovation and efficiency gains in, for example: photovoltaics (energy); self-cleaning surfaces (environment and productivity); and instant disposable medical tests (healthcare provision). Project outputs will boost turnover and competitiveness by removing barriers to the use of novel R2R fabrication methods in the parallelised mass production of everyday devices as well as supporting anti-counterfeiting technology.

List of publications

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[9] Leach R K, Sims-Waterhouse D, Medeossi F, Savio E, Carmignato S and Su R 2018 Fusion of photogrammetry and coherence scanning interferometry data for all-optical coordinate measurement *CIRP Ann.* **67** 599–602

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[12] Madsen J S, Thamdrup L H, Czolkos I, Hansen P E, Johansson A, Garnaes J, Nygård J and Madsen M H 2017 In-line characterization of nanostructured mass-produced polymer components using scatterometry *J. Micromechanics Microengineering* **27** 085004

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[14] Madsen M H and Hansen P E 2016 Scatterometry-fast and robust measurements of nano-textured surfaces *Surf. Topogr. Metrol. Prop.* **4** 023003

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Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. NPL, United Kingdom	6. LU, United Kingdom	10. CU, United Kingdom
2. DFM, Denmark	7. NILT, Denmark	11. FSPEC, Finland
3. INRIM, Italy	8. UNOTT, United Kingdom	12. IBSPE, the Netherlands
4. VSL, the Netherlands	9. UOULU, Finland	13. Offcode, Finland
5. VTT, Finland		