METROLOGY FOR HIGHLY PARALLEL MANUFACTURING

FINAL PUBLISHABLE REPORT

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1 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.

2 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.

3 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.

4 Results

The MetHPM consortium has advanced the instrumentation state of the art for each of the key dimensional metrology objectives of the project. The workplan covered truly novel techniques and methods that have been adapted to and introduced into HPM markets. The project's results are described by objective below.

4.1 Objective 1: To develop measurement techniques to measure 2D and 3D surface structure (topography and/or defects) to high resolution (down to 1 µm lateral and 100 nm in height) in a manufacturing environment. This includes large-area, often transparent or non-reflective, substrates up to 1.5 m in width. Point, line and areal sensing, and scattering-based technologies will be considered, along with intelligent sampling routines, methods to discriminate defect types and methods for working on machine floors with high levels of noise and vibration. Hybrid technologies will also be developed where single instruments cannot achieve the required dynamic ranges.

Dimensional surface metrology is required to control advanced manufacturing processes for products such as large-area electronics, microfluidic structures, and light management films, where performance is determined by micrometre-scale geometry or roughness formed over metre-scale substrates. Although they are able to perform 100 % inspection at a low cost, commonly used 2D machine vision systems are insufficient to assess all of the functionally relevant critical dimensions in such 3D products on their own. Currently available high-resolution 3D metrology systems are able to assess these critical dimensions, but they have a relatively small field of view (1 mm^2 to 10 mm^2) and are thus 2-3 orders of magnitude too slow to keep up with HPM production.

The MetHPM consortium has gone beyond the state of the art by delivering: the 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.

The consortium has delivered smarter 2D inline defect detection for hybrid inspection systems. NPL has designed a **low cost reconfigurable illumination** system to enable the rapid digital optimisation, by end users, of the different contrast mechanisms that are available for a machine vision system in a pilot line or short run high volume manufacturing that is common in European industry. The illuminator and image processing tools were also demonstrated on low-reflectivity nanoimprinted parts, then repurposed as a training tool for postgraduate engineers. This 2D vision development contributed to the development and demonstration of NPL's **hybrid 2D/3D instrument concept** and hierarchical measurement strategy (see **Highlight 1**). This hybrid instrument and to the hierarchical measurement strategy is capable of high dynamic range measurements of sparsely located 2D and 3D surface structures and defects with up to 2.5 µm lateral resolution and 100 nm axial resolution (and in principle higher) over large area substrates with up to 180 mm width (and in principle up to and above the target 1.5 m width with additional 2D sensors), thereby addressing objective 1 of the project.

UNOTT realised a general concept for the **all-optical difference** engine (AODE) sensor and demonstrated measurement of 2D defects on R2R printed conductors on transparent flexible substrates. This scaled prototype showed there is no technical barrier to meeting both the substrate size and resolution aspects of objective 1 (see **Highlight 2**). Model-based detection sensitivity analysis showed that the AODE sensor would tolerate the vibration and substrate movement typical for an R2R manufacturing process. This is the first ever attempt to apply an ODE system for quality control in HPM processes and to address the practical issues of online inspection. The AODE concept will enable commercial realisation of flexible and configurable defect inspection systems with characteristics uniquely qualified for HPM processes.

UOULU designed and implemented an **online synchronised thermography** (ST) module, to extend vision-based inspection beyond the visible range in a hybrid inspection approach. The ST based system was capable of locating defects in conductive and often transparent large area thin films at web speeds relevant to existing thin film manufacturing lines. 100 % inline inspection was demonstrated on 1.5 m lengths of ITO/PET substrate. Whilst the width was limited to 150 mm by the supporting R2R winder, the measurement system would handle much wider substrates without modification. The testing coverage of the sample area was 100 %. This comfortably meets the requirements described in objective 1. The simplicity and relatively low cost of the ST-system makes the approach well-suited for incorporation into the online process quality monitoring of the R2R (and S2S) manufacture of large area conductive thin films.

The consortium has also enabled faster localised topography for feature dimensions up to 1 m s^{-1} in hybrid systems. VTT and NPL have developed **methods and artefacts to determine the metrological characteristics of inline optical topography line sensors**. VTT developed an accurate depth scale calibration method using a single prototype groove depth sample for the Focalspec (FSPEC) LCI line sensor and they validated it with laser-interferometric sample tracking, attaining (sub-) micrometre level or better than 0.1 % scale accuracy. VTT also studied the effects of surface slope angle, specularity and colour on the metrological characteristics, in particular scale magnification and linearity. Objective 1's target of a 0.1 µm Z resolution is achievable with LCI technology, and 1.5 m width substrates may be inspected subject to parallelisation approaches. Partly based on the use of etched matte calibration samples and also on the use of samples generated within the project, FSPEC have gained a deeper understanding of their measurement principle, and are better equipped to develop enhanced sensors and widen their customer base. FSPEC also expect to integrate the developed calibration and characterisation methods into their sensor manufacturing workflow.

NPL have studied the feasibility of using a **point-array sensing concept** to inspect the critical dimensions of printed linear conductors – or equivalent HPM features – at up to 1 m s^{-1} in, for example, a hybrid solution. Strategies to achieve this throughput using slower commercially-available sensors were discussed and trialled using the pre-measured topography of conductors on a photovoltaic wafer.

The consortium has demonstrated reliable, process-speed shop floor inline inspection on low reflectivity micro-/nano-structured surfaces. DFM developed a fast and robust scatterometer to characterise nanostructures imprinted on transparent polymer discs (from NILT). The scatterometer was shown to determine the structural parameters of the samples with an accuracy of a few nanometres in less than a second, thereby enabling the **process-speed in-line characterisation of low-reflectivity nanostructures**. With the developed scatterometry method, NILT will be able to produce nano-textured samples of better quality and with a much lower scrap-rate, as changes in moulding conditions are immediately found. Good practice in mould cleaning can therefore evolve from a fixed schedule to one driven by direct sample quality measurement. The instrument also improves the efficiency of optimising a new or existing injection moulding recipe. These capabilities will enable better and cheaper products to be produced. NILT as an end-user partner in the project, contributed heavily to the development, and provided stakeholder feedback.

NPL developed a departure detection sensor that simultaneously measures the critical dimension, orientation and displacement of a 1D diffraction grating. This technique is suitable for in-line metrology in a R2R manufacturing environment and it complements the DFM/NILT scatterometry work as an alternative method for **detecting the departure of grating critical dimensions from nominal**. The calculation of the grating parameters is analytical and fast to compute, meaning it can be implemented in real time at the high bandwidths required for in-line characterisation and closed loop substrate control. The equipment required by this sensor is low cost, meaning it could be installed at multiple locations in a production line for improved quality control or monitoring, or it could be applied to other applications at low cost, such as the secondary in-house metrology of gratings or the inspection of diffractive structures.

Finally, the consortium has developed two independent systems to realise high dynamic range 3D measurement using the selective reconstruction of large volumes of cheaply-acquired image data from specialised imaging arrangements. These techniques will achieve an axial resolution performance of better than 100 µm.

LU has designed a novel implementation of **synthetic aperture imaging** (SAI), targeting requirements for online inspection including in the roll-to-roll context. This lab-scale activity was structured to demonstrate the direct scalability to metre-width substrates within relevant production environments. The system uses compact digital holographic cameras, is scalable, and includes a bespoke calibration plate. LU have demonstrated the capability of SAI as a means to provide high resolution measurements over exceptionally large fields of view. The results presented, clearly show that it is possible to synthesise interferograms from coherent images that are essentially the same as those generated by coherence scanning interferometry, but which extend over a field of view that is orders of magnitude greater. The work has gained interest from instrument manufacturers and end users, and it has enabled a collaborator to optimise and sell large scale, high resolution artefacts that are calibrated by NPL.

VSL designed and built an adaptable metrology instrument for coherent scatterometry and microscopy applications, and they used it to test developed image reconstruction algorithms such as **ptychography** in the visible wavelength range. The developed reconstruction algorithm together with user-friendly measurement software allows an automatic measurement/reconstruction routine to be used. VSL evaluated the metrological characteristics of the system using a calibration artefact developed under MetHPM. The method may be used for metrology application even with instrument errors of up to 50 %. Exemplar HPM measurements of gratings on NILT's nanostructured polymer discs have been carried out. Analysis of the 'ideal' (no-noise) reconstruction and reconstruction with artificial camera and encoder position errors showed the robustness of this method and hence the potential to implement it for metrology based application in the NMI network as well as in industrial applications where only amplitude information is a limiting factor, like for transparent R2R fabrication. Further work is planned to determine the range of applications of the algorithm, compared to the prior state of the art. VSL has initiated a calibration service using ptychographic microscopy for, e.g., 2D calibration artefacts.

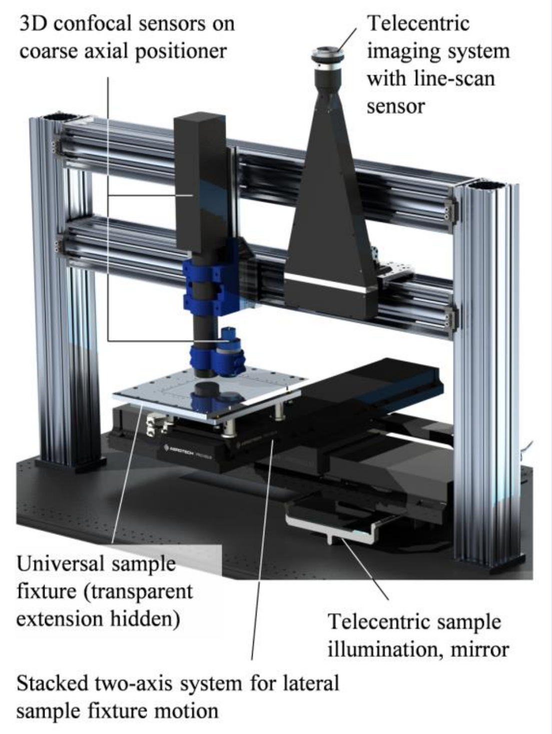
In summary, the MetHPM consortium has demonstrated (a) hybrid 2D/3D inspection of large area, high resolution HPM-relevant surfaces, including optimisation of lighting and an all-optical difference engine and supported in principle by synchronised thermography; (b) process-speed departure detection and dimensional characterisation of nanostructures on low reflectivity surfaces; (c) methods and artefacts to determine the metrological characteristics of inline optical topography line sensors; and (d) two independent systems to realise true high dynamic range 3D measurement through smart reconstruction. In delivering this portfolio of activities, the consortium has **addressed all aspects of objective 1** of MetHPM.

Highlight 1: A hybrid 2D/3D inspection concept with smart routing optimisation for high throughput, high dynamic range and traceable critical dimension metrology

To support in-process metrology innovators in European industry, NMIs need the means to evaluate new sensor technologies, to help characterise process defects, and to demonstrate the possibilities for novel inline inspection strategies. Smarter dimensional surface metrology is required to improve manufacturing process control for products such as large-area electronics and microfluidic structures, where performance is determined by micrometre-scale geometry or roughness formed on metre-scale substrates. Machine vision alone is insufficient to assess such critical dimensions, and current 3D metrology is much too slow.

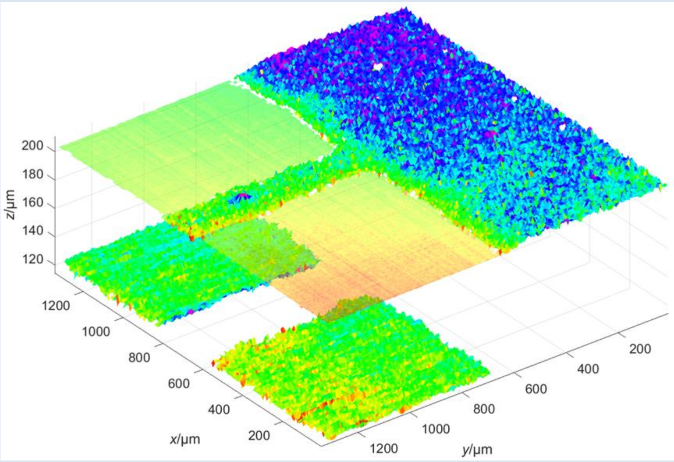
NPL developed and demonstrated a hybrid 2D/3D inspection platform intended to (a) demonstrate the core high dynamic range surface metrology approach, (b) provide a controlled recreation of inline metrology scenarios for the hosted development of new sensors and techniques, and (c) with the addition of appropriate sensors, enable the rapid functional characterisation and co-location of data to feed surface/function correlation models. In this concept, a small field of view, high-performance 3D topography-measuring instrument is combined with a large field of view, high-throughput 2D machine vision system. The location of critical dimensions and defects are first registered using the 2D system, then smart routing algorithms and high dynamic range measurement strategies are used to efficiently acquire local topography using the 3D sensor. A motion control platform with a traceable position referencing system is used to recreate various sheet-to-sheet and roll-to-roll inline metrology scenarios. High dynamic ranges of both height and reflectivity were demonstrated using a hybrid approach to inspect screen-printed electrodes on photovoltaic Si wafers and screen-printed electronic interconnects on plastic film.

Since European innovation is often driven by SMEs working across multiple disciplines and without formal metrology training, an important application of the hybrid metrology platform will be to demonstrate both current good practice and novel methods to ensure their metrology instrumentation works harder. The concept demonstrator is a lasting laboratory capability in its own right, and it 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.



◄ *A rendered representative image of the lab based simulation platform, showing an example configuration for a hybrid 2D/3D inspection system.*

▼ *The 3D measurement of a bright silver printed conductor on a transparent polymer film.*

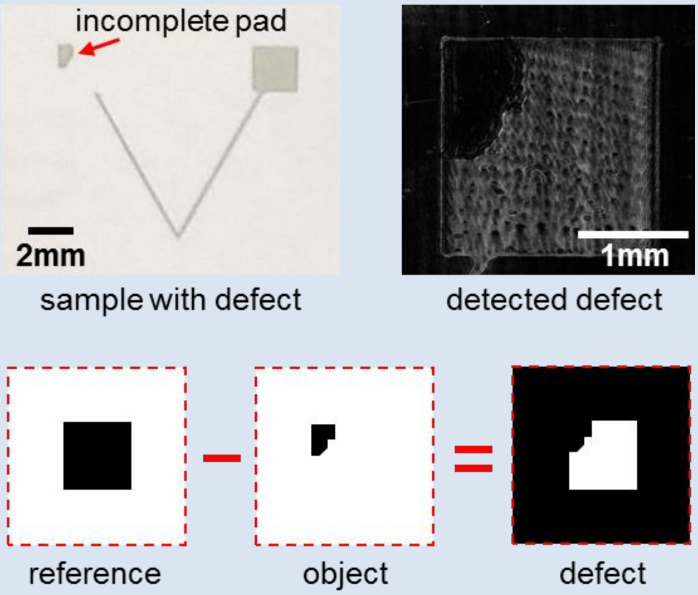


Highlight 2: All-optical difference engines (AODEs) for efficient defect detection

For repetitive vision-based inspection in fast, low-margin highly-parallel manufacturing processes, the required image processing infrastructure can prove too energy or cost intensive. Direct optical comparison with a known gold standard would simplify the post-processing task, or enable the use of much faster sensors for departure detection, in an enhancement to traditional machine vision techniques for inline inspection.

UNOTT has developed a benchtop defect detection demonstrator that optically evaluates differences in the diffracted optical field, from a feature under test and from an adjacent feature or gold standard. The all-optical difference engine is a scalable technique, which can be applied to inspect complex deterministic surface structures with relatively frugal post-processing. The camera can be easily replaced by a low-cost photodiode to realise high-speed all-optical information processing and inspection.

One example application would be in the inspection of printed electronic sensors, which are printed in arrays on large flexible substrates. This scaled demonstrator was tested on flexographically-printed conductors on a transparent polymer sheet, from VTT; it was capable of inspecting areas of 4 mm width with a resolution in the order of several micrometres, and it can be duplicated in parallel to inspect larger areas without significant cost.



◄ *AODE's principle and defect detection example.*

▼ *The AODE demonstrator.*

4.2 Objective 2: To develop methods for handling large-area substrates (up to 1.5 m wide) in sheet-based and roll-to-roll applications to allow substrate handling and overlay accuracy of less than 1 µm. This includes the measurement of substrate deformation and the dynamic properties of substrate materials. Such techniques will enable the next-generation of substrate-handling systems for high-resolution patterning applications. Methods involving instrumenting the substrate will be considered.

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 measurement of substrate alignment and overlay enables the major sources of defects to be controlled. Multiple techniques have been developed to provide the substrate positioning feedback needed for precision overlay and reprocessing in production R2R systems, as follows.

Multiple reviews were undertaken of the state of the art in R2R and S2S parallel manufacturing overlay registration (DOF detection and registration), and of the behaviour and modelling of large flexible polymer substrates. This provided a suitable basis for developing and enhancing registration control, substrate instrumentation and monitoring approaches in the project.

In work to support high-volume printed electronics, VTT and Offcode demonstrated not only more accurate overlay measurement but also improved overlay control, exploiting the new measurement capability (see **Highlight 4**). The consortium also set out to exceed the current ± 50 µm overlay accuracy state-of-the-art with conventional camera-based substrate monitoring adapted from the conventional print industry. Developed tools such as gravure-cylinder registration mark metrology and camera-based registration control, and a concept for overlay accuracy detection, quickly resulted in 1 µm to 5 µm accuracy in substrate position measurement, and ± 30 µm to ± 50 µm in physical registration error (i.e. overlay accuracy).

For example, Offcode and VTT have developed the ARCOS registration camera, which has been shown to achieve 5 µm measurement accuracy in substrate monitoring in a running R2R gravure printing platform. Performance approaching 1 µm should be possible with good registration markings. The new metrology has created headroom for further improvement in physical overlay accuracy following future developments in substrate control mechanics.

New substrate handling mechanisms and the tuning of the control parameters of the high resolution camera based feedback system resulted in the further reduction of registration errors, with **± 20 µm level registration accuracy** demonstrated at VTT’s Oulu pilot printing facilities. The system design, verification and target accuracy were based on a survey of stakeholder needs and the resulting performance meets those requirements, as validated through stakeholder interaction. VTT has developed guidance on substrate positioning uncertainties for line operators and customers, and pre-normative concepts have been developed for the verification of the overlay accuracy in printed electronics. DFM provided uncertainty analysis support.

NPL and CU have developed the concept of a substrate tracking system in which simple grating patterns are embossed and UV cured in/onto the substrate, and optically detected with a laser interferometric setup that is sensitive to the movement of the patterned substrate (see **Highlight 3**). The signal containing position information is obtained by an interferometric read head and signal processing optimised to monitor a simple encoder scale fabricated on the surface of the web that acts like a high precision ruler. The designed instrumentation is in principle compatible with S2S as well as R2R processes, by re-engineering of the optical paths. Tests of the system using a well-formed grating structure revealed that measurement repeatability as low as 20 nm to 40 nm is possible. NPL and CU have since achieved faster real-time readout (using improved optics, electronics and software), and improved position resolution (practical repeatability down to 21 nm from 32 nm). This performance clearly exceeds the target of Objective 2 of MetHPM, i.e. new metrology that can measure the position of a web with sufficient performance to enable 1 µm accuracy motion control for overlay. On the strength of early results from the project, CU agreed to finance an early uptake activity in which NPL delivered a gantry with the first two of six substrate tracking encoders, to implement 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 summary, through two key results applicable to R2R and S2S the consortium has **fully satisfied, and in places exceeded, objective 2** of MetHPM. Firstly, a novel position referencing system achieved 21 nm position measurement repeatability with directly instrumented webs, and will enable overlay accuracy to better than 1 µm on a state of the art 1.4 m wide R2R web guidance system. Secondly, new registration mark metrology, substrate behaviour uncertainty analysis and camera-based registration control enabled sub-5 µm accuracy in substrate position measurement, and was immediately exploited to improve true overlay accuracy from ± 100 µm to ± 20 µm.

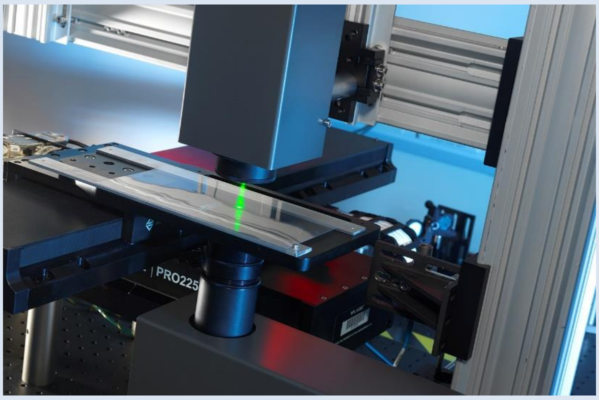
Highlight 3: A high precision position-referencing system for roll-to-roll manufacturing processes

NPL's position-referencing system directly measures the in-plane motion of transparent flexible substrates, enabling the next generation of Advanced Manufacturing processes that require high-precision data on-demand for high volume production on R2R film fabrication platforms. The system operates like an optical encoder, reading the position *via* a simple scale that is pre-fabricated on the substrate.

Key features:

- Direct measurement of film motion for a small metrology loop
- Sub-micrometre performance for advanced processes
- High sampling rate and real-time signal processing for data on-demand

In contrast to the low sampling rate and resolution offered by standard machine vision based systems, NPL's position-referencing system offers low noise, high precision measurements at the rapid sampling rates needed for advanced web handling and fabrication processes.

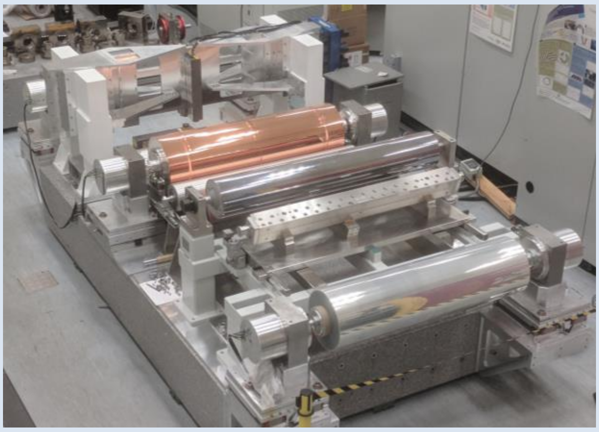


◄ *Photograph of the position-referencing system during tests on NPL's hybrid metrology system*.

Specifications:

Web speed[1]	up to 0.25 m/s (15 m/min)
Sampling rate[2]	up to 50 kHz
Measurement repeatability[3]	20.6 nm

(1) *Maximum web speed available when using a typical 40 µm period encoder scale.* (2) *Internal data acquisition rate.* (3) *Standard deviation of displacement residuals (corrected for systematic errors) obtained from measurement of 10 mm linear motion of reference encoder scale with respect to traceable reference interferometry.*



◄ *Photograph of 1.4 m wide precision R2R platform at Cranfield University (CU), with two copies of NPL's position-referencing system installed on an NPL-designed gantry (top-left of picture)*.

NPL's position-referencing system achieves this high specification by exploiting optical interferometry and real-time signal processing. The signal containing position information is obtained by an interferometric read head that has been optimised to monitor a simple encoder scale fabricated on the surface of the film that acts like a high precision ruler. These scales can be produced in-line on existing roll-to-roll systems by various means e.g. the addition/modification of a fabrication module. Alternatively, the scales could be pre-fabricated on the roll of substrate web material.

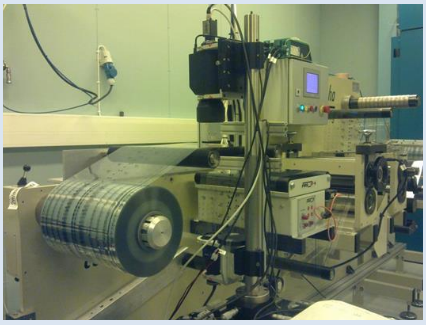
Highlight 4: Overlay accuracy verification

Overlay accuracy during film lamination is important for the function and reliability of printed electronics, and requirements become tougher and tougher and designers look to miniaturise printed components. As VTT provides pilot line services for Europe's printed electronics innovators, it was important for VTT to maintain world-class substrate alignment abilities through better *detection* and *correction*.

VTT surveyed a range of stakeholders to define current and upcoming requirements for precision alignment; participants represented print machine manufacturing, printing, instrumentation and applications. The target real overlay accuracy was set at ± 25 µm, compare to VTT's ± 100 µm starting point.

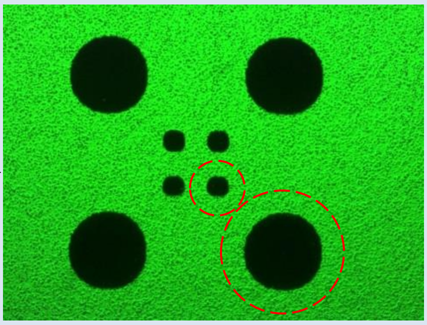
Working with Offcode and other industrial stakeholders, VTT delivered a package of work to meet this accuracy goal. Procedures were developed to verify both the assembly and the performance of registration accuracy instrumentation. Stakeholders agreed with the proposed verification strategy. A system-level uncertainty analysis helped the consortium understand the contributions from the substrate, the printing hardware, printed registration marks and the accuracy instrumentation itself. This knowledge will help suppliers understand their role in optimising system performance.

The production technology providing partner Offcode worked with VTT to test a new camera-based registration control system, applying the stakeholder-validated strategies. The camera system was optimised through a series of offline then online tests.



◀ *Initial reliability testing of Offcode's camera registration system.*

Registration marks used; the circled marks are printed on the second layer; the rest are printed on the first layer. ▶



After the successful pre-tests, Offcode's camera system was installed onto VTT's ROKO line for R2R printing trials. Servo control hardware was added to make machine direction (MD) corrections to the registration. Registration markings were printed using rotary screen printing, with 12 registration marks per rotation to robustly verify the current registration accuracy. After configuring the feedback control gains, threshold and update rate, VTT completed a campaign of test runs in order to find the registration accuracy that the system can achieve. To verify suitability for different printing conditions different printing materials and different process speeds were tested.

VTT and Offcode not only achieved a **1 µm to 5 µm measurement accuracy** for registration error, using the camera-based registration system at VTT Oulu, but immediately exploited the new metrology to show **± 20 µm accuracy in actual substrate overlay**. There is still headroom in the camera system's resolution and accuracy, and further improvements to registration accuracy are expected with better substrate handling and modelling of periodic error components.

◀ *VTT's ROKO line used for R2R printing trials.*

4.3 Objective 3: To define and characterise morphological parameters to be used for real-time process control and correlation between these parameters and functional behaviour of the devices under test.

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. For a summary of the primary test case from each family, see **Highlight 5** and **Highlight 6**. Specific good practice guidance has been developed, and will be made available shortly.

Printed linear conductor (PLC) theme.

The electronic function and reliability of printed electronics – such as photovoltaic (PV) cells, disposable medical devices and smart packaging – depends in part on the cross-section geometry of the printed conductors. Similarly, the flow characteristics of microfluidic devices depends on the cross section of the imprinted fluid channels. Quality control demands faster, more accurate surface structure measurement for critical dimensions of tracks and channels based on 3D surface metrology.

PLC-theme test cases were defined to inspect (a) screen-printed front-contact electrodes during the metallisation of c-Si photovoltaic wafers, (b) screen- and flexoprinted test structures for monitoring a R2R printing pilot line (with VTT); and (c) fluid channels on a polymer embossed microfluidic test structure (with NILT). A common requirement was identified to replace slow direct line resistance measurement with estimates inferred from fast topography measurement.

Led by INRIM, a conductor topography/resistance correlation model was developed and validated for the AMAT (collaborator: Applied Materials Italia SRL (AMAT)) and VTT test cases based on laboratory resistance and topography measurements on purpose-made test structures. This process used new tools and procedures appropriate for the industrial user's laboratory.

INRIM and NPL developed the concept of a universal substrate sample fixture (USSF) for the handling and sharing of flexible, planar samples up to (160 mm)^2 as the photovoltaic wafers, into a cost-effective lab tool for efficient and traceable process output study. The USSF incorporates a universal base plate for permanent installation, kinematic locators and semi-disposable substrate clamps. The USSF will also incorporate calibration artefact holders to encourage routine use of, for example, stage calibration line-scales and areal calibration artefacts.

Traceable morphological parameters have been identified to quantify the relationship between texture, form, sizes and resistance features of AMAT PV wafer fingers and busbars. A strategy and proposed control architecture for topography-based online process control was developed for the Applied Materials test case, exploiting the defined morphological parameters; this strategy may be adapted to other printed conductors and abstracted to microfluidic channels.

A complementary NILT microfluidic test case considered to what extent fluid channel cross section geometry and floor roughness could be described using simple numerical parameters. These candidate parameters were used to describe the variation in channel morphology across the polymer chip; although some general dependencies were noted, further refinement is required before pursuing the process control of microfluidic channels using these methods.

Highlight 5 (test case): Topography-based process control of printed conductors

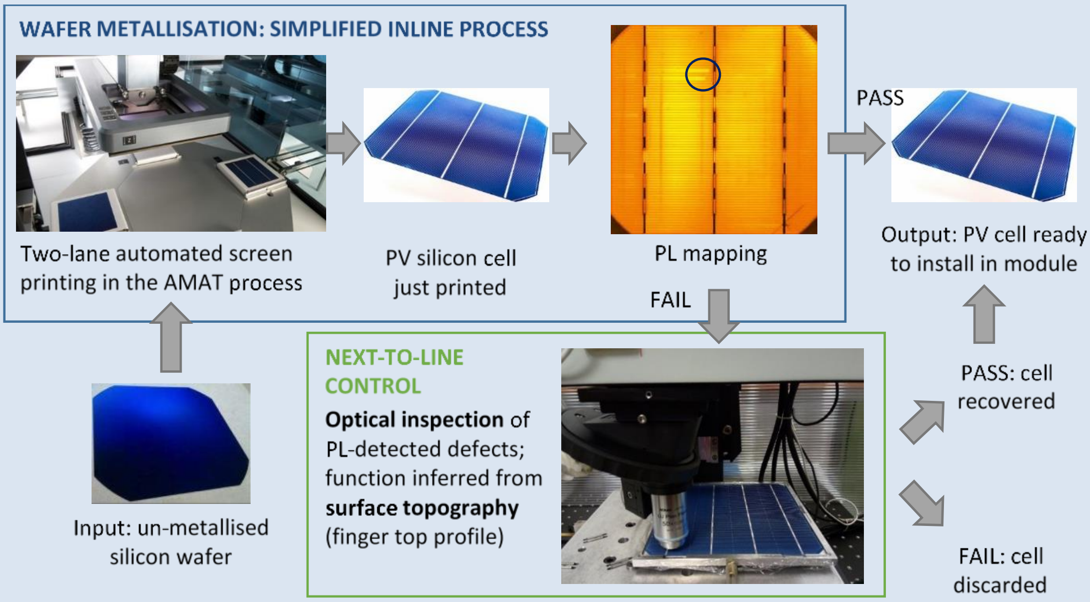
Direct 3D measurement unlocks new ways to inspect printed conductors that are not feasible with conventional machine vision. However, topography measurement has been too slow for closed loop process control. With industrial support from collaborator Applied Materials Italia SRL (AMAT), the MetHPM consortium developed new metrology tools to enable 3D topography-based process control.

Europe's manufacturers increasingly exploit the appearance, flexibility and reduced cost of printed electronics, using reduced-cost printing techniques like offset lithography, screen printing and inkjet to print conductors for rigid or flexible substrates, and on moving freeform surfaces too. For PV cells, screen-printing is cost effective and continuously improved, and the dominant method to deposit silver-based contacts onto wafers. The electronic efficiency and reliability of a PV cell depends on the cross-section geometry and the cure quality of the printed conductors, known as fingers and bus-bars. Finger inspection therefore needs 3D geometrical measurements. The MetHPM consortium targeted: faster, more accurate surface structure measurement for critical dimensions of tracks and channels; process optimisation, inline feedback exploiting defect-function correlation; and traceability, standards and metrology guidance.

Applied Materials Italia SRL supplied the consortium with metallised cells for study: standard-layout c-Si (with electro-luminescence data); and specialist test cells with modified finger dimensions on c-Si and alumina. INRIM and NPL used confocal microscopy and mosaic techniques to reconstruct the 3D morphology of extended finger segments, and to analyse for finger thickness, width, texture and form. This revealed local defects on the fingers and generated global parameter variation. Local variation in finger line resistance can be inferred from local 3D finger morphology. Two useful parameters have been identified to represent the morphology of fingers: cross-section area and top roughness. A topography-resistance correlation was validated using a theoretical model and inferred resistance values verified with laboratory reference measurements.

The consortium worked with Applied Materials to determine how the new capability would be implemented within current production, which is extremely high-throughput. In a hybrid approach, automated next-to-line 3D inspection would be used to check local defects found using photoluminescence inspection. Print quality would be evaluated through top roughness and cross-section area waviness parameters of the metallisation grid. 3D inspection decides the likely fate of a defective cell, and provided process feedback for operators.

▼ *Proposed role for 3D optical inspection in PV wafer metallisation.*



Highlight 6 (test case): Scatterometry for inline optimisation of polymer injection moulding

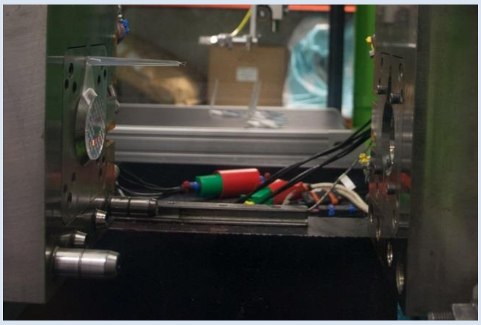
Precision micro- and nanostructured masters can be combined with conventional injection moulding techniques to impart novel optical or bio-interface functionality onto plastic devices in a cost-effective way. This approach demands new production-speed quality control of micro- and nanostructures. Deterministic nanostructures help to ensure that surfaces have the desired optical, mechanical or bio-interface properties. Nanoimprinting methods – adapting polymer injection moulding or roll-to-roll embossing – enable low-cost addition of nanostructures to products and have been a key focus of the MetHPM project.

The consortium explored how to use scatterometry to inspect the representative diffractive nanostructures that are precision injection-moulded onto rigid polymer discs by industrial partner NIL Technology (NILT) – these structures produce an iridescent colour effect.

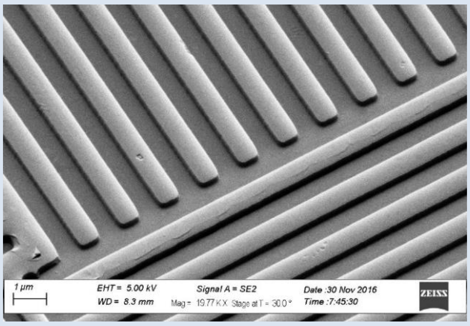
DFM constructed a portable spectroscopic scatterometer for in-situ characterisation of the nanostructured discs. The method was validated by comparison with confocal microscopy, AFM and SEM, with good agreement found between techniques. DFM's portable scatterometer was tested at an injection moulding production line at DTU Danchip using a nano-structured shim fabricated by NILT.

The scatterometer successfully characterised nanostructured discs quicker than the typical injection moulding cycle time, demonstrating real time feedback on the quality of injection moulded polymer structures. This can potentially increase the speed and efficiency of injection moulding production by providing in-line optimisation of the moulding parameters and reducing scrap rates.

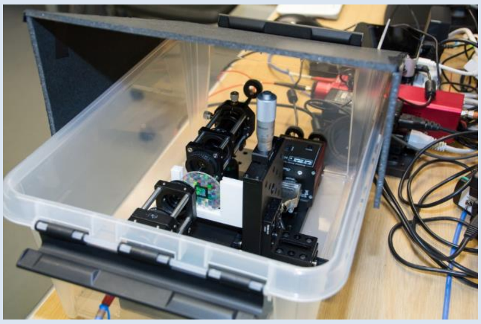
In related work, NPL developed and demonstrated a diffraction-based critical dimension measurement system used to detect departure from nominal geometry for roll-to-roll imprinted gratings on flexible polymer sheets. This demonstrator employs spot measurement and high speed electronics for high throughput inspection of continuous gratings.



Injection moulding is used to create polymer items with imprinted nanostructures…



…such as these regular gratings for optical effects, created using technology from NILT.



DFM produced a portable spectroscopic scatterometer to characterise nanostructures…

…and used it in field trials to demonstrate real time process feedback for moulding quality.

Structured surfaces (SS) theme.

Precision micro- and nanostructured masters can be combined with conventional injection moulding techniques to impart novel optical or biomechanical functionality onto plastic devices in a cost-effective way. This approach demands new production-speed quality control of micro- and nanostructures.

The primary SS-theme test case considered the use of precision injection moulding to imprint diffractive nanostructures onto rigid polymer discs (with NILT). This reduced-cost technique may be used, for example, to create colour effects on plastic products. A method was developed to extract the colour information from an emitted light spectrum by calculating the overlap of the spectrum with the red, green, and blue (RGB) colours. A developed test structure design contained around 100 grating areas with different orientations and periods suitable for various characterisation tools. The RGB colour distribution of a grating was correlated with values for grating height and width parameters indicated by scatterometry, with known 'good' and 'bad' samples used as a continuity reference from existing inspection.

The new parameter-based capability for fast inspection made it much more efficient to optimise the moulding temperature of system components, and enabled real-time process control of the system during stable mass production.

In summary, through a set of key HPM test cases, partners have delivered new practical tools, techniques and good practice to enable use of morphological parameters to efficiently quantify correlations between a functional surface's performance (such as photovoltaic efficiency, or nanostructure 'colour') 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. These outputs, which increase the efficiency of implementing process control at HPM pilot lines, **achieved objective 3 of MetHPM**.

4.4 Objective 4: To provide a traceability infrastructure for large-area, high resolution, high throughput surface measurement technology, including the use of transfer artefacts, reference instrumentation and new reference-free measurement methods. To supply input to relevant standards bodies.

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 procedures (including consideration of optical property matching) have been developed, including a calibration artefact for high resolution instruments (VSL), calibrated areal standards for general topography-measuring instruments including high speed confocal line sensors (NPL), and multi-property artefacts (VTT) (see **Highlight 7**). 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 (see **Highlight 8**). Project calibration-related outputs have been documented for dissemination into standards working groups who specialise in surface topography and applications e.g. printed electronics.

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. INRIM's surface-function proposal for printed linear conductors relates to the definition of new surface parameters linked to the cross-sectional area of the printed conductor. DFM's surface-function proposal for structured surfaces (for colour-generating diffractive structures) relates to quantitative parameters describing the surface structures.

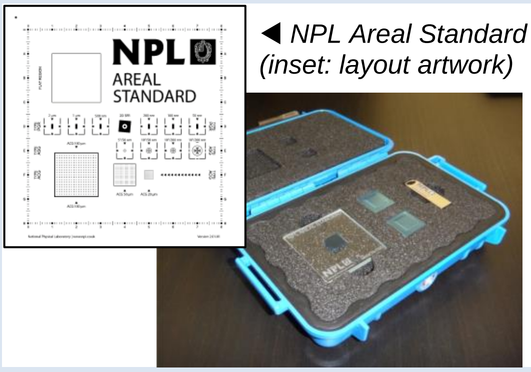
Active support for the **transfer of standardisation and skills** between the industrial partners has been encouraged through review exercises and test case measurement activities, in order to promote good practice to the wider industry by example. Uncertainty analysis has been documented for instruments, such as the University of Nottingham's AODE and DFM's portable scatterometer, for substrate overlay accuracy, and for surface-function correlation work. Uncertainty sources were combined using a Monte Carlo technique for NPL's linear diffraction grating critical dimension departure detector. DFM developed a **reference-free method** for the scatterometric characterisation of nanostructures, an important step towards implementing spectroscopic scatterometry as an in-line characterisation tool in production environments. An uncertainty budget for overlay accuracy was developed from experimental data, and used to determine the primary causes of substrate deformation during roll-to-roll printing. Project outputs have been presented at high-profile workshops and trade shows for wider industry awareness and skills transfer. The project has 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.

In summary, the consortium **achieved objective 4** of MetHPM by providing the required traceability infrastructure for large-area, high resolution, high throughput surface measurement technology, consisting of new HPM-compatible inline transfer artefacts and calibration procedures, new stakeholder-matched training, guidance and relevant test cases, and pre-normative proposals and other inputs to relevant standards bodies.

Highlight 7: New HPM-compatible inline transfer artefacts and calibration procedures

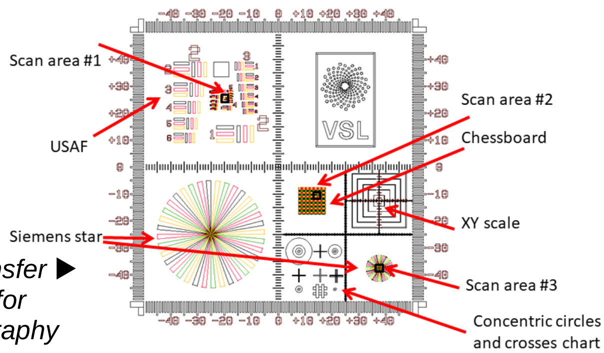
Continuous development of calibration artefacts is required to help manufacturers test and benchmark their inline inspection sensors, and to facilitate the traceability demanded for quality control. The MetHPM consortium developed new HPM-compatible inline transfer artefacts and calibration procedures.

NPL's Areal Standard and VSL's ptyychography transfer artefact are single-chip artefacts bearing multiple features designed for the calibration of areal surface topography measuring instruments. By placing multiple features onto the same chip, it is more feasible to automate artefact use – especially inline – and the cost of ownership is reduced. NPL designed the packaging for the Areal Standard to make it more compatible with clean room operations, associated with the operation of precision research and manufacturing steps for many applications. The design was developed based on feedback on the bento box packaging from industrial stakeholders. NPL's Areal Standard was used to calibrate, for example, a fast confocal line sensor that is typically used for inline display inspection. VSL's transfer artefact, calibrated by AFM, was used to establish the metrological characteristics of their new multi-function scanning ptychographic instrument.



◀ *NPL Areal Standard (inset: layout artwork)*

VSL transfer artefact for ptychography ▶



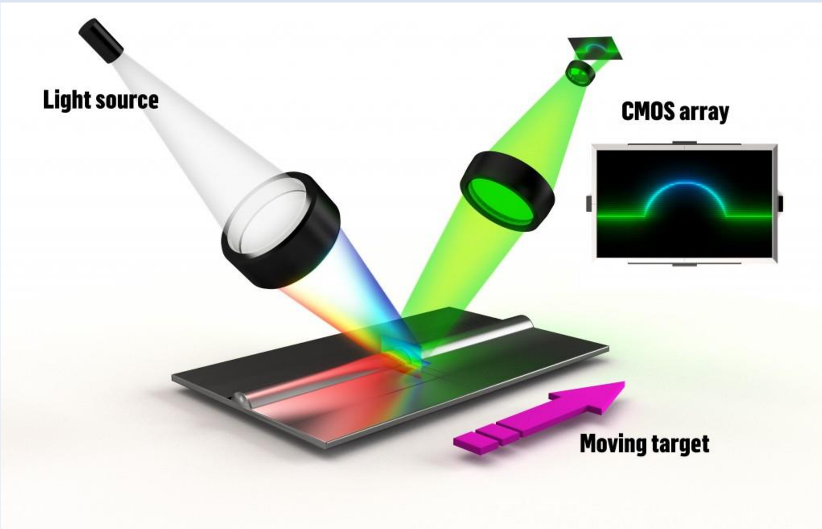
Other artefacts supported novel sensor development. Large area (230 mm or 9 in) calibration plates from a popular manufacturer were characterised at NPL for Loughborough University's activity; the results also enabled the manufacturer to identify a ten-fold improvement to plate manufacturing precision.

Highlight 8: Metrological characterisation methods for confocal chromatic line sensors

Fast confocal point and line sensors – often based on the confocal chromatic principle – are being used more and more for the in-line optical topography of deterministic structures: conductors, scribed channels, *etc.* but optical techniques are affected by optical surface properties such as reflectivity, specularity, roughness and colour. Industry needs not only robust, standard and practical methods to establish a 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.

VTT and the instrument manufacturing partner FocalSpec (FSPEC) worked to develop methods suited for optical line sensors to characterise scale magnification and linearity, sensitivity to sample properties, and dynamic characteristics. An accurate depth scale calibration method using a single prototype groove depth sample was developed for a line sensor and validated with laser-interferometric sample tracking, attaining a (sub-) micrometre level, or better than 0.1 % scale accuracy. The partners also looked at the effect of different surfaces and materials on the measurement and depth scale, especially slope angle, specularity and colour. Dynamic performance, noise, lateral scale and resolution were also characterised.

By using the new methods, FSPEC was able to show that their LCI 1200 sensor’s performance depends only minimally on sample colour, and identified a small (1 %) sample-dependent change for steep slopes at the edge of the field of view, which can now be addressed in planned development.



◀ *FSPEC’s lateral chromatic imaging (LCI) principle used in their line sensors*

5 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 and demonstrated 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.

6 List of publications

[1] Bellotti R, Furin V, Maras C, Picotto G B and Ribotta L 2018 A function-driven characterization of printed conductors on PV cells *Surf. Topogr. Metrol. Prop.* **6** 025002

[2] Bellotti R, Maras C, Picotto G B, Pometto M and Ribotta L 2018 3D characterization of printed structures by stylus- and optical-based measurements *Proc. euspen 18th Intl. Conf., Venice, IT, 04 – 08 June*

[3] El Gawhary O 2017 Helmholtz Natural Modes: The universal and discrete spatial fabric of electromagnetic wavefields *New J. Phys.* **19** 013021

[4] Feng X, Su R, Happonen T, Liu J and Leach R K 2018 Fast and cost-effective in-process defect inspection for printed electronics based on coherent optical processing *Opt. Express* **26** 13927

[5] Hornby R, Jones C W and O’Connor D 2017 Direction cosine space approach to period and alignment measurement for high speed optical metrology of gratings *Proc. EOS Top. Meet. on Diffr. Opt., Joensuu, FI, September*

[6] Jones C W and O’Connor D 2018 A hybrid 2D / 3D inspection concept with smart routing optimisation for high throughput , high dynamic range and traceable critical dimension metrology *Meas. Sci. Technol.* **29** 074004

[7] Jones C W, Santiano M, Downes S, Bellotti R, O’Connor D and Picotto G B 2016 A universal substrate sample fixture for efficient multi-instrument inspection of large, flexible substrates, with absolute position registration support *Proc. euspen 16th Intl. Conf., Nottingham, UK, 30 May – 03 June*

[8] Kouko J, Paakkolanvaara M and Retulainen E 2017 Measurement of Thermoplastic Properties of Packaging Materials *Proc. 28th IAPRI Symposium on Packaging, Lausanne, CH, 9–12 May*

[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

[10] Madsen J S 2016 Exploring the capabilities of the imaging scatterometry technique - Measuring nanostructures with visible light *Masters Thesis* University of Copenhagen

[11] Madsen J S, Hansen P-E, Bilenberg B, Nygård J and Madsen M H 2016 Measuring multiple nano-textured areas simultaneously with imaging scatterometry *Proc. euspen 16th Intl. Conf., Nottingham, UK, 30 May – 03 June*

[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

[13] Madsen M H, Boher P, Hansen P-E and Jørgensen J F 2016 Alignment-free characterization of 2D gratings *Appl. Opt.* **55** 317

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

[15] Madsen M H, Madsen J S, Bilenberg B, Dwarakanath D, Jørgensen J and Hansen P-E 2016 User-friendly Scatterometry *Proc. EOSAM 2016, Berlin, Germany, September*

[16] Madsen M H, Madsen J S, Hansen P-E, Boher P, Nygård J, Dwarakanath D and Jørgensen J F 2016 Comparison of Scatterometry, Imaging Scatterometry, AFM and Confocal Microscopy *Proc. 4M/ IWMF2016, Kgs. Lyngby, DK, 13–15 September* (Singapore: Research Publishing Services) pp 265–8

[17] Park I S, Middleton R J C, Coggrave C R, Ruiz P D and Coupland J M 2018 Characterization of the reference wave in a compact digital holographic camera *Appl. Opt.* **57** A235

[18] Remes K, Leppänen K and Fabritius T 2018 Thermography based online characterization of conductive thin films in large-scale electronics fabrication *Opt. Express* **26** 1219

[19] Seppä J, Niemelä K and Lassila A 2018 Metrological characterization methods for confocal chromatic line sensors and optical topography sensors Meas. Sci. Technol. 29 054008

7 Contact details

See the contact details on the cover page.